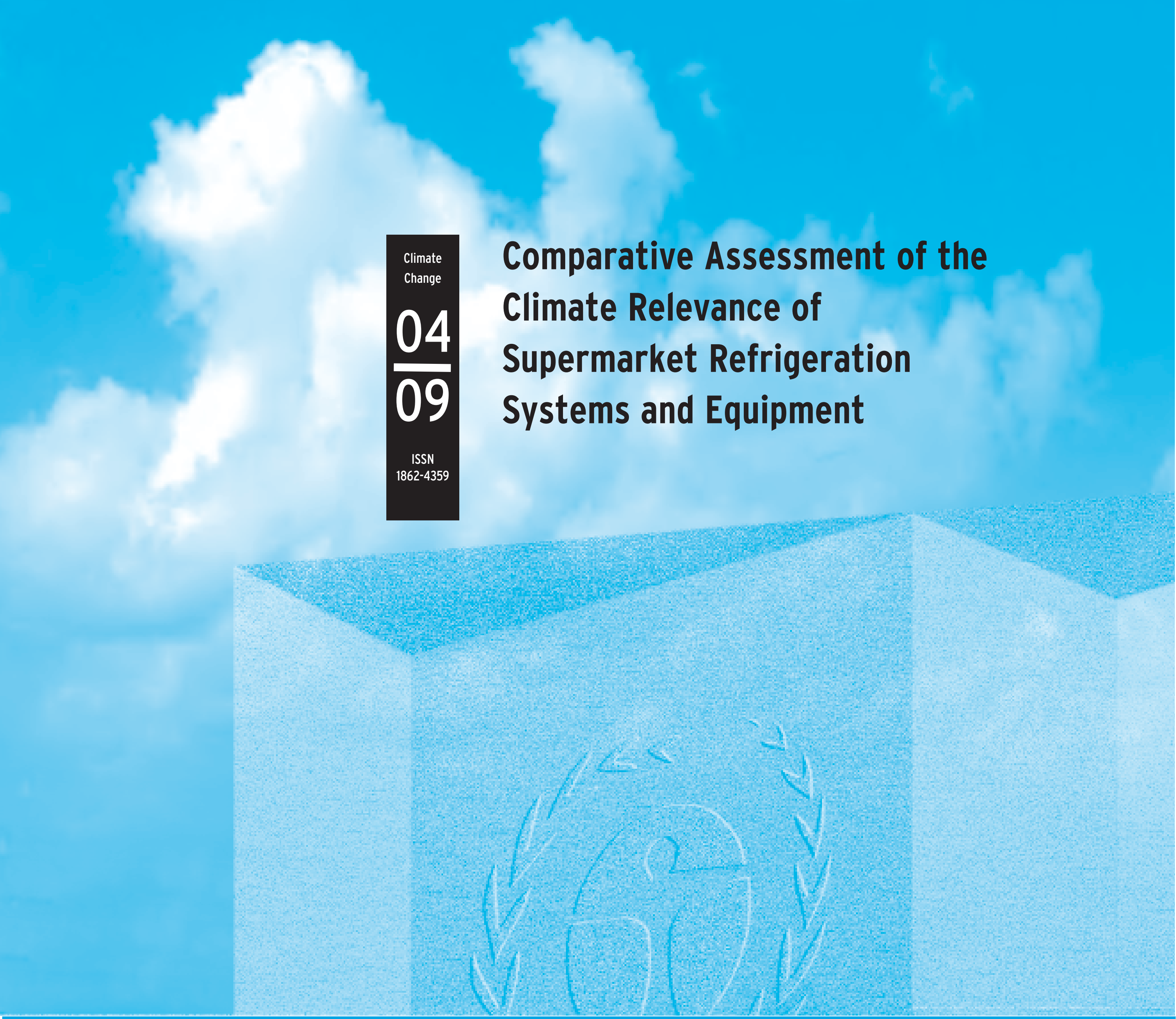
Climate Change



Climate Change

04
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ISSN
1862-4359

Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment

Umwelt
Bundes
Amt

Für Mensch und Umwelt

ENVIRONMENTAL RESEARCH OF THE
FEDERAL MINISTRY OF THE ENVIRONMENT,
NATURE CONSERVATION AND NUCLEAR SAFETY

Research Report 206 44 300
UBA-FB 001180/e

Climate Change

04 | 09

ISSN
1862-4359

Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment

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This publication is only available as download under
http://www.umweltbundesamt.de

The contents of this publication do not necessarily reflect the official opinions.
This publication is a translation of Climate Change 12/2008 "Vergleichende Bewertung der Klimarelevanz von Kälteanlagen und –geräten für den Supermarkt". The report was translated by Context GmbH (Dortmund).

Publisher:	Federal Environment Agency (Umweltbundesamt) P.O.B. 14 06 06813 Dessau-Roßlau Tel.: +49-340-2103-0 Telefax: +49-340-2103 2285 Internet: http://www.umweltbundesamt.de
Edited by:	Section III 1.4 Kerstin Martens / Katja Becken Dessau-Roßlau, March 2009

Report Cover Sheet

1. Report No. UBA-FB 001180/e	2.	3.
4. Report Title		
Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment		
5. Author(s), Family Name(s), First Name(s)		
Rhiemeier, Jan-Martin; Harnisch, Dr. Jochen; Ters Christian Ecofys Germany GmbH	8. Report Date 30.08.2008	
Kauffeld, Prof. Dr.-Ing. habil. Michael University of Applied Sciences – Karlsruhe	9. Publication Date March 2009	
Leisewitz, Dr. André Öko-Recherche GmbH	10. UFOPLAN-Ref. No. 206 44 300	
6. Performing Organisation (Name, Address)		
Ecofys Germany GmbH Landgrabenstrasse 94 D-90461 Nuernberg	11. No. of Pages 267	
University of Applied Sciences – Karlsruhe Moltkestrasse 30 D-76133 Karlsruhe	12. No. of References several	
Öko-Recherche GmbH Münchener Strasse 23 D-60329 Frankfurt am Main	13. No. of Tables, Diagrams 51	
7. Sponsoring Agency (Name, Address)		
Federal Environment Agency Postfach 14 06 D-06813 Dessau-Roßlau	14. No. of Figures 57	
15. Supplementary Notes		
The full version of the technology data sheets is only published in the German version of the report.		
16. Abstract		
In the first part, “Market Summary”, the present survey offers a comprehensive overview of HFC free refrigeration systems and equipment for supermarkets offered and applied in Germany and Europe. The second part, “Final Evaluation and Assessment”, provides information about the energy efficiency and economics of HFC free systems in comparison to conventional systems on the basis of the Total Equivalent Warming Impact (TEWI). Technical, economical, and structural barriers for the expansion of the future insertion of natural refrigerants are identified in the third part, “Barriers and Improvement Potentials”. Furthermore, steps are described for near and mid-term options for overcoming market launch barriers. Additionally, recommendations for potential subsidies for the promotion of HFC free refrigeration systems are developed.		
17. Keywords		
fluorinated greenhouse gases, commercial refrigeration, climate relevance, food retail industry, natural refrigerants, TEWI analysis, abatement costs		
18. Price	19.	20.

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COMPARATIVE ASSESSMENT OF THE CLIMATE RELEVANCE OF SUPERMARKET REFRIGERATION SYSTEMS AND EQUIPMENT
(FKZ 206 44 300)

After the entering into force of EU regulation (EC) No. 842/2006 and the EU directive 2006/40/EC, refrigeration systems in supermarkets remain the last big subsector and the strongest emission source of fluorinated hydrocarbons (HFC) in Germany.

With regard to existing improvement possibilities for components, technologies, and their application, the EU-political process up to now refrained from a use ban of HFCs in refrigeration systems and other applications. A central point for this decision was that it was not clear for certain important applications if comparable reliability, energy efficiency, and safety standards could be provided with HFC free technologies at adequate costs.

Though, a differentiated bundle of obligations for the operation, the maintenance, and the disposal of all bigger refrigeration systems was included into Regulation (EC) No. 842/2006. With regard to the ongoing review of the regulation the question positions itself whether this approach of the so-called "refrigerant containment" is sufficient as a sole measure for the reduction of HFC emissions, or whether use bans on the basis of further experience with alternative technologies seem more appropriate.

However, in wide parts of Europe and Germany the following problems arise for the majority of relevant refrigeration systems: Due to missing legal obligations to date, only limited experience with the use of HFC free refrigerants exists in the very cost-conscious retail market, so that a comprehensive and accurate data basis of energy efficiency and economics for systems operating without fluorinated greenhouse gases often does not exist. However, this is again necessary to justify further restrictions for the use of HFCs if necessary.

At this point the present survey starts. In the first part the survey offers a comprehensive overview of HFC free refrigeration systems for supermarkets offered and applied in Europe. The second part offers information about the energy efficiency and economics of the HFC free systems in comparison to conventional systems on the basis of the Total Equivalent Warming Impact (TEWI). In the third part technical, economical and structural barriers for the expansion of the future insertion of natural refrigerants are identified. Furthermore, steps are described for near- and mid-term options for overcoming market launch barriers. Additionally, recommendations for potential subsidies for the promotion of HFC free refrigeration systems are developed.

The fourth part of the project consisted in the hosting of an international conference named “Co_2oL Food - Climate Friendly Refrigeration in Supermarkets“ on the 22nd and 23rd of May, 2007 in Berlin. The event with more than 140 participants is not an object of this final report. The most important result of the conference was the clear trend in the retail sectors as well as technology suppliers towards environmentally friendly refrigeration concepts. Further results and presentations of the conference are available for download at: http://www.umweltbundesamt.de/produkte/fckw/CO_2ol.htm.

Market survey

The first part of the report contains a market survey of supermarket refrigeration systems that are completely or partially operated with HFC free refrigerants, including information on their actual market penetration in the EU. Beside the respective relevance of the technology in the market, it is also displayed to what extent appropriate operational experiences exist. In a detailed data compilation, the so-called technology data sheets, 30 main characteristics for *decentralized plug-in units*, *condensing units* and for *central multiplex systems* are given. These characteristics provide information on equipment data, refrigerant losses, energy consumption, life cycle costs, market share, operational experiences, and suppliers. Furthermore, all currently relevant refrigerants are described with regard to their physical properties, with an in depth look at their cost effectiveness and climate relevance for the food retail sector. The data compilation is based on an extensive literature research of scientific technical literature as well as on numerous interviews with manufacturers, suppliers, and retail representatives.

Beside the description of the equipment technology itself the market survey also offers an overview of the relevant store categories in which the respective technology is used, substantial details on energy saving measures, a compilation of leakage rates of supermarket refrigeration systems, as well as examples of already existing F-Gas regulations in selected European countries.

TEWI Analysis & Validation

This part of the report gives an overview of the emissions from refrigeration systems used in supermarkets and indicates abatement costs which arise by conversion of conventional systems to new systems with natural refrigerants.

The effect of a refrigeration system on global warming is described by the Total Equivalent Warming Impact (TEWI). The TEWI value of a refrigeration system describes according to DIN ISO 378-1 the sum of indirect emissions of the equipment from its energy consumption and direct emissions caused by refrigerant losses.
Due to the high amount of technical possibilities and the heterogeneous German market scenery, the model technologies to be examined were selected during two expert's meetings together with system providers and retail representatives for the following three store categories: discounter, supermarkets, and hypermarkets.
Great emphasis was put on a trusted empiric data base for the calculation of the TEWI analysis. Hence, refrigerants supplies and energy consumptions of the examined reference technology were determined in cooperation with several German retail chains. As reference technology a central multiplex system on the basis of R404A is defined for all three store categories. R404A is currently most often used in the German food retail sector.
Due to several factors, as for example weather conditions, equipment age, and consumer behavior, the energy consumption of refrigeration systems tend to considerable variability. Also one cannot extinguish the same typical refrigerant charge in every single system. Therefore a detailed uncertainty analysis was carried out with the help of Monte Carlo simulations. The Monte Carlo results clearly show that emissions of the examined model technologies in spite of high uncertainties vary only in a certain bandwidth, what allows robust comparisons of the respective climate impact of each model technology.

Other important input factors for the calculation of TEWI analyses are refrigerant leakages and losses. Refrigerant losses appear at all refrigeration systems. The extent of the losses caused by leakages depends on the complexity of the refrigeration system, the operating conditions, the quality of maintenance, and many other factors. The differences of reported leakage rates are accordingly high. To illustrate refrigerant losses adequately, the TEWI analyses are calculated for three different policy scenarios. In each policy scenario fix leakage rates according to political tightness restrictions are assumed. In practice higher leakage rates can appear because of unforeseen system damages through which considerable amounts of refrigerant escape. This case is examined in a sensitivity analysis separately.

On the basis of the TEWI results specific abatement costs are calculated for all selected model technologies. The calculated abatement costs show the costs per ton of avoided CO_2 equivalent relating to the reference technology. Abatement costs are also calculated for each different policy scenario, because costs as well as emissions vary according to tightness obligations.

As a result of the TEWI analyses it becomes clear that new CO_2 systems within the scope of all considered uncertainties significantly provide the environmentally superior solution compared to systems using R404A. For discount markets the significance does not persist for high leak tight systems (annual refrigerant loss of 2.65%) any more. The abatement cost calculation also shows, that the placing on the market can be realized at the moment still at rather high specific abatement costs, however, these will clearly decrease with increasingly stricter tightness obligations for conventional systems with HFCs and cost degression for systems with natural refrigerants in the near future. Table 1 summarizes the quantitative results from TEWI analyses and the abatement cost calculations for all examined technologies in a transparent way.

Particularly should be pointed out that in case of higher refrigerant losses as assumed in the policy scenarios, HFC free technologies offer considerably higher emission reduction potentials. In that case also abatement costs will decrease clearly for alternative HFC free technologies. Therefore the influence of refrigerant losses on emissions and abatement costs is analysed in a separate sensitivity analysis.

Table 1: Combined overview to TEWI results and abatement costs for different tightness scenarios and model technologies

		Tightness scenario 1 (11.65%)	**Tightness scenario 2** (6.15%)	**Tightness scenario 3** (2.65%)
Discounter				
I	**Reference system *)**	B-	B-	B-
II	R134adir. MT	A +	A +	B +
III	ind. R290 MT	A-	A-	B ++
IV	dir. 744 MT	A-	A-	B ++
Supermarket				
Ia	**Reference system *)**	B-	B-	B-
Ib	R134a MT+R404A LT	A-	A-	A-
IIa	R404A MT+R744 LT	B-	B-	B-
IIb	R134a MT+R744 LT	A-	A-	A-
III	ind. R717	A-	A-	B-
IVa	R717 / R744 MT+LT	A-	A-	A ++
IVb	R290 / R744 MT+LT	A-	A-	A ++
V	dir. R744	A-	A-	A +
Hypermarket				
I	**Reference system *)**	B-	B-	B-
III	ind. R717	A-	A-	B-
V	dir. R744	A-	A-	A ++

***)** R404A direct evaporation system

Coding of the evaluation

Climate balance:	**A** :	Significantly superior to the reference system
	B :	No significant difference to the reference system
	C :	Significantly inferior to the reference system
Cost-effectiveness:	**++** :	negative abatement costs
	+ :	abatement costs <=50 Euros per ton CO_2 equivalent
	- :	abatement costs > 50 Euros per ton CO_2 equivalent

The results show that, with regard to future investments in new refrigeration systems, beside the cost question also the right choice of refrigerant will increasingly matter. The actual public discussion about men made climate change shows that sustainable and environmentally friendly management becomes more and more important and also increasingly becomes a strong sales argument.
By applying the use of natural refrigerants in new systems certain retailers step towards environmentally friendly refrigeration already today, because thereby they can avoid double investments initially for compliance with higher tightness standards and then later for the installation of new technology with natural refrigerants.

A further strengthening for the use of fluorinated greenhouse gases is to be expected in Germany as well as throughout Europe during the next years. This is reflected for example by the “integrated energy and climate program” of the German Federal Government, published in August 2007, as well as in article 10 of regulation (EC) No. 842/2006 on certain fluorinated greenhouse gases, which foresees a review of the regulation by July 2011.

Barriers and Improvements

This chapter analyses the state of the art of refrigeration systems with natural refrigerants available in the market. A special focus is put on the further development of the CO_2 technology, because equipment and component manufacturer increasingly work on the market introduction and the improvement of the systems. Besides, essential barriers are indicated which prevent the use of new HFC free systems and complicate their expansion in the food retail sector. Here is to be distinguished between technical and economical barriers. Big technical barriers are the availability and the level of development of important components, above all for equipments with carbon dioxide. Due to the thermodynamic properties of CO_2, e.g. compressors, valves, and heat exchangers have to be entirely new designed. Currently, a large part of necessary components has not yet matured finally and is not available in the necessary width to carry out a quick introduction of the new technology in the market. As a consequence also economical barriers arise, because due to the missing readiness for the market of some components still no serial production could be reached so that prices for certain components stay high. This chapter indicates how economical and technical barriers can be overcome by a growing demand for CO_2 systems from the retail sector in the coming years.

For the support of an increased future use of natural refrigerants in the retail sector two possible measures for public funding are suggested. A financial supporting measure is suggested for the promotion of the demand for new systems with natural refrigerants within the scope of the “integrated energy and climate programme” of the German Federal Government. This demands a reduction of the German fluorinated greenhouse gas emissions of about 8 million tons of CO_2 equivalents under article 23. For the implementation a subsidy payment is planned to cover the extra costs for refrigeration systems in the food retail sector: This subsidy should be paid only under exclusive use of natural refrigerants and should intend a progressive rate for new systems in new or existing markets or for the substitution of an old R22 system. With a suitable subsidy volume and a change over to batch production of CO_2 systems the market launch can be made substantially easier.

The second funding measure is a competition. It should award a prize to the environmentally friendliest German supermarket. Within the scope of the competition new refrigeration systems with natural refrigerants and a low TEWI value should be awarded. The award of the competition can be a combination of public-relations symbolism as a main aspect and a (limited) financial incentive. Therefore an award in the form of a quality label, which also can be used for PR and marketing purposes, and a financial bonus, should be assigned to the winner.

The dimension of the suggested subsidy programme is likely to bring movement in a market whose dynamics is presently still limited by the existing cost thresholds of different actors (component manufacturers, system manufacturers, retailers). The competition additionally raises the attention for the climate relevance of refrigeration systems in the food retail sector, and helps to improve the public acceptance and demand for climate friendly refrigeration systems as well as their "image factor".

Additionally the energy saving potential of refrigeration systems through the implementation of cover sheets is analysed. The continuous covering of refrigeration units with sliding lids (chests) or doors (shelves) is considered as an important energy saving measure. The reduction potential is estimated up to 40 percent of the energy consumption compared to an open refrigeration unit. The fitting and retrofitting of refrigeration units, with continuous covers started about ten years ago. Beside the energy savings the better temperature guarantee for the chilled goods is a determining motive for the covering of refrigeration units. To be able to better estimate the meaning of this potential, the status of the current coverage quota in Germany was assessed by questioning relevant food retailers.

Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment” (FKZ 206 44 300)

Market Summary – Model Technologies

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Table of Abbreviations

BVL	Federal Association of German Food Trade (registered Association)
CFD	Computerized Fluid Dynamics
CO_2	Carbon Dioxide (R744), when referred to in this document as a secondary refrigerant (heat transfer fluid), will be abbreviated "CO_2", when used as a refrigerant, will be referred to as "R744".
DaiPro	Dairy products, that is milk, yogurt and cheese
DKK	Danish Kroner
DKV	German Refrigeration and Air Conditioning Association (registered Association)
EHI	European Retail Institute
F-Gas	Fluorinated Hydrocarbon
GWP	Global Warming Potential. As a rule, the indicated GWP values relate to a CO_2 time period of 100 years. Over the course of time the GWP values are adjusted in compliance with the latest research data. The text in this report always derives from the latest IPCC and as the case may be UNEP 2006 publicised values.
HACCP	Hazard Analysis and Control of Critical Points – of all steps, the preparation, processing, manufacturing, packaging, storage, transporting, distributing, handling and sales of chilled products.
HP	Heat pump
HR	Heat recovery
HTF	Heat Transfer Fluid (secondary refrigerant)

IDHL	Immediately Dangerous to Health and Life – Concentration levels of toxic chemicals that represent an immediate danger for humans.
FRI	Food Retail Industry
LCCP	Life Cycle Climate Performance – An analysis of the climate relevance of a product / process from its state of manufacturing until decommissioning.
LT	Low temperature, usually product temperature below -18 °C
MAC	Maximum allowable work place concentration level; defines the maximum allowable concentration of a substance as a gas, vapor or aerosol (that is breathed) at the work place, that is not expected to be detrimental to one's health, even if one were exposed to as a rule for 8 hours a day, a maximum of 40 (42) hours a week (shift operation).
MWp	Megawatt Peak – the maximum attainable performance of a solar power system generating electric power, calculated with optimum sun shine.
NH_3	Ammonia (R717)
MT	Medium Temperature, e.g. "plus cooling", product temperatures above 0 °C
NOK	Norwegian Kroner
ODP	Ozone Depletion Potential
PAG	Fully synthetic refrigeration machine oils based on polyglycol for applications with the refrigerant R134a and other HFCs; there are variations that are (partially) soluble in ammonia.
PAO	Fully synthetic refrigeration machine oils based on polyalphaolefins for applications with the refrigerant R717.

POE	Fully synthetic refrigeration machine oils based on polyolester for applications with R134a, R404A, R404C, other HFC (-blends) and R744.
R290	Propane
R600a	Isobutane
R717	Ammonia (NH_3)
R744	Carbon Dioxide (R744), when referred in this document as a secondary refrigerant (heat transfer fluid), it will be abbreviated “CO_2”, when used as a refrigerant, will be referred to as “R744”
SS	Self Service
TEWI	Total Equivalent Warming Potential – an examination of the overall green house contribution, this means that both the direct and indirect green house emissions have been weighed in.
VRF	Variable Refrigerant Flow – a type of multiple-split air conditioners, i.e. multiple vaporizers each with variable refrigerant flow to an external unit (condensing unit)

1. Introduction

This part of the report contains a market overview of refrigerants used in supermarket refrigeration equipment and devices which are either completely or partially free of halogens including information on their current market penetration in the EU. In addition to the respective ranking of the technology in the market, the report will also demonstrate to which extent practical experience with the technology is at hand.

First, all the model technologies and applications which are relevant for the EU were pooled together in a pre-selection. This pre-selection was based on all the information available. The market overview accounts for which ranking the individual model technologies have. As often as possible, the report specifies which store category[1] is the topic of discussion for that particular application.

Applications[2)] which have shown to be significant to the aim of this study are:

- bottle coolers,
- refrigerated counters,
- refrigerated shelves,
- refrigerated islands,
- freezers,
- freezer islands,
- refrigerated rooms, and
- freezer rooms.

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[1] At present, the significant categories are: self service (ss) grocery stores, grocery discount markets, supermarkets, consumer markets, and hypermarkets with their typical grouping upon sales area, see the description of significant markets in chapter 2.

[2] This choice of application orients itself towards the typical refrigeration units used in commercial refrigeration.

The information in this report has been structured according to the recommendations from the contracting authority, the Federal Environmental Agency, on how to categorize model technologies.[3]

- Decentralized plug-in refrigeration units
- Individual equipment with an external condensing unit
- Central multi-compressor refrigeration systems

Provided they were available, the following thirty attributes have been determined for each model technology and documented in technological data sheet form.

Refrigeration Data

1. Intended use
2. Refrigeration (power) output range
3. Type of cold transfer
4. Type of refrigerant
5. Refrigerant charge

Refrigerant Loss

6. Typical refrigerant losses
7. Source of the refrigerant loss information
8. Type of refrigerant discharge
9. Destination of the refrigerant after decommissioning

Energy

10. Energy consumption
11. Possibility of implementing waste heat recovery
12. Other possibilities to conserve energy
13. Climate and operational conditions at which the respective data was retrieved

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[3] The terms “decentralized plug-in refrigeration unit” and “central multi-compressor refrigeration system” are principally a case of double terminology restating the same point. To explain, plug-in refrigerator units are used de-centrally and central multi-compressor refrigeration systems are usually centrally arranged. However, these are basic refrigerator laymen terms, used by people who usually aren’t aware they are using double terminology. For this reason they will be used both within the framework of this study.

Life-Cycle Costs

14. Investment / component costs
15. Installation costs
16. Operating costs
17. Maintenance intervals
18. Maintenance costs

Market Share

19. Number of installed equipment and systems
20. Regional distribution

Operational Experience

21. Estimate of the number of years of operational experience, in cases where no concrete data is available
22. Details about the reliability
23. Eventually, problems unique to that technology
24. Description of attributes unique to that technology
25. Possibility of application if a supermarket were to be modernized
26. Significant details about the safety of the equipment / system

Sources

27. Manufacturer
28. Eventually, Importer
29. Component Manufacturer
30. System operator

The following methods were applied to gather the required data:

- Statistically verified user company data
- Scientific literature
- Relevant data bases, e.g. FRIDOC (IIR), SCOPUS
- Data from manufacturers and suppliers
- Interviews and
- Own estimates

1.1 Statistically verified user company data

The companies EPTA (D), Frigo-Consulting (CH), Hauser (A), KWN Engineering (A), Linde/Carrier (D), and SSP Schmutz, Starkl and Partner (CH) have provided data that have been evaluated within this project.

1.2 Scientific Literature

The evaluation includes the following literature:

- DKV status report No. 20: Carbon Dioxide, 3rd revised issue 2006, and No. 22: Energy demands for the technical generation of low temperatures, June 2002.
- Forschungsrat Kältetechnik, significant research reports
- IEA Annex 26: Advanced Supermarket Refrigeration/Heat Recovery Systems

Scientific journals:

- ASHRAE Journal (online archive 1997 – 2007)
- hk gebäudetechnik (CH) (2005 – 2007)
- Ki Luft- und Kältetechnik (online archive 1994 – 2007)
- KK (online archive 1997 – 2004)
- KKA (2004 – 2007)
- Koude & luchtbehandling (NL) (2006 – 2007)
- Kulde (N) (2004 – 2007)
- Scanref (DK) (2004 – 2007)

Conference transcripts:

- DKV annual conferences 2005 in Würzburg, 2006 in Dresden, and 2007 in Hannover
- Greenpeace London Workshop 2006
- IEA Annex 31 short course in Peking, China on the 25th of August 2007 (http://www.energy.kth.se/index.asp?pnr=10&ID=1270&lang=1)
- IIR Gustav Lorentzen Natural Working Fluids, Glasgow 2004 and Trondheim 2006
- IIR Congress of Refrigeration, Washington D.C. 2003 and Peking 2007
- IIR Commercial Refrigeration, Vicenza 2005
- IIR Ammonia, Ohrid 2005
- IIR Refrigeration Science and Technology, New Zealand 2006

Internet discussion sites, partially with lectures from conferences and seminars:

- Forum for Heating, Refrigerating and Air-Conditioning Engineers, Norway (FOKU), www.foku.org
- Information service for HFC-free refrigeration systems in Denmark, www.hfc-fri.dk
- ProCool, www.procool.info
- R744 Information platform, www.r744.com
- VDA Alternative Refrigerant Winter Meetings Saalfelden, http://www.vda-wintermeeting.de/

Further, miscellaneous publications in the context of different dissertations, projects of the International Energy Agency (IEA), different energy providers (e.g. Southern California Edison) and associations (e.g. Asercom and Eurammon). Quotations from these sources are marked in this report and the reference to the corresponding literature can be found at the end in the chapter literature. The following labelling has been used [Last Name1234] – Last Name of the first author and four-digit year of publication; in cases where the publishers / authors are not persons, the name of the organization has normally been used, e.g. “UNEP“. If an author has made several publications in the same year an a, b or c will appear after the year.

Additional quotations taken from other literature sources can be found in the section “Technological Data Sheets“. The respective references can be found there listed immediately in connection with the corresponding technology.

1.3 Pertinent Data Bases, e.g. FRIDOC (IIR), SCOPUS

- FRIDOC IIR Data Base
- SCOPUS (Elsevier Data Base)

Search Terms: supermarket, supermarket cooling / supermarket (refrigeration)

1.4 Data from Manufacturers and Suppliers

- Bitzer on compressors and condensing units
- Bock on compressors and condensing units
- Danfoss on hermetic compressors
- Dorin on R744 compressors
- Epta on multi-compressor refrigeration systems
- Frigoglass, Liebherr, Mammut et. al. on plug-in units
- Georg Fischer on plastic piping systems
- Hauser on multi-compressor refrigeration systems and energy conservation
- Linde/Carrier on multi-compressor refrigeration systems

1.5 Interviews

The following interviews were conducted and are listed in chronological order:

- Thomas Tiedemann, Danfoss USA, on 10th of Dec. 06 to the topic „Plug-in refrigeration units”.
- Per Henrik Pedersen, Danish Technological Institute, on 11th of Dec. 06 to the topic „Plug-in refrigeration units”.
- Bernd Kaltenbrunner, KWN, on 10th of Jan. 07 to the topic „Multi-compressor refrigeration systems with heat transfer fluids“ on 13th Sep. 07 to the topic „Distributed systems”.
- Mark Bulmer of Georg Fischer on 10th Jan. 07 to the topic “Multi-compressor refrigeration systems with heat transfer fluids“.
- Udo Görner, BKT/EPTA, on 12th and 18th Jan. 07 to the topic „Multi-compressor refrigeration systems using R744 and HFC“.
- Bernd Heinbokel, Erik Wolfgang Bucher, Linde/Carrier, on 18th Jan. 07 to the topic „R744“.
- Holger Schneider, Aldi Süd, on 18th Jan. 07 to the topic „R744 and HFC in multi-compressor refrigeration systems and R290 in plug-in chest freezers“.
- Thomas Bader, Tebeg (refrigeration agent from Aldi Süd) on 18th Jan. 07 to the topic „R744 and HFC in multi-compressor refrigeration systems and R290 in plug-in chest freezers“.
- Gerd Haug, Zent-Frenger, on 23rd Jan. 07 to the topic „Waste heat recovery“.
- Erik Wolfgang Bucher, Linde / Carrier, on 24th Jan. 07 to the topic „R744 and HFC in multi-compressor refrigeration systems“.
- Mr. Post, Linde/Carrier, and Mr. Empen and Mrs. Tischler from the company Gebauer (EDEKA) on 7th Feb. 07 to the topic „R744 used as a cascade to HFC in low temperature”.
- Mr. Brouwers, Mr. Bucher, Mr. Heinbokel, Mr. Haaf, Mr. Kammler, Linde/Carrier, on 14th Feb. 07 to the topic „Multi-compressor refrigeration systems”.
- Bjarne Dindler Rasmussen, Danfoss in Denmark, on 27th Feb. 07 to the topic „Control and components for R744 multi-compressor refrigeration systems“.

- Jan Hellsten, Temper in Sweden, on 7th March 07 to the topic „Heat transfer fluids”.
- Steffen Vogelbacher, Daikin, on 20th March 07 to the topic „Conveni-Pack“.
- Kenneth B. Madsen, Danish Technological Institute, on 11th April 07 to the topic „Supermarket refrigeration systems in Denmark“.
- Alexander Cohr Pachai, Johnson Controls (York/Sabroe Cooling Technology) on 22nd May 07 to the topic „CO_2 – Cascade refrigeration units“.
- Mats Schenk, Frigotech, while visiting two supermarkets in Stockholm, Sweden, on 8th June 07.
- Tobias Sienal, Carrier/Linde, on 24th Aug. 07 to the topic „R744“.
- Deepak Perti, DuPont, on 25th Aug. 07 to the topic „New synthetic refrigerants with low GWP“.
- Dirk Raudonus and Joachim Schadt, Lidl, on 13th Sep. 07 on discounter refrigeration units.
- Jörg Peters, the German Federal Technical Institute for Refrigeration and Air Conditioning (Bundesfachschule Kälte-Klima-Technik), on 3rd Oct. 07 to the topic „Glass doors / -lids and leakages“.

Furthermore, numerous discussions took place within the EUROSHOP fair 2008 on 26th and 27th Feb. 08 in Düsseldorf, Germany, with representatives from the following companies:

- Hauser, Carrier/Linde, Epta, Daikin, J+E Hall and Frigo Consult to the topic multi- compressor refrigeration systems.
- AHT, Hauser, Carrier/Linde, Epta to the topic plug-in units.
- Hauser, Coolexpert, and Prof. Becker to the topic control for multi-compressor refrigeration systems and the integration of technologies designed for the entire building under a superior control system.
- Schott Glass, Behr, Anthony International to the topic glass doors.
- Georg Fischer, Flexi Chiller, Area, Indirect Cooling Technology, and Pipetech to the topic secondary refrigerant systems.
- Philips to the topic LED illumination.
- Aldi Süd, Kaufland, and Lidl to the topic implementing energy-saving solutions and alternative refrigerants.

During all of these meetings any opportunities for energy-saving were also discussed.

While collecting the data especially for halogen-free model technologies, an EU-wide search was conducted for documented use because in Germany, even in large retail store chains, equipment operated with halogen-free refrigerants is rare. Halogen-free technologies can be found above all in the Scandinavian countries that are subject to strict regulations regarding F-gas-control. Details about laws in countries exceeding the European F-Gas regulations are covered in chapter 4, also included are the implications on the supermarket cooling area. There are many technologies where only a few publications exist. Oftentimes, the publication will only do a case study type of reporting. What is missing for many technologies is a sufficient broad statistical data base. Nevertheless, individual installations can be used as an indicator, for example, as to how the energy consumption for that type of installation can be.

2. Description of the relevant Markets

The food retail industry (FRI) for the end consumer in Germany incorporates the following store categories (this is categorized according to the sales area size) [EHI2001],[4] see accordingly also table 1.

- Gas stations with convenience stores,
- Small grocery stores with self service,
- Grocery discount markets,
- Supermarkets,
- Consumer markets, and
- Hypermarkets, respectively.

Gas stations with convenience stores typically have open refrigerated shelves for drinks, bottle coolers, and chest freezers for ice cream. The sales area is clearly smaller than 400 m².

Small Grocery stores with self service have a sales area that is smaller than 400 m². The assortment is predominately foods.

Grocery discount markets have a sales area that is generally between 400 and 800 m². A food discount store is a grocery that focuses on high volume articles [EHI2001]. The share of food related items in these stores is 80 to 85 %.

Supermarkets typically have a sales area between 600 and 1,500 m² and in some cases up to 2,500 m² [DKV2002]. A supermarket is a self service grocery store with a sales area of at least 400 m² that has a food assortment which includes fresh products and also has a section reserved for non-food items not to exceed 25 % [EHI2001].

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[4] There are other classification possibilities. A subdivision of the markets and the grocery stores with self service with more steps can be found for example in [Jakobs2006]; a broader subdivision can be found in [BVL2007].

Consumer markets typically have a sales area between 1,500 and 5,000 m². The sales area reserved for groceries amounts to approximately 1/3 of the entire sales space [DKV2002].

Hypermarkets typically have a sales area that is larger than 5,000 m². The sales area reserved for the sale of groceries amounts to approximately 1/3 of the entire sales space which can be as large as 20,000 m² [DKV2002]. Notably, it is the French who label these large self service stores as “hypermarkets”. In France these “hypermarkets” can have a sales area up to 25,000 m² of which between 25 to 40 % is dedicated to groceries [Zoughaib2005].

The following document describes the refrigeration technologies presently in use in grocery discount markets, supermarkets, consumer markets, and hypermarkets. Aside from that, there are also the so-called “cash and carry markets”. These are large cash and carry markets that do not sell to the end consumer [Jakobs2006]. In the technology data sheets there is a description of the methods which to date have only been implemented by the cash and carry markets, this however will not be receiving special attention in the scope of the TEWI analyses in part 2 of the study.

In fact, small grocery stores with self service represent a large group, see 3.1; however, they use very small refrigeration units with correspondingly small refrigerant capacities compared to the larger super markets. Because of this, it has been decided not to include the small grocery stores with self service in the scope of this study.

3. Individual Market Forms

3.1 Germany

Store categories

According to a study of the German Refrigeration and Air Conditioning Association (DKV), there were approximately 38,000 food retail self service stores in Germany in the year 2000, see table 1 for the classification of the individual store categories. [DKV2002].

Information Resources GmbH (IRI) indicated that for the end of 2005 there were 49,600 food retail stores, see table 1 [IRI2006]. At the same time, a trend was indicated for the industry showing a decrease in the total number of supermarkets. IRI indicated a decrease of 25 % from the years 2000 to 2006. When one compares the total number from DKV for the year 2000 with the decrease of 25 % from IRI, this is confirmed. During the same time the number of food discounters has continually increased, while the number of conventional food retailers has decreased [IRI2007], see also 3.4 Market Development. Similar numbers and tendencies have been indicated by the Federal Association of German Food Retailers e. V. and the EHI Retail Institute [BVL2007, EHI2007].

Jakobs indicated a total of 57,175 (FRI)[5] food retail stores for 2005 [Jakobs2006]. Irregularities with the IRI-Data are found above all with the small food stores with self service, with the supermarkets, and with the consumer markets.

Table 1: Size and Number of Various Store Categories

Store Category [EHI2001]	Area in m²	Percentage of food products	Year 2000 [DKV2002]	Year 2005 [IRI2007]	Year 2005 [EHI2007]	Year 2006 [EHI2007][5]
Self service food stores and markets	< 400	> 90 %	38,000	26,870	32,740	28,900
Food discounters	400 – 800	80 – 85 %	13,000	14,800	14,745	14,806
Supermarkets	600 – 1,500 (2,500)	> 75 %	9,000	6,190	8,430	8,170
Consumer markets	1,500 – 5,000	ca. 30 %	1,600	1,030	2,995	3,150[7]
Hypermarkets	5,000 – 20,000	ca. 30 %	650	710		
Total			62,250	49,600	58,910	55,026

According to a VDMA survey in the year 2000, there were approximately 17,000 gas stations in Germany. The typical performance requirement for chilled goods used in mid-sized gas stations is around 12 to 15 kW [DKV2002]. The number of gas stations in Germany is again declining [IRI2006]. Correspondingly, there were still 15,187 [IRI2006] in the beginning of 2006 and 15,036 in the beginning of 2007, showing a regressive tendency of approximately 150 per year since 1999 [ARCD2007]. Gas station shops will not be included within the scope of this study.

3.2 Other Parts of Europe

In Southern and Eastern Europe there are considerably more small food retail stores and fewer supermarkets. Figure 1 shows the per capita number of food retail stores in all EU member states. Assuming that, in all countries, approximately the same amount of food will be bought per capita, in countries with few food retail stores per capita such as Germany or Holland, it is clear that the size of the individual store has to be larger than in countries with a lot of food retail stores per capita like in Bulgaria or Greece.

[5] The estimated 30 food retail services in department stores will not be considered.
[6] The EHI-Data for 2007 is preliminary.
[7] Food retail services in department stores have been included in the data from the EHI, e.g. 127 Kaufhof and 67 Karstadt.

Figure 2 itemizes the size of the food retail stores for each country confirming this assumption.

The food discounters were primarily a German (Aldi, Lidl, Netto, Norma, Penny, Plus etc.) and Danish (Fakta, Netto, Rema1000 etc.) phenomenon. However, now these discounters are moving into other European countries and it is especially the German chains that are opening stores abroad.

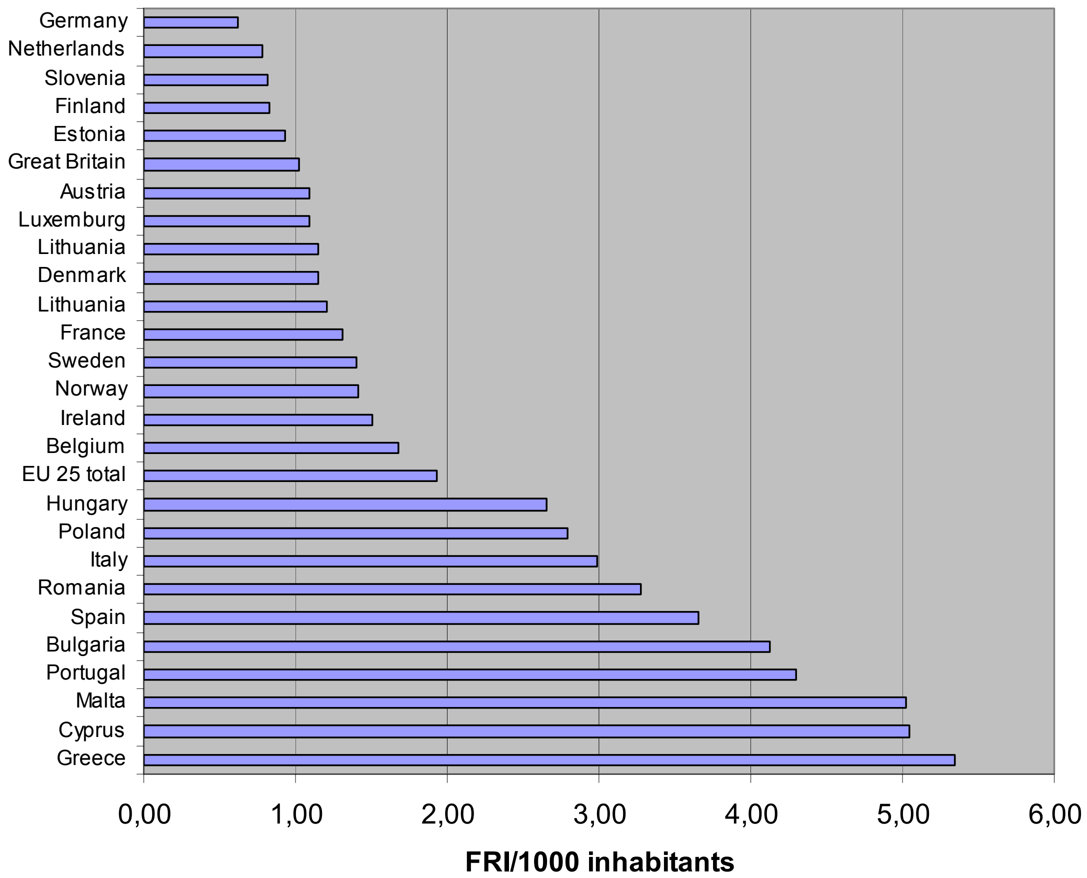

Figure 1: Number of food retail stores per 1,000 inhabitants for EU 27 based on available data. Number of (FRI) food retail stores from [Eurostat2004], number of inhabitants from [Eurostat2007].

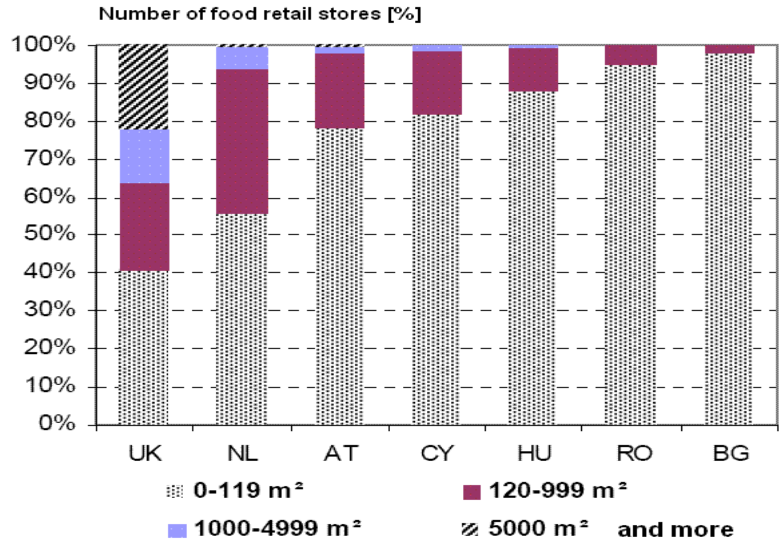

Figure 2: Number of food retail stores in percent according to their sales area (m²) for countries for which data were available for the year 2002 [Eurostat 2006]. The retail stores encompass food and non-food-retail sales (not including gas stations and not including retail stores with vehicles). Food sales made up about 44 % of all retail sales turnovers [Eurostat2006] in 2002 EU-25-wide.

3.3 USA

Some of the model technologies described, see the technology data sheets, can only be found in the USA. In some cases, studies, especially comprehensive and accessible to the public, which include also energy consumption data, can be found in the USA on technologies that are also used in Europe. In this report, in order to better evaluate the data, it is necessary to know about several particularities concerning the American market. Among others, differences that come to mind when comparing the USA with Germany are:

– the opening hours that in general are from 6 to 24, for the so called Supercenters 24 hours a day seven days a week [MacDonald2007];
– the space available, the American markets generally have wider aisles;
– the air quality, American markets are almost without exception with air conditioning;
– and the level of knowledge of the refrigeration technicians: vocational training lasting several years does not exist in the USA.

The status report from the DKV (German Refrigeration and Air Conditioning Association) No. 22 indicated that there are 30,000 supermarkets in the USA with central refrigeration units [DKV2002]. The source for this data comes from the year 1996, which means that this was most likely the number of American supermarkets from the year 1994 or 1995. The EHI Retail Institute indicated that for the 24 largest food retail companies in the USA (not including 7-Eleven) in the year 2006, there were 30,247 sales outlets, as well as for the five largest convenience store operators there were 15,223 sales outlets [EHI2007]. The American trade magazine “Supermarket News” with its listing of the top 75 supermarket chains with the highest turnover for the beginning of 2008 listed 41,120 supermarkets and convenience stores [SN2008]. With approximately 300 million inhabitants in the USA this corresponds to a supermarket density of app. 0.13 per 1,000 inhabitants compared to app. 0.7 per 1,000 inhabitants for Germany, see figure 1. There are however other clearly higher numbers for the USA. Faramarzi indicated for the year 2003 that there were 199,000 supermarkets that have a collective consumption of 95.8 TWh of electrical energy [Faramarzi2004]. The annual energy consumption is between 463 and 754 kWh/m², of which app. 50 % are applicable for refrigeration (without air conditioning) [Faramarzi2004], see figure 3. The costs for the energy consumption can be higher than the revenue from the supermarkets that are typically 1.2 % [Faramarzi2004]. Still refrigeration units are chosen solely based on investment costs [Faramarzi2007].

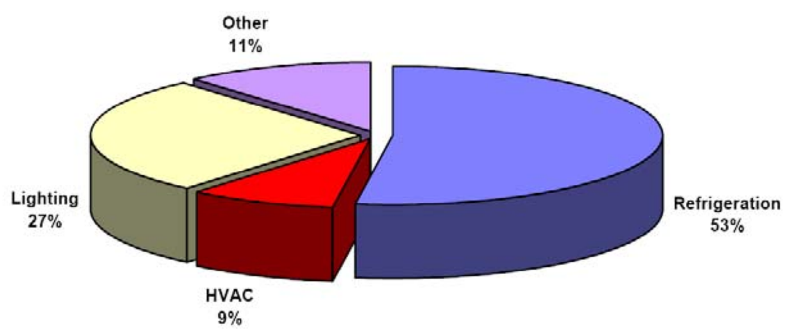

Figure 3: Energy consumption in a typical American supermarket with app. 4,650 m² and an energy consumption of 4.65 kWh/m² [Faramarzi2004].

The training situation for the American refrigeration technician is often worse than that of the German refrigeration technicians. At the same time, the American supermarkets are larger and use refrigeration units that consist of many more meters pipe and more refrigerated display cases. This results in higher leakage rates up to 30 % [Walker 1999]. The legislators permit a maximum annual average of leakages of 35 % (Clean Air Act, Section 608).

In the USA a project by the name of “EPA (Environmental Protection Agency) GreenChill Partnership” has been underway since the year 2007 where the supermarket chains can voluntarily submit data about their energy consumption and refrigerant leakages. The data will be analysed by Oak Ridge National Laboratory. Results are to be published in the middle of 2008. Up till now the willingness of the supermarket chains to submit data has been if anything bad [Perti2007].

3.4 Market Development

The overall development in the sector of food retail stores shows Germany having more discount markets with the same amount of large and less small food retail stores. In Eastern Europe one can expect more supermarkets and therefore less small food retail stores [IRI2007]. In all of Europe, there is an increase in the “discount and hypermarket” types of markets, however with respect to large areas the speed of growth is smaller [BVL2007]. Figure 4 shows the development in the last 27 years in Germany. This development toward more discount markets is even more obvious when one considers the profit development over the last 17 years, figure 5 [RP2007].

In Germany the volume of chilled products is increasing and with that the size of the refrigerated area. This is due to the expansion of the service area for meat and cheese (especially in large markets), an increase of the temperature controlled convenience products as well as the expansion of the dairy and freezer assortments [Lambertz2008].

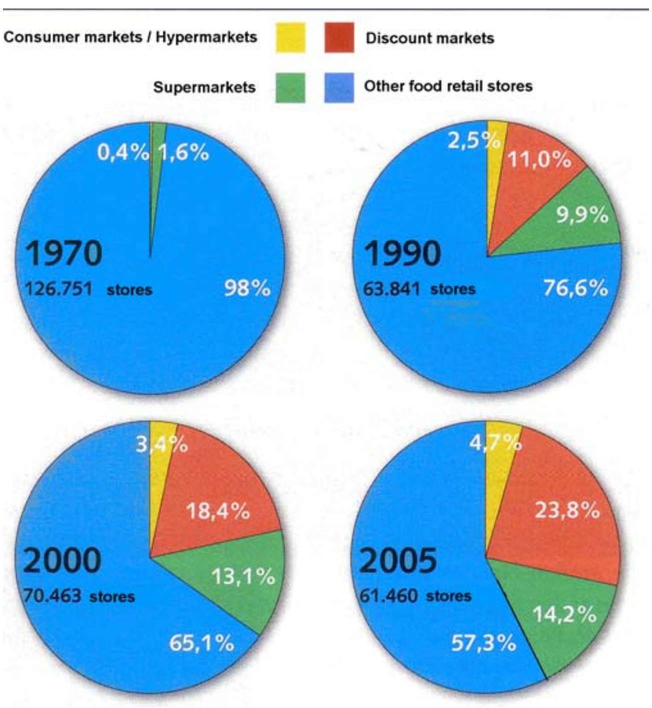

Figure 4: Number of food retail stores according to their business form 1970 – 2005 in relation to current market [IRI2007].

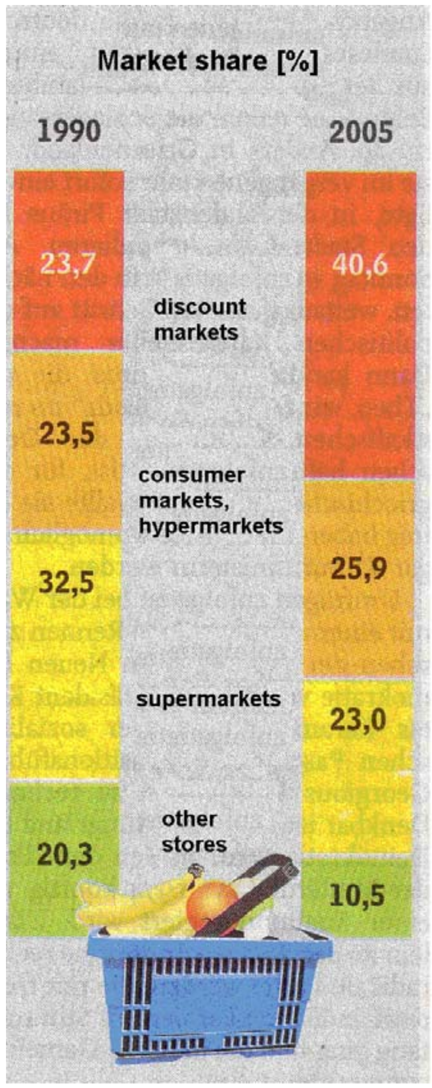

Figure 5: Market Share according to business form 1990 and 2005 following EHI [RP2007].

4. Legislation on F-Gases

4.1 EU F-Gas Regulation

In the EU, as of the 4th of July 2007 all stationary refrigeration units with fluorinated hydrocarbons must comply with the so-called F-Gas regulation (Regulation (EC) No. 842/2006). Among other things, the F-Gas regulation prescribes regular checks for tightness of the system, e.g. a unit with a refrigerant charge of more than 30 kg must be checked for leakages every six months and units with a charge of more than 300 kg are to be checked every three months. Units with a charge of more than 300 kg of fluorinated refrigerants are to be fitted with a leak detecting system[6]. For units with a smaller charge it is allowed to lengthen the time interval between system checks provided it has been fitted with a leak detecting system that functions according to the regulation. These measures are supposed to reduce greenhouse gas emissions. Within the scope of the F-Gas regulation there are however no restrictions on the use of the fluorinated refrigerants for stationary equipment.

Individual countries (e.g. Denmark, Netherlands, Norway, Austria, and Sweden) have regulations that function more or less restrictive. These countries have been listed below with their regulations in alphabetical order.

4.2 Denmark

In Denmark there are about 2,200 supermarkets [Bertelsen2002]. Since 1st January 2007 a prohibition of HFC has been imposed for the whole refrigeration industry including systems with refrigerant charges of more than 10kg. According to EU decision, the Danish prohibition is provisory permitted to be in force until 2012.

Further, in Denmark a CO_2 tax is collected for the emission of greenhouse gases. This is collected in connection with the generation of electrical energy from gas or coal as well as from the fuelling of heating oil. The customer pays the CO_2 tax when

[6] A comprehensive overview of leak detecting systems is given in “Forschungsvorhaben FKT 118/05 of the “Forschungsrat Kältetechnik e.V” [FKT2007].

purchasing current, fuel or heating oil. Since 1st March 2001 this CO_2 tax is also collected when purchasing refrigerants with a high global warming potential. Currently, the CO_2 tax is 100 DKK per ton CO_2 (0.10 DKK/kg) on average. Initially, this tax was introduced to create an incentive for energy saving. Based on this CO_2 tax, since several years a CO_2 tax is also collected for other greenhouse gases where the rate of 0.10 DKK per kg CO_2 equivalent is used. The upper limit of the tax is capped at 400 DKK/kg. Table 2 contains the greenhouse gas tax for refrigerants normally used in supermarkets which are collected in addition to the recycling charge (SME – 30 DKK/kg corresponding about 4 €/kg) and value added tax (25 %).

Table 2: Danish greenhouse gas taxes for selected refrigerants, (state 2007) [http://www.skm.dk/tal_statistik/satser_og_beloeb/184.html]

R134a	130 DKK/kg [1)]	ca. 17.33 €/kg
R404A (HFC-143a/HFC-125/134a)	378 DKK/kg	ca. 50.40 €/kg
R507A (HFC-125/HFC-143a)	385 DKK/kg	ca. 96.25 €/kg

1) 1 EUR corresponds to about 7.5 DKK.

In Denmark, the tax on greenhouse gas is not refunded with the return of refrigerants because it was not imposed upon refrigerants already used in systems before the enactment of the law. Even if from the point of view of environment policy this would make sense, the Danish treasury was afraid of an infringement against EU legislation because with the return of refrigerant it is not obvious whether a tax had been paid or not [Jensen2007].

In the aftermath of the tax on greenhouse gas several different supermarket refrigeration systems without F-gases were installed in the years 2001-2006, where the number in comparison with the entire Danish supermarket refrigeration sector of about 200 new systems per year had a quite moderate magnitude [Madsen2007]. The additional costs caused by the Danish tax on greenhouse gas for a standard HFC system were not high enough in order to justify the surplus expenditure for HFC-free system technology. Since the enactment of the charge limit of 10 kg for HFC as of 1st January 2007, almost only systems with natural refrigerants or those with very small refrigerant charge were built. As the entire Danish refrigeration industry does not have the same knowledge, at the moment many faults are made partially in connection with system engineering [Madsen2007]. In Denmark, the legislation was significantly faster than the corresponding training of the refrigeration technician. Only short time before the enactment of the HFC prohibition as of 1st January 2007 adequate consulting measures were offered based on governmental subsidy payments. For each “task” a free 5-hour consulting of an experienced engineer is offered [www.hfc-fri.dk]. This free consulting is paid by the Danish state for three years (2007 up to 2009).

4.3 Netherlands

Since 1992 there is a program in the Netherlands which aims to increase the tightness of refrigeration systems: STEK. The leakage rates reported lie at 4 to 5% [Maaten2007 and Yellen2002]. However, the efficiency of STEK and the leakage rates reported is not without debate. In accordance with the leakage information reported, the rates increase from 4.5 % up to 12.6 % [Anderson2005].

4.4 Norway

In Norway even higher taxes on greenhouse gases than in Denmark are collected on all refrigerants. Table 3 shows an extract taken from these taxes. Since 2007 the tax rate has been increased to 0.19 NOK/kg CO_2 equivalent so that the cost for R404A now amounts to about 740 NOK per kg. In Norway, the tax on greenhouse gas is redeemable in connection with the return of refrigerant used. Contrary to Denmark, Norway is not a member of the EU and therefore it had not to fear any infringement against EU legislation.

Table 3: Norwegian greenhouse gas taxes on selected refrigerants, state 2007 [Toll2007]

	Until 2007		As of 2007	
	NOK/kg [1)]	€/kg	NOK/kg [1)]	€/kg
R134a	243	ca. 31.60	252	ca. 32.50
R404A	610	ca. 79.20	632	ca. 82.10
R507A	617.50	ca. 80.20	640	ca. 83.10

[1)] 1 Euro corresponds to about 7.7 NOK.

Furthermore, the Norwegian retailers and refrigeration technicians consider the discussions within the EU F-gas regulation as a sign that the time for HFC applications will be limited. Therefore the different Norwegian retail store chains (COOP, IKA, Rema and Norgesgruppen) respond very positively to natural refrigerants [Bakken2007].

4.5 Austria

In Austria, since 2002 a corresponding regulation is in force governing the use of partially fluorinated and fully-fluorinated hydrocarbons, the HFC-PFC-SF_6 regulation (Industriegas-V, BGBl. II Nr. 447/2002, with amendments from BGBl. II Nr. 86/2006 and Nr. 139/2007). Virtually, it is a HFC prohibition. In practice, however, there are no real restrictions achieved by means of upper limit refrigerant charges of 100 kg or 1.5 kg per kW cooling capacity related to “locally fixed systems with distributed piping”, i.e. supermarket refrigeration systems [Kaltenbrunner2007].

4.6 Sweden

Until the enactment of the F-gas regulation, in Sweden (about 6,060 supermarkets in 2003 [Jansson2004]) the maximum refrigerant charge allowed in a refrigeration system was restricted to 20 kg for medium temperature and 30 kg for low temperature [Colbourne1999]. In total, any refrigeration units and air conditioning devices were not allowed to exceed 200 kg [Schenk2007]. Therefore a lot of indirect refrigeration systems were manufactured in any sector of refrigeration technology and these were divided into many small systems. Concerning indirect systems, the development moves towards small systems ex factory with plate heat exchangers, which on the warm side are connected to a glycol cycle with a dry cooler and chill the coolant (secondary refrigerant / heat transfer fluid - HTF) on the cold side. In large consumer markets with several thousand square meters in sales area one can find by far more than ten of such parallel-switched systems. By reason of manufacture ex factory, the tightness of the individual system is significantly higher than that of a conventional multi-compressor refrigeration system. Furthermore, in case of a breakdown only the charge of one system will leak, that is about 20 up to 30 kg. Many small systems offer also an easy adjustment of performance so that Swedish indirect refrigeration systems often consume less energy than comparable multi-compressor refrigeration systems [Hellsten2007].

4.7 Switzerland

Since 2007 a so-called “Minergie-Label“ for points of sale exists in Switzerland. This voluntary directive allows, among other things, an energy consumption of 4 MWh per meter open cooling shelve in the maximum [Schmutz2007]. In future, Migros and Coop want to erect only stores that comply with the Minergie standard [Schmutz2007]. Apart from that, in Switzerland, legislation exists which prescribes indirect refrigeration systems for supermarket refrigeration systems with more than 80 kW refrigeration capacity and more than 3 cooling points [Schmutz2007]. Furthermore, the law requires the registration, permission, and tightness control of systems with aerosol-stable refrigerants. Currently (2007), efforts are made in Switzerland to legally prescribe the use of R744 for low temperature applications [Schmutz2007].

5. Description of refrigerants and technologies

5.1 Introduction

Supermarket refrigeration systems serve for the fresh-keeping and freezing of goods, especially food. Several goods which are sold in supermarkets need different storage temperatures. The following list shows the different temperatures which are required in a typical store in accordance with the chilled goods:

Frozen food:	-29	up to	-18 °C
Ice cream:	-26	up to	-22 °C
Fish and seafood:	-5	up to	-1 °C
Meat and poultry:	-1	up to	3 °C
Fresh products:	-3	up to	8 °C
Fruit and vegetables:	7	up to	10 °C

A typical supermarket refrigeration system will provide for evaporation temperatures of about -38 °C (LT – low temperature) or about -8 °C (MT – medium temperature).

In accordance with the area of application and purpose, many technology variants can be distinguished. In the commercial refrigeration sector one often makes a difference between three model technologies:

- Plug-in/stand-alone refrigeration units
- Individual systems with external condensing unit
- Multi-compressor/parallel compressor/multiplex refrigeration systems

A further distinction can be made according to central and decentralized systems.. In connection with central systems (i.e. multi-compressor refrigeration systems), there is one refrigeration system serving for several cooling points. The multi-compressor refrigeration unit consists of several parallel-switched compressors. While in most cases the cooling points are in the sales room, the refrigeration system (compressor) is installed in a separate room (machine room). Refrigeration system and cooling points are connected by means of distributed piping systems. Most supermarkets are provided with separated systems for the low temperature range (LT – product temperature about -18 °C) and the medium temperature range (MT – product temperature about 0 up to +8 °C). The refrigeration capacity for central supermarket systems with parallel-switched compressors range from about 30 up to 1,500 kW. According to the location of the installation, central systems may also include condensing units. In smaller food stores such pre-manufactured units consisting of compressor(s), condenser, receiver, and control devices are used and installed at a central place. These provide refrigeration capacities up to 50 kW.

Decentralized systems (units) can be delivered as industrially pre-manufactured, compact units with integrated compressor and condenser (i.e. plug-in refrigeration units, bottle cooler or plug-in aggregates for refrigerated rooms) or as individual systems with external condensing unit (single refrigeration unit or single refrigeration room). The refrigeration capacity of decentralized systems with condensing unit ranges to about 20 kW for larger cooling rooms or supplementary refrigeration units. Typical areas of application are, e.g., butcher shops or meat counters in smaller supermarkets, but also supplementary installations in larger stores.

The different versions mentioned above show different flexibility when remodelling a supermarket, size, and refrigeration capacity, but specifically also different energy consumption based on „unit chilled product." The specific energy consumption of condensing units of individual systems is often higher than that of a multi-compressor refrigeration system. On the one hand, compact units (plug-in refrigeration units) often consume even more specific energy compared to individual systems (condensing units) (see table 4). On the other hand, plug-in refrigeration units are particularly flexible and, above all, appropriate for small stores (kiosks) for which the installation of a multi-compressor refrigeration system would not make sense. In practice, stores are often equipped with a combination of two or three technologies.

Table 4: Energy consumption of plug-in refrigeration units compared to multi-compressor refrigeration systems based on measurements in Danish supermarkets in 1994 [Bertelsen2002]

Type of consumer	kWh/year/meter or kWh/year/door
Refrigerated shelve connected to multi-compressor refrigeration system	3,000
DaiPro[1)] room per door	2,450
Chest freezer connected to multi-compressor refrigeration system	2,400
Plug-in freezer	3,500
Medium temperature refrigerator cabinet connected to multi-compressor refrigeration system	900
Medium temperature plug-in refrigerator cabinet	1,500

[1)] In Denmark it is custom to build the cooling room for dairy products (DaiPro) in direct connection with the sales room where the customer is taking his goods by means of glass doors. The individual shelves are filled from behind, that is from the refrigerated room.

From the system manufacturers' point of view, the supermarket refrigeration units and refrigeration systems can be divided once more into the following two groups:

- Ready-to-use units and systems, manufactured in a factory
- Systems installed on site from individual parts

Under the first group fall plug-in units, e.g. freezers or shelves, condensing units, but also components for refrigeration systems (evaporator, condenser, compressor, expansion valves). Multi-compressor refrigeration systems and systems operating with a condensing unit fall under the second group. These are installed on site.

The energy costs for the operation of the refrigeration system of a supermarket are different according to their technology and often they are in the same order of magnitude as the revenue of such supermarket. From the economical point of view, the choice of the refrigeration system is therefore an important decision.

The required specifications of the model technology are the following:

- Low investment costs
- High reliability (in connection with breakdown the value of the goods deteriorated is eventually greater than the investment costs for the refrigeration system)
- Medium temperature: Temperature and humidity are important (drying/dehydration of groceries)
- Low temperature: only temperature is important
- Environmental aspects (globally: depletion of the ozone layer, direct and indirect contribution to greenhouse effect, environmental pollution during manufacture and/or disposal, etc.; locally: e.g. toxicity and flammability of refrigerants)
- Energy consumption and thus energy expenses during the entire life cycle of the system
- Maintenance costs

As a rule, German supermarkets are remodelled in intervals of seven years where normally also the refrigeration system is changed because the units obtain a partial retrofitting. After about 14 years, that is when the second rebuilding is made, the whole refrigeration system is renewed. Yet, often the piping and some refrigeration units are reused [Schmidt2007a].

5.2 Refrigerants for supermarket refrigeration systems

Until the first half of the 1990s, the refrigeration systems of supermarkets were operated with chlorinated refrigerants such as R22, R502, and partially R12. The hole in the ozone layer and the restrictions enacted against the use of chlorinated refrigerants were the reason for the shift to partially fluorinated hydrocarbons (HFC), here R404A and partially R134a. During this shift, similar thermodynamical properties of the refrigerants were desired. The greenhouse effect and the resulting restrictions on the use of fluorinated synthetic refrigerants with high global warming potential led in recent time also to the reassessment of natural substances in order to use them as refrigerants for supermarket systems.

Important specifications required for refrigerants used in supermarket systems are among other things the following:

- Zero ozone depletion potential
- Low global warming potential
- High energetic efficiency - including:
    - High capacity of heat transfer
    - High heat conductivity
    - Low viscosity
    - Low pressure ratio – ratio of condensing to evaporating pressure
    - Low pressure drops in piping
    - High efficiency during compression
- Chemically stable in order to prevent the decay during high compression end pressures in the refrigeration system
- inert
- high dielectric strength with hermetical and semi-hermetical compressors
- non-flammable
- non-toxic
- non-corrosive
- inexpensive
- compatible with the refrigeration system's materials
- high heat of evaporation in relation to specific volume at compressor suction
- evaporation pressure above 1 bar absolute for the prevention of air entrance in leakages
- freezing point below evaporation temperature
- Condensing pressure below 25 bar or 32 bar
- Good solubility / mixing capacity with lubricants
- Easy detectable for leak detection

It should be clear that no refrigerant is able to meet all requirements. Among a plurality of possible refrigerants, the most appropriate one must be selected in accordance with the case of application or the system's design. Table 5 contains an overview of the refrigerants currently used in new supermarket refrigeration systems, together with some of their properties. Concerning the global warming potential (GWP), both the values of the Kyoto Protocol internationally recognized and politically mandatory, published 1996 by the IPCC [IPCC1996], as well as the values most recently used by IPCC and UNEP [UNEP2006] are shown.

Table 5: Properties of selected refrigerants for supermarket refrigeration systems [UNEP2006]. R22 is not included as an alternative, but only as reference refrigerant because it was the preferred refrigerant in times before the ozone hole. R407C, R410A, and R507A are only seldom used in retail stores and therefore are only shown by reason of completeness.

	Normal boiling point in °C	Critical temperature in °C	Pressure in bar at boiling temperature of			Flammable	Toxic	ODP	GWP[1)]		Volumetric evaporation heat at 0 °C in kJ/m³
			-30 °C	0 °C	40 °C				IPCC 1996	UNEP 2006	
R22	-40.8	96.1	1.6	5.0	15.3	no	no	0.04	1,500	1,810	4,360
R134a	-26.1	101.1	0.8	2.9	10.2	no	no	0	1,300	1,430	2,870
R404A	-46.5	72.1	2.1	6.1	18.2	no	no	0	3,260	3,900	5,070
R407C[2)]	-43.6	86.0	1.9	5.6	17.5	no	no	0	1,530	1,800	4,230
R410A	-51.4	72.5	2.7	8	24.3	no	no	0	1,730	2,100	6,780
R507A	-46.7	70.9	2.1	6.2	18.7	no	no	0	3,300	4,000	5,230
R600a Isobutane	-11.7	134.7	0.5	1.6	5.3	yes	no	0	?	~20	1,510
R290 Propane	-42.2	96.7	1.7	4.7	13.7	yes	no	0	6.3	~20	3,880
R1270e Propene	-47.7	92.4	2.1	5.9	16.5	yes	no	0	?	~20	4,670
R717 Ammonia	-33.3	132.3	1.2	4.3	15.5	(yes)	yes	0	?	< 1	4,360
R744 Carbon dioxide	(-78.4)[3)]	31.0	14.3	34.8	90 - 120	no	< 10 % no	0	1	1	22,550

1) Related to CO_2 within a lifetime of 100 years

2) Temperature glide from 6 up to 7 K

3) Triple point of CO_2 at 5.18 bar and –56 °C

(green) ”Natural” refrigerants

Figure 6 shows vapor pressure curves of all refrigerants used in supermarket refrigeration systems: R22, R134a, R404A, R600a, R290, R1270, R717, and R744. For R134a there exists no pure natural substance showing a similar vapor pressure curve. R600a implies lower system pressures, whereas R290 and the other natural alternatives imply higher system pressures. The situation is different with R22. R290 has approximately the same vapor pressure curve and can therefore, regarding system pressure, be used rather trouble free in systems designed for R22 (see below). Within the temperature range relevant for supermarket refrigeration systems, R744 has a significantly higher pressure than any other refrigerant (see below).

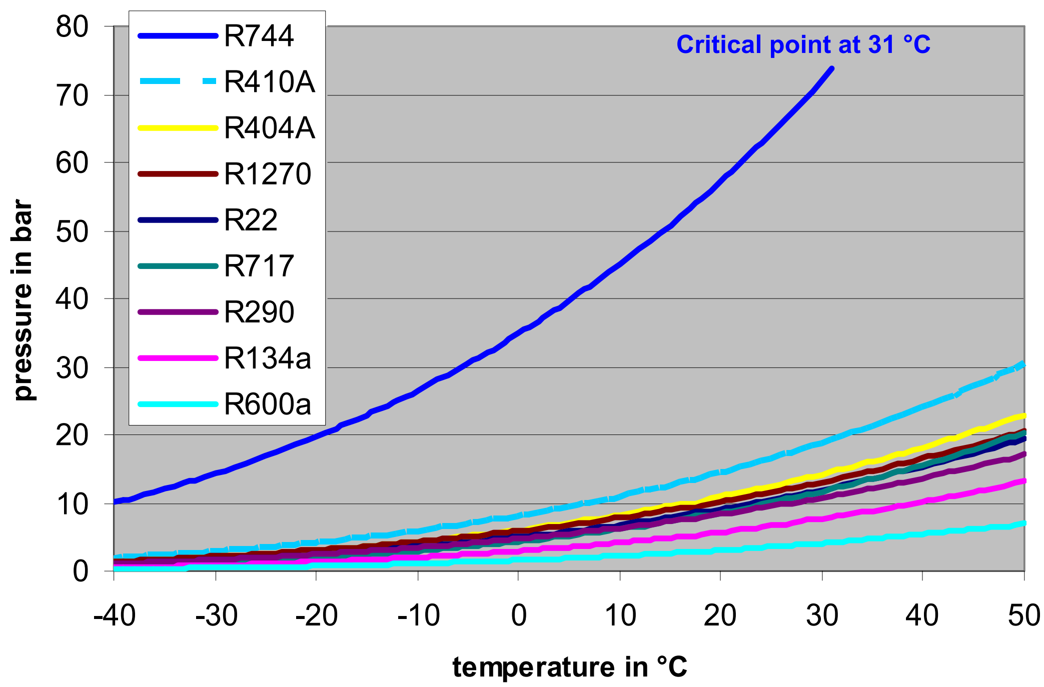

Figure 6: Vapor pressure curves of refrigerants used in supermarket refrigeration systems calculated with CoolPack version 1.46. In the caption, the refrigerants follow their vapor pressures, i.e. R744 with the highest evaporation pressure at given temperature on top and R600a with the lowest evaporation pressure at the same temperature at the bottom.

5.3 Halogenated hydrocarbons

Both mainly used halogenated chlorine-free refrigerants R134a and R404A (refrigerant blend) for supermarket refrigeration systems are non-flammable and non-toxic. However, both show a rather high global warming potential, especially R404A. In order to secure the return of the refrigerant oil to the compressor in central supermarket refrigeration systems (multi-compressor refrigeration systems) one must use oils that are soluble with the refrigerant. In the case of halogenated hydrocarbons, these are synthetic oils such as PAG or POE. These oils are highly hygroscopic so that one also has to observe air tightness. PAG and POE oils are also used partially for R717 and R744. The issue of hygroscopic oils is also given there.

R134a

R134a is the standard refrigerant for automobile air conditioning and smaller South-European and Asian plug-in refrigeration units. On the one hand, as one-component-refrigerant it has a better heat transfer than refrigerant blends and therefore it may imply higher figures of the coefficient of performance (COP) than e.g. R404A. On the other hand, the density of R134a at suction pressure is significantly smaller compared to R404A, which may lead to large pressure drops within the suction pipe, especially in connection with multi-compressor refrigeration systems. In connection with multi-compressor systems, R134a is only used for the MT range.

With R134a the operational and stand-still pressures of the refrigeration system are significantly lower than with R404A, e.g. at 40 °C the condensing pressure with R134a is 10.2 bar against 18.2 bar with R404A. Due to the lower pressures, leakages are more seldom and the leakage volumes in connection with small leaks, e.g. a fissure at a flare joint not correctly tightened, are smaller because the driving pressure difference is lower [Schmidt2007a]. R134a has a global warming potential of 1,430[7].

[7] In the text the latest GWP values are given according to [UNEP2006].

R404A

R404A is a zeotropic refrigerant blend including 44 % R125, 52 % R143a and 4 % R134a with a temperature glide of less than 0.5 K. In relation to evaporation and condensing temperature it thus behaves like a pure substance. Figure 6 shows that the vapor pressure curve is very similar to R22. R404A has been specially developed for commercial refrigeration systems previously operated with R22. Due to its different oil solubility and oil mixing characteristics, it is not appropriate to be used as a drop-in refrigerant.[8] When an existing refrigeration system is altered from R22 into R404A, the refrigerant oil has to be replaced. Instead of mineral oil used with R22, normally ester oil is used with R404A. Components of the refrigeration system without elastomeric gaskets do not need any change, whereas any parts with elastomeric gaskets, e.g. valves, require replacement in connection with the change from R22 to R404A [Görner2007]. R404A has a global warming potential of 3,900[9].

R407C

R407C is a zeotropic refrigerant blend including 23 % R32, 25 % R125 and 52 % R134a with a temperature glide of 6 to 7K. R407C behaves in relation to evaporation and condensing pressures similar to R404A, nonetheless showing a difference related to temperature glide. In most cases it is used for air conditioning equipment. To the extent that the systems are hermetic, the temperature glide does not result in any problem. When leakages occur, first the component with lower boiling point will escape following a shift in concentration. In the supermarket refrigeration sector R407C is used by the company Daikin in the so-called Conveni-Packs – a combination of refrigeration and air conditioning system with integrated heat recovery, see technology data sheet C16. R407C has a global warming potential of 1,800[2].

[8] As drop-in refrigerants are understood any refrigerants which can be used in an existing CFC or HCFC system without oil change.
[9] In the text the most recent values are given pursuant to [UNEP2006].

R410A

R410A is a zeotropic refrigerant blend including 50 % R32 and 50 % R125 with a temperature glide of about 0.1 K. In relation to evaporation and condensing temperature it behaves approximately like a pure substance. Evaporator control and recharge of refrigerant are therefore simplified to a large extent compared with R404A and especially R407C [Rivet2007].

Figure 6 shows that the vapor pressure curve is higher than those of R22 or R404A. Therefore, any component must be permitted for higher pressure levels, normally 32 bar and partially according to manufacturer even up to 40 bar. As a rule, conventional equipment is designed for up to 25 bar. Therefore, the use of R410A occurred later than, e.g. the use of R404A or R407C, as the more pressure-proof components were first to be developed. The higher pressures imply smaller systems and components. So the compressor, the suction gas piping, and liquid piping may decrease in size by up to 40 % compared to R404A [Rivet2007]. Consequently, the refrigerant charge is diminished by 30 % [Rivet2007]. With R410A the COP is better than for R404A between 5 % up to 15 % in medium temperature as well as in the low temperature range [Rivet2007].

To date, R410A is mainly used in air conditioning systems and heat pumps as well as in transport refrigeration systems of a German manufacturer. Further, there is one application in a central refrigerated warehouse in Germany [Frommann2006]. R410A has a global warming potential of 2,100[1].

R507A

R507A is an azeotropic refrigerant blend of 50 % R125 and 50 % R143a, which means that it does not show any temperature glide in relation to evaporation or condensing. R507A has a global warming potential of 4,000[10].

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[10] In the text the most recent values are given pursuant to [UNEP2006].

New halogenated refrigerants

Pursuant to EU Directive 2006/40/EC, mobile air-conditioning systems may only have a global warming potential of less than 150 as of the year 2011 („Directive of the European Parliament and of the Council relating to emissions from air-conditioning systems in motor vehicles and amending Directive 70/156/EEC"). At the time of the draft of this directive, only CO_2 (R744) or flammable refrigerants such as R152a or R290 were still considerable. Until the end of 2006, the automotive industry and their suppliers had developed R744 air-conditioning systems ready for series production because flammable refrigerants in motor vehicles are not accepted by automotive manufacturers. As R744 requires new components due to the significantly higher pressure level, and the driver may suffer a physiological affectation during leakages into the interior of the vehicle, the chemical industries were searching for alternative refrigerants at the same time. During the VDA conference in February 2007 in Saalfelden all renowned refrigerant manufacturers presented comprehensive studies for new synthetic refrigerants [VDA2007]. Accordingly, the new refrigerants are mainly produced as blends from two or three different components having a global warming potential significantly below 150, and evaporation pressures as well as COP's similar to R134a. The refrigeration capacity of an existing system, however, seems to be about 10 % lower [Minor2007]. At the moment, the toxicity investigations for these new materials are still not accomplished so that there is no statement possible concerning their eventual market launch. To the extent that these new refrigerants would pass all tests and in consequence be applied for mobile air-conditioning systems, they eventually are also appropriate candidates at least for medium temperature appliances in supermarkets.

At the automotive workshop in Turin at the end of 2007 the companies DuPont and Honeywell presented a joint development: the HFO-1234yf. By reason of a double bond between the second and third carbon atom, the atmospheric life time is very short and the global warming potential therefore is only 4. Initial tests in a mobile air-conditioning system show similar results to R134a. Further toxicity tests and system comparisons are expected for 2008. HFO-1234yf shows flammability similar to ammonia [DuPont2007].

5.4 Hydrocarbons

Hydrocarbons are essentially less expensive than synthetic refrigerants. They have global warming potentials below 20 and no ozone depleting potential, are non-toxic, nearly odourless and accomplish many of the specifications required for refrigerants. However, they are flammable, see table 6. Nevertheless, they became prevailing in small plug-in units with charges of up to 150 g in North and Central Europe and in the meantime they are also used by a couple of Asian producers for domestic refrigeration units. In IEC 60335-2-89 150 g are defined as the upper limit. Upon larger charges peculiar requirements are stipulated concerning explosion control. Normally, the refrigerant charge related to the unaltered refrigeration cycle is about 40 % to 50 % smaller than with a HFC refrigerant [Kauffeld1996], so that current plug-in units with refrigerant charges below 150 g may achieve refrigeration capacities up to approximately 1,000 Watt, see also technology data sheets. From introductory investigations during a research project with R290 used with mini-channel condensers and evaporators resulted 120 g refrigerant charge for a refrigeration system with 1 kW refrigeration capacity, with the projection of an improved refrigeration system of 50 g per 1 kW for plug-in units [Hoehne2004]. With this technology (mini-channel heat exchanger), up to 3 kW refrigeration capacity with maximum refrigerant charges of 150 g should be possible in the long term.

Table 6: Ignition limits and ignition temperatures of some hydrocarbons [AirLiquide2007]. Also electric sparks are sufficient as ignition source – the required ignition energy is about 0.25 mJ.

	Ignition limits in dry air Vol.- %	Ignition temperature °C
R600a (Isobutane)	1.3 – 9.8	543
R290 (Propane)	1.7 – 10.9	470
R1270 (Propene)	2.0 – 11.1	460
In comparison: gasoline	ca. 1.1 – 7.0	ca. 300

The hydrocarbons used as refrigerant are heavier than air. Ignitable blends therefore form themselves in proximity to the soil/floor. When larger refrigerant charges are used, appropriate gas sensors and air removal devices are to provide at soil/floor level.

Hydrocarbons mix very well with mineral oils, even so well that lubricants should be selected from one viscosity class above compared to e.g. R22. Due to the very good oil solubility problems may arise from foaming up of the oil in the crankcase of the compressor.

Isobutane – R600a

Isobutane is the standard refrigerant for North and Central European domestic refrigerators and freezers. Meanwhile, worldwide 30 Million appliances per year are produced with R600a [UNEP2006]. R600a is also used for smaller commercial plug-in units, e.g. in chest freezers for ice cream. Due to lower pressure levels and pressure ratios of R600a, R600a units are running more silent than comparable R134a units. By reason of the lower density of R600a, larger piston displacements of the compressor are necessary. With higher refrigeration capacities often the space for the compressor is not enough and one has to change to R290.

Propane – R290

Propane is used by a couple of producers for plug-in drink refrigerators (e.g. Liebherr and Vestfrost) and freezers (e.g. AHT and Liebherr). When the statutory requirements for safety are met (i.e. IEC 60335-2-89), Propane is the ideal refrigerant for such units. It can be used together with available components, is well mixable with mineral oils and causes lower compression end temperatures and often has 10 % to 15 % better COP than e.g. R134a or R404A [Jürgensen2004]. Furthermore, the pressure ratios and pressure differences are lower than with R404A, R407C or R410A, resulting in lower noise emissions (similar to domestic units running normally more silent with Isobutane than with R134a). With the same piston displacement of the compressor the refrigeration capacity is reduced by about 4 % to 10 % compared to R22 [Mali1995].

Propene – R1270

Propene is a hydrocarbon with one unsaturated carbon bond. Correspondingly, it is less stable than e.g. R290. In the middle of the 1990s, R1270 was used for indirect supermarket refrigeration systems. The investment costs of indirect supermarket refrigeration systems are often more expensive than comparable direct evaporation refrigeration systems with R404A. Therefore, and due to the concerns of the retail store chains in relation with inflammable refrigerants, these systems have disappeared.

5.5 Ammonia – R717

Among all refrigerants suitable for supermarket refrigeration systems, ammonia (R717) has the lowest global warming potential ($GWP_{R717} < 1$). Also from the energetic point of view, it is very interesting. Ammonia refrigeration systems normally achieve higher refrigeration coefficients of performance than HFC refrigeration systems. Unfortunately, R717 is toxic (maximum-workplace-concentration value (MAC) 50). It has a pungent odour and thus a high warning effect. R717 vapors are lighter than air. In some countries, ammonia compressors installed on the building's roof are therefore considered less critical than those standing on the soil. Ammonia is flammable, too, though only in connection with a fire source. Ignition limits lie between 15 and 30 percent by volume.

Ammonia is an alkaline gas. The contact between ammonia and a couple of other substances may cause explosive products or reactions, respectively, among others the contact with mercury, zinc, chlorine, calcium, and silver oxide. Gaseous ammonia is susceptible to react very strong with nitrogen oxides and strong acids. In connection with water the well-known liquid ammonia water (ammonium hydroxide) is created. In connection with carbon dioxide ammonium carbonate is formed. Humid ammonia which contains water acts very corrosive to copper and brass. Among any materials appropriate for ammonia refrigeration systems, steel is the most known, not at least by reason of common application for industrial refrigeration systems. Yet, also in connection with steel some rules are to be observed [Kauffeld1998a]. Apart from that, copper and zinc-free aluminium alloys can be used. Already since 1966, these aluminium alloys are used for evaporators, heat exchangers, and piping within ammonia production plants. In Norway, a company offers seawater-chilled condensers based on aluminium pipe bundles for ammonia refrigeration systems since already 30 years. Aluminium is resistant to ammonia-water-mixtures consisting of water contents of up to 10 % [Kauffeld1998a].

In refrigeration systems ammonia causes high compression end temperatures due to which refrigeration systems for low temperature applications must be designed in two stages with intermediate cooling between both compression stages. Ammonia is not miscible with mineral oil. Consequently, ammonia refrigeration systems must be planned and installed very carefully in respect of their oil balance.[11] Since more than 100 years, ammonia has been the standard refrigerant for industrial refrigeration systems. By reason of its toxicity and panic effect, it can only be used for indirect refrigeration systems in the retail sector. As such, systems are known with liquid and evaporating secondary refrigerant for the medium temperature and/or low temperature range, recently also as upper stage in connection with R744 in the lower stage of a cascade refrigeration system. However, refrigeration technicians had not the appropriate know-how for the handling of ammonia in the supermarket area as well as about components for ammonia refrigeration systems of small capacity.

5.6 Carbon Dioxide – R744

Carbon dioxide (CO_2 – R744) is a refrigerant with significantly higher evaporation pressures than other refrigerants in use, see figure 6. In plug-in bottle coolers R744 achieves levels up to 130 bar on the high pressure side. The high operational pressures require stronger housing materials and/or larger wall thicknesses. On the other side, the compressor often becomes very small due to the high volumetric refrigeration capacity (see table 7). Pressure drops lead equally to significantly smaller temperature losses and thus to smaller losses of the COP. Consequently, and due to smaller mass flows required, the piping can be installed in essentially smaller size than

[11] An azeotropic mixture from R717 and dimethyl ether (DME) marketed under the brand name R723 yields condensing end temperatures about 20 to 30 K lower and, due to the DME proportion, improves the solubility with mineral oils and hence the heat transfer [Kraus2007]. Similar results one may achieve with zeotropic mixtures from R717 with hydrocarbons, i.e. R290 or R600a [Chmelnyuk2007].

with HFC refrigerants. Thus, despite the larger wall thicknesses due to pressure, the use of material for piping is less [Heinbokel2005]. Table 7 shows some characteristics of R744. Due to higher heat transfer coefficients, e.g. evaporation temperatures can be increased by about 2 K compared to HFC [Heinbokel2005].

Table 7: Characteristics of R744 / CO_2 as refrigerant [Kauffeld2004].

Environment	***Refrigeration system***
• Low global warming potential (GWP = 1 per definition)[1)] • In small concentrations non-toxic - pure natural air = 330 ppm - convenience limit = 1000 - 1500 ppm - MAC = 5,000 ppm (0.5 %, corresp. to 9,000 mg/m^3) - breathing air = 3 - 4 vol.-% - IDHL = 40,000 ppm (4.0 vol.-%) - above 10 vol.-% in breathing air benumbing effect - immediately lethal above 30 vol.-% • Non-flammable (is used as fire extinguishant) • Heavier than air • No affectation of food 1) CO_2 used as a refrigerant is usually the by-product of other processes and therefore it may be deemed as “greenhouse-neutral”.	• High volumetric refrigeration capacity (8 times higher than R134a; 5 times higher than ammonia) → small compressor piston displacement + piping cross sections • High coefficient of performance at low temperatures • Low viscosity → small pressure drops • Pressure drops cause only small temperature drops • High levels of system pressure (e.g. 40 bar at +5 °C) • Low pressure ratios → high compressor efficiency • High heat transfer coefficients during evaporation and condensation (two to three times higher than HFC [Stenhede2007]) • Good material compatibility with customary materials and refrigerant oils • High temperatures in the gas cooler → use for heating • Triple point at 5.18 bar and -56.6 °C • Low critical temperature (31.05 °C) → maximum condensing temperature at 20 to 25 °C

With R744, the critical temperature below which condensing of the refrigerant is feasible, is only 31 °C. In the classical vapor compression refrigerating machine process with evaporation on the low pressure side and condensation on the high pressure side, R744 can only be used with temperatures of the heat sink at the condenser of up to about 25 °C. In connection with supermarket refrigeration systems especially in summer and with air-cooled condensers, the temperatures on the system's high pressure side are above 31 °C. Consequently, R744 does not admit any condensing of the refrigerant and the system is then working as a so-called transcritical process (figure 7). Usually, the COP of transcritical refrigeration systems are worse than that of conventional refrigeration equipment with condensing of the refrigerant on the high pressure side. This characteristic can be partially compensated by application of an internal heat exchanger. The effect resulting from an internal heat exchanger increasing the COP is greater with the transcritical R744 process than with other refrigerants. The choice of the pressure on the high pressure side has equally critical impact upon the refrigeration COP. For any gas cooler discharge temperature, thus in principle for any ambient temperature with air-cooled high pressure side, there exists an optimal pressure in relation to the COP (figure 8). The control of a R744 refrigeration system must account for this characteristic in order to ensure low energy consumption. Here, the electronic control versus a control by means of a purely mechanic difference pressure valve is able to secure over a wide range that the system is operating with the best possible COP and hence at the lowest energy consumption [Cecchinato2007].

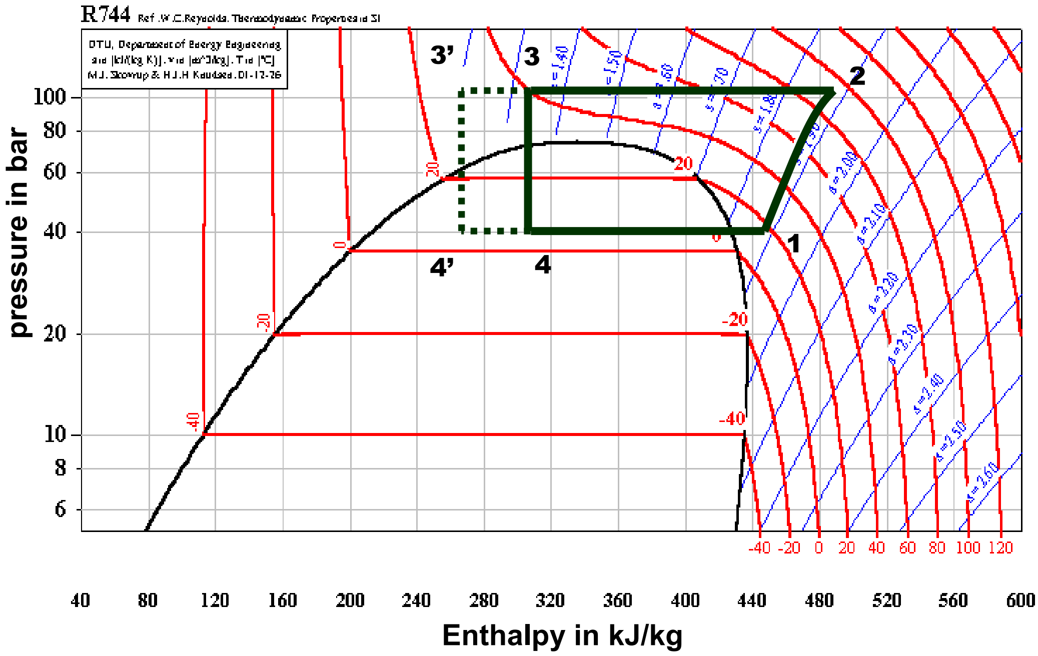

Figure 7: A transcritical R744 process in the lg p,h-diagram. One can clearly observe that the discharge temperature of the gas cooler (3) has an impact on the coefficient of performance of the process. The lower the gas cooler discharge temperature (3'), the better the coefficient of performance [Kauffeld2004].

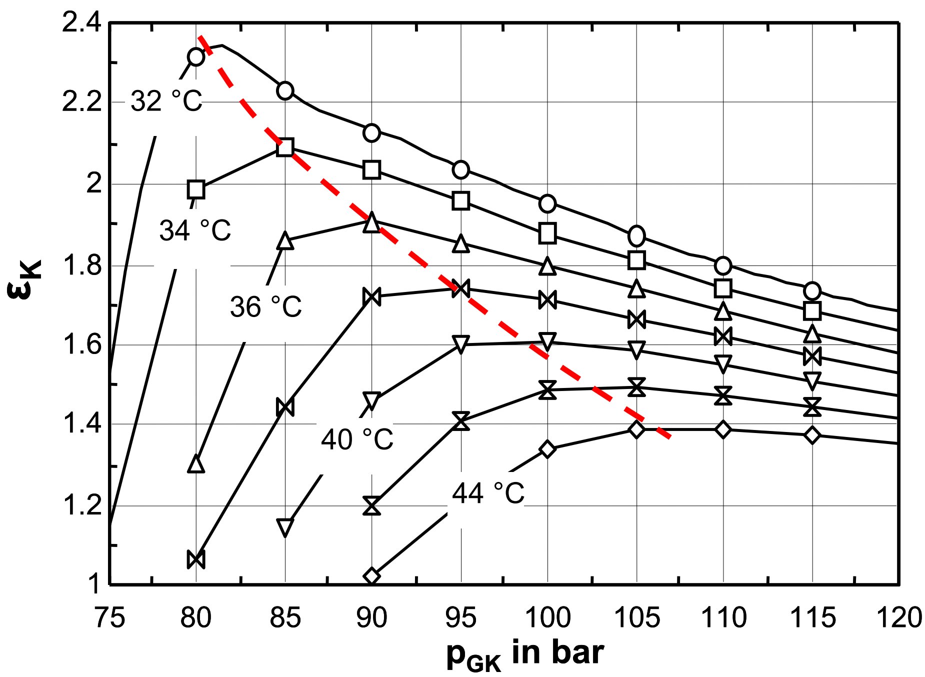

Figure 8: Refrigeration coefficient of performance depending on pressure on high pressure side (p_{GK}) with different gas cooler discharge temperatures [Kauffeld2004].

At ambient temperatures below ca. 26 °C an air-cooled R744 refrigeration system operates with condensing on the high pressure side and achieves a comparable COP to a R404A direct evaporation refrigeration system. At low ambient temperatures, the R744 system achieves an even better coefficient of performance, see technology data sheet C13 for further details.

As R744 at low condensing and evaporation temperatures provides very good coefficients of performance, it is often used for low temperature systems in the supermarket, as cascade subsystem of, e.g., an ammonia or a HFC refrigeration system, see technology data sheets C5, C6, C7, C10, C12, and C14. Meanwhile, large refrigeration system manufacturers offer such systems as part of their standard product range [Sienel2007], and they are competitive in relation to investment costs incurred especially for large supermarkets [Post2007]. In the context of these applications, typical condensing temperatures of the R744 system are at about 0 °C. In Switzerland, currently legal efforts are made in order to prescribe the statutory use of R744 for low temperature [Schmutz2007].

A further feature of the transcritical R744 process seems worth to be noted. In figure 7 one can clearly observe the continuously changing temperature in the gas cooler. Starting from the compressor discharge port, state 2, the temperature is passing continuously, from the isotherm at about 90 °C through the 80 °C down to those of 60 °C and 40 °C at the gas cooler discharge. Contrary to condensing refrigerants, the transcritical R744 releases approximately the same amount of heat during the entire gas cooling process. With a transcritical R744 refrigeration system one therefore obtains a superb opportunity to heat water or air; a reason for using R744 as refrigerant for many Japanese heat pumps [Kusakari2006]. In connection with heat recovery, a transcritical R744 refrigeration system is beside hydronic heating water heating especially appropriate for the heating of service water.

Due to R744's improved heat transfer characteristics, see table 7, the evaporation temperatures are increased by about 2 K [Gernemann2003, Heinbokel2005]. Resulting from the high pressure level of R744, a reduced saturation temperature loss by about 1 K will result in the suction pipe, compared to R404A [Gernemann2003]. The return of the oil to the compressors is still assured. The R744 compressors can thus be operated in medium temperature range with a suction pressure which, in sum, corresponds to a saturation temperature increased by 3 K compared to R404A [Heinbokel2005]. The peculiarities of the transcritical process and the good heat transfer characteristics of R744 in the gas cooler make the cooling of the gas near to ambient temperature possible [Heinbokel2005]. At low ambient temperatures, R744 enables a reduction of the condensing temperature down to about +5 °C because, due to the higher pressure level of R744, a sufficient large difference pressure against evaporation pressure also exists at these low temperatures in order to ensure the proper function of the expansion valves [Heinbokel2005]. In Germany, transcritical R744 refrigeration systems installed at discounters have shown in their first year of commissioning slightly lower energy consumption than comparable R404A systems, given proportionally many operating hours under cold condition. The first of such R744 systems show the highest energy consumption. Systems of the "second generation" consume less energy [Bader2007].

In concentration levels above 10 %, R744 has a toxic effect. The maximum value at the workplace is 5,000 ppm corresponding to 0.5 % (app. 9,000 mg/m^3 air). As a consequence, especially in small rooms, the CO_2 concentrations must be monitored. As CO_2 is heavier than air, appropriate sensors must be installed near to the soil/floor. In supermarkets such sensors are often installed in the cooling and freezing rooms as well as in the machine room, in a few cases also in the sales room and/or in the discharge channel of the ventilation system.

For any system parts which may be locked individually, safety valves are necessary because the system's standstill pressure is significantly higher than the design pressure of the components of the low pressure side. Care has to be taken for the eventual creation of carbon dioxide snow during relaxation of R744 below 5.2 bar. There should be no blow-off pipes connected after the safety valves [Vestergaard2006]. The liquid pipe may eventually be blown-off into the suction pipe in which pressures above 5.2 bar exist. From there, it can be blown off directly into the atmosphere by means of a second safety valve without further need of a blow-off pipe [Vestergaard2006].

5.7 Heat Transfer Fluids (secondary refrigerants)

Any heat transfer fluid (HTF) for indirect refrigeration systems should meet a couple of requirements. A HTF should have good thermo physical properties enabling the transport of large refrigeration capacities with only a small temperature change and little volume flow. A HTF should have high heat transfer coefficients which cause only small temperature differences in the heat exchanger. It should show as small as possible pressure drops in the piping systems in order to reduce the work required by the pumps. A HTF may not cause corrosion of materials. Further, it should be non-toxic, environmentally friendly, non-flammable, and easy to handle, free of risk. In addition, it should be affordable – at an acceptable price. The HTF that meets all of these requirements does not exist. For any purpose, one therefore has to select the most appropriate refrigerant with as little as possible disadvantages.

Heat transfer fluids can be divided into single-phase liquids which enable the heat transfer by means of sensible heat and generally have relatively low energy content, and secondary refrigerants with phase change realized by means of melting or evaporating. In general, the latter cooling media have higher energy content.

Traditionally, in supermarket refrigeration systems single-phase liquids – either water-based or synthetic, non-water-based liquids – are used. Recent developments look for melting HTFs, so-called ice slurry, or evaporating secondary refrigerants, e.g. carbon dioxide. The corresponding descriptions are to find in the technology data sheets C2, C3, C6, C8, C9, and C11.

Regarding single-phase HTFs, the freezing point must lie below the application temperature. At this temperature, the viscosity may not be too high; in addition, the liquid should have a high specific heat capacity and good heat transfer properties.

The most commonly used water-based HTFs are [Kauffeld1998b]:

Water:	Water freezes at about 0 °C. Water is corrosive when oxygen exists, and this is true for any water-based liquids without appropriate corrosion control.
Ethylene glycol:	Toxic and dangerous to the environment in larger volumes (easily biodegradable), but inexpensive; therefore, it is used in supermarkets only for liquid loops cooling the condenser.
Propylene glycol:	High viscosity at low temperature as well as risk of environmental pollution, but less than with ethylene glycol; the most used HTF in medium temperature range.
Ethanol:	Pure ethanol (ethyl alcohol) is flammable, ethanol diluted with water in concentrations under about 50 % not; used in Europe predominantly in connection with ice slurry systems.
Methanol:	Also flammable and dangerous to health. Doses of 0.1 g methanol per kg body weight are dangerous, above 1 g per kg body weight methanol includes a risk to life; very seldom used as secondary refrigerant.
Glycerine:	Glycerine possesses high viscosity at low temperature; very rarely used as secondary refrigerant.
Ammonia:	Pure ammonia is flammable, has a low boiling point and pungent odour; from mixture with water results ammonia water (ammonium hydroxide), very rarely used as HTF – it would have good characteristics for ice slurry.
Potassium carbonate:	High pH-value being dangerous through eye contact. The eutectic point lies at -37.5 °C; very rarely used as secondary refrigerant.
Calcium chloride:	Corrosive, eutectic point lies at -55 °C. Corrosive control through chromate may be dangerous to health, especially during the mixing procedure; (applicable to any liquid, if chromate is used); very rarely used as secondary refrigerant in the supermarket sector, application e.g. in food industry.

Magnesium chloride: Corrosive, eutectic point at -33.5 °C; very rarely used as secondary refrigerant.

Sodium chloride: Corrosive, eutectic point at -20.7 °C; especially used for fish direct cooling (sea water), very rarely used as secondary refrigerant in the supermarket sector.

Potassium acetate: Rather high pH-value, relatively new HTF (commercial use since about 1995); use predominantly in LT range.

Potassium formate: Higher pH-value as with potassium acetate and even newer as secondary refrigerant, therefore so far less experience. Viscosity at low temperatures is very good, thus preferred use for low temperature applications.

Apart from these water-based HTFs there are some synthetic liquids which are especially used for low temperatures because they prove low viscosity within this temperature range. An elaborated overview of the different water-based and commercial heat transfer fluids was published in 1997 by the International Institute of Refrigeration [Melinder1997]. One can find an update in the dissertation of Melinder [Melinder 2007].

Melting secondary refrigerants (ice slurries) can be made on the basis of any of the water-based HTFs described in the last section. To date, the most extensive experience has been made with ethanol and glycol as additive, as well as with sodium chloride (sea water). Descriptions of corresponding supermarket refrigeration systems with ice slurry as HTF are contained in technology data sheet C4.

Ice slurry is a composition of very fine ice particles in a liquid. The freezing point for, e.g., a 16 % ethanol water composition is at -8 °C. At this temperature the first water particles begin to freeze. Consequently, the remaining liquid becomes richer in ethanol and the freezing point sinks. When the cooling process is continued, more and more ice particles, always containing pure water, are frozen so that the remaining liquid becomes even richer in ethanol and the freezing point sinks further.

Now, if one allows a temperature change of, e.g. -12 °C up to -8 C in a refrigeration system, the enthalpy content for ice slurry will be approximately eight times higher than for any conventional liquid HTF based on water. The pressure losses under moderate ice concentrations, i.e. up to 20 % ice content, are more or less the same as with conventional liquids. At the same time, the heat transfer coefficient is nearly two times better than that for a conventional HTF [Kauffeld2005]. The large energy content and the good heat transfer coefficients allow the reduction of the pipe diameter by about 50 % and this with nearly the same pressure drops. Simultaneously, the work required for the pump is reduced to 1/8 of the size necessary for conventional liquid secondary refrigerant [Kauffeld1999].

Evaporating secondary refrigerants are used according to the same principles as known from vapor compression refrigeration systems. The sole difference consists in the fact that the refrigerant evaporating at the cooling points is normally not the same as that one used in the primary refrigeration system. To date, especially carbon dioxide has been used as evaporating, secondary refrigerant. In this context, one has to take care for the high pressure levels during standstill with CO_2. Further, one has to ensure that non-evaporated CO_2 is running back to the pump station. The thermodynamic characteristics of CO_2 are favorable in such high degree that CO_2 HTF refrigeration systems do not consume more energy than comparable direct evaporation refrigeration systems with HFC [Rees2007].

5.8 Decentralized plug-in refrigeration units

Decentralized plug-in refrigeration units integrate all components (compressor, condenser, expansion organ and evaporator) in the equipment. For installation only the power connection is necessary. Installation work related to refrigeration technology is not required in the supermarket. The complete manufacture is accomplished at the corresponding factory with resulting high quality and low leakage probability.

Decentralized plug-in refrigeration units exist (following their frequency of application) as:

- Bottle coolers,
- Chest freezers,
- Refrigerated cabinets,
- Refrigerated counters,
- Refrigerated shelves, and
- Frozen food shelves.

There are different refrigerants for the individual types of plug-in refrigeration units, normally HFCs, hydrocarbons, and carbon dioxide. Beside the above mentioned plug-in refrigeration units, there are so-called plug units or straddle refrigerating units. These factory assembled refrigeration aggregates with refrigeration capacities from 0.5 up to 9 kW are used for, e.g., the refrigeration of medium temperature or freezing rooms which underwent retrofitting. Furthermore, they are especially used by some discounters which refrigerate their freezing rooms by means of such plug units. Then, the central multi-compressor refrigeration system has only a medium temperature part because the low temperature in the store is provided by plug-in chest freezers.

The following model technologies are described in the corresponding technology data sheets of part A:

A1 Bottle cooler with HFC R134a
A2 Bottle cooler with hydrocarbons (R600a, R290)
A3 Bottle cooler with carbon dioxide (R744)
A4 Chest freezer with HFC (R134a, R404A)

A5 Chest freezer with hydrocarbons (R600a, R290)

A6 Chest freezer with carbon dioxide (R744)

A7 Refrigerated chest cooler – only existing as switchable chest freezer

A8 Refrigerated counters with HFC (R134a, R404A)

A9 Refrigerated shelves with HFC (R134a, R404A)

A10 Refrigerated shelves with carbon dioxide (R744)

A11 Plug units with R404A

Refrigerator islands and freezer islands are not available as plug-in units, though in particular discounters are used to put together individual plug-in units as islands (see e.g. A4, A5, and A6). Nevertheless, they remain individual units, each with its own refrigeration system.

Table 8 contains a summary of the technology data sheets, part A, related to plug-in units. Today R134a, R404A, R507A, R290, R600a and R744 are used as refrigerants for plug-in units. Units with hydrocarbons as refrigerant (R600a and R290) achieve energy consumptions 10 to 15 % lower than comparable units with HFC [Jürgensen2004]. The energy consumption of units with R744 is more depending on the ambient temperature of the installation place than units using the other refrigerants. The refrigerant charge applied begins with 50 g (R600a) and ends at approximately 1,400 g (R404A), which corresponds to approximately 23.5 up to 162 g/100 l gross volume. The refrigeration capacity of such units ranges from 200 W up to 2,000 W. The emissions caused by these units are low, due to the hermetic design. The annual leakage rates through damages of the individual units as well as for disposal at the end of life cycle are around 1 % [IPCC/TEAP2005]. In relation to the individual unit, the emissions at end of life have greater impact because the complete recovery of the refrigerant is only possible at waste management facilities as they exist for domestic appliances. The use of hydrocarbons and carbon dioxide is limited (to date) to a couple of manufacturers. The development efforts for the use of hydrocarbons are oriented towards two different directions. On one side, one attempts to reduce the necessary refrigerant charge by means of subsequent system optimization [Hoehne2004]. On the other side one attempts to increase the standardized charge limit of flammable refrigerants from 150 g to 500 g, to the extent that this seems feasible from the point of view of safety technology [Jürgensen2004]. On commercial grounds, R744 has been previously only used in bottle coolers, while Nestlé has announced to use R744 prospectively also for ice cream chest freezer.

A variant of plug-in units until lately not available on the market are units with water-cooled condensers where water cooling takes place in an air-cooled heat exchanger for all plug-in units. The supermarket would need an appropriate water cooling system. During the EUROSHOP 2008 a company presented such plug-in units with water-cooled condensers for the first time [AREA2008].

Similar approaches based on larger, sound-proof cooling aggregates are offered in the USA by the company Hussmann under the name “Hussmann Protocol”, see technology data sheets C15 “Distributed Systems“.

Table 8: Summary of technology data sheet, part A, plug-in units

		Technology data sheet	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
			Decentralized plug-in refrigeration units										
			Bottle cooler with R134a	Bottle cooler with R600a, R290	Bottle cooler with CO_2 (R744)	Chest freezer with R134a, R404A	Chest freezer with R600A, R290	Chest freezer with CO_2 (R744)	MT refrigerated chest cooler	Refrigerated counter with R134a, R404A	Refrigerated shelves with R404A	Refrigerated shelves with R744	Plug unit / straddle refrigerating unit
Refrigeration data	1	Intended Use	Drink refrigeration unit near cash counter and at gas stations			As plug-in, flexible freezers in the supermarket and gas stations. Discounters prefer plug-in freezers due to high flexibility			No plug-in MT refrigerated chest cooler, unless adjusted LT-model with corresponding data, see there	Plug-in, flexible refrigeration counters /shelves mainly at gas stations and in small supermarkets or for sales actions			Plug refrigeration system mainly for refrigerated cells
	2	Cooling capacity	400 to 950 W	300 to 600 W	400 up to 1000 W	200 up to 3000 W	200 up to 1000 W	200 up to 1000 kW		420 up to 1657 W	590 up to 4700 W	unknown	Approx. 0.5 up to 9 kW
	3	Type of heat transfer	direct	direct	direct	direct	direct	direct		direct	direct	direct	direct
	4	Refrigerant	R134a	R600a; for large units R290	R744, in transcritical mode during summer	R134a and R404A	R290, only for small units R600	R744, in transcritical mode during summer		R134a and R404A	R404A	R744	R404A
	5	Refrigerant charge	95 up to 310 g, directly corr. 23.5 up to 72 g/100 l gross volume	Up to 150 g	Up to 300 g	120 up to 1200 g, corr. 36 up to 162 g per liter volume	Below 150 g	unknown		210 up to 1400 g, corr. 245 up to 700 g/m^2 sales area	390 up to 3300 g, corr. 290 up to 730 or 84 up to 125 per 100 g/l gross volume	2300 g, corr. 467 per 100 g/l net volume	Approx. 0.5 up to 3 kg
Leakage	6	Typical refrigerant losses	Near 0 as long as the units are not opened for repair purposes; during disposal eventual losses may occur.										Low as factory-made
	7	Source of leakage information	Qualified estimate and communication with manufacturers										Estimate
	8	Type of discharge	Direct at site	Direct at site	Direct at site	Direct at site	Direct at site	Direct at site		Direct at site	Direct at site	Direct at site	Direct at site
	9	Decommissioning	Disposal	Disposal; previously blow-off to atmosphere	Disposal, ev. blow-off, but then capture oil!	Disposal	Disposal; previously blow-off	Disposal, ev. blow-off, but then capture oil!		Disposal	Disposal	Disposal, ev. blow-off, but then capture oil!	Disposal
Energy	10	Energy consumption (empirical) statistical coverage possible	Glass door: 1.1 up to 1.6 kWh /24 h per 100 l gross volume; closed door: 0.6 kWh/24 h per 100 l gross volume	Up to 30 % lower than bottle coolers with R134a	At moderate temperatures 5 up to 10 % lower than HFC bottle coolers, at high temperatures also above	With glass lid 0.8 up to 1.8 kWh/24h per 100 l net volume; without glass lid 3.9 up to 5.4 kWh/24 h per 100 l	0.468 up to 0.718 kWh/24 h per 100 l volume; normally 10 up to 15 % lower than comparable HFC freezer	Not known, at installation room temperatures probably higher than with HFC, with low installation room temperatures probably lower	No plug-in MT refrigerated chest cooler unless for LT with corresponding data, see there	From 0.5 (natural convection) or 5.9 (forced convection) up to 12.5 kWh/24 h per m^2 sales area	7.3 up to 19.4 kWh/24 h per m sales area or 2.5 up to 4.4 kWh/24 h per 100 l gross content	7.5 kWh/24 h per 100 l gross content	Depending on cooling capacity
	11	Possibility for heat recovery	Heat emission to sales area all over the year										
	12	Further possibilities for energy savings	Speed control of compressor (approx. 10-15 % of energy can be saved), use of energy saving light bulbs, light source outside refrigerated space, improved insulation, optimized fans and fan motors, fan motor outside refrigerated space, improved expansion valves, improved evaporators, lower temperature of condenser through water cooling										e.g. speed controlled of compressor and/or fan
	13	Conditions of climate and use from which data were extracted	Entire EU	Calorimeter measurements and measurements in environmental chambers under equal conditions	Denmark	Entire EU	Calorimeter measurements and measurements in environmental chambers under equal conditions	unknown		25 °C, 60 % relative humidity	25 °C, 60 % relative humidity	Climate chamber by German Technical Inspection Agency (TÜV)	
Life-cycle cost	14	Investment / component costs	Reference system/technology for bottle coolers	Similar to HFC bottle coolers	At the moment considerably higher than for HFC bottle coolers	Considerably lower costs than multi-compressor refrigeration systems	Approx. 15 % higher than HFC chest freezers	Higher cost than comparable plug-in HFC refrigeration units		Considerably lower cost than multi-compressor refrigeration systems	Considerably lower cost than multi-compressor refrigeration systems	Higher cost than comparable plug-in HFC refrigeration units	Depending on installation place, lower costs than refrigeration rooms chilled by multi-compressor refrigeration system
	15	Installation costs	None, as no installation work related to refrigeration technology is required										
	16	Operational costs	Reference system/technology for bottle coolers	Approx. 15 - 30 % lower than for HFC bottle coolers	Energy costs up to 10 % lower than HFC bottle-coolers with moderate temperature in installation room	Reference system/technology for chest freezers	Energy costs approx. 10 - 15 % lower than HFC chest freezers	Not known	No plug-in MT refrigerated chest cooler – only switchable chest freezers with corresponding thermostat - for data see there	Higher than refrigerated counter with multi-compressor refrigeration systems	Higher than refrigerated shelves with multi-compressor refrigeration system	Depending on temperature in installation room higher or lower than HFC refrigerated shelves	Higher than for a refrigeration room chilled by a multi-compressor refrigeration system
	17	Maintenance intervals	None	None	None	None	None	None		None	None	None	None
	18	Maintenance costs	None	None	None	None	None	None		None	None	None	None
Market share	19	Number of units/systems installed	Several 100 000	More than 1000 with R600a and several hundred with R290	Approx. 6000	AHT systems up to beginning of 2007: 240 000	More than 100 000 as ice cream freezers and several ten thousand as chest freezers	So far only prototypes		Not known	Not known	Not known, probably only several hundred	many
	20	Regional distribution	Entire EU	Mostly Scandinavia, in future also West-Europe	Worldwide	Entire EU	Chest freezers in North and West Europe; ice cream freezers worldwide	None; Nestlé is considering worldwide use		Entire EU	Entire EU	Not known	Entire EU
Operational experience	21	Duration of operational experience	15 years with R134a, before, experience with CFC	Approx. 6 years in commercial refrigeration and approx. 15 years in domestic refrigeration	Since 2003 with prototypes, since 2004 in small-batch production and since approx. 2006 several thousand	With R134a 15 years; before experience with CFC	Approx. 6 years in commercial refrigeration and approx. 15 years in domestic refrigeration	So far only prototypes		With HFC since mid-nineties, before experience with CFC	With HFC since mid-nineties, before experience with CFC	Prototypes since 2003, small-batch production since 2004, large-batch production since 2005	With HFC experience since mid-nineties
	22	Reliability	Very reliable	High reliability, partly higher than with HFC	Reliable	Very reliable	Very reliable, partly higher than with HFC	Reliable		Very reliable	Very reliable	Not known	Very reliable
	23	Eventual special issues	None	R600a only usable up to a certain cooling capacity	High pressure levels when in operation and during standstill; noisier than bottle coolers with HFC and HC	None	Maximum cooling performance limited by maximum charge of 150 g and 50 bar – liter compressor size	High pressure levels		None	None	High pressure levels, esp. in hot installation places	None
	24	Special characteristics	Very flexible as it requires only a power connection										Very flexible
	25	Usability in connection with supermarket refurbishing	Very good. For plug-in devices no installation work related to refrigeration technology is required. However, one has to take into account that the entire heat of the condenser and compressor is emitted into the sales area. This is an advantage for the heating period, yet in the summer months it can lead to high room temperatures in non-air-conditioned supermarkets and an increased cooling load of other installations. If the supermarket is air-conditioned, the energy consumption of the air-conditioning system will increase.										yes
Supply chains	26	Safety requirements	None	None when charge up to 150 g	None	None	None when charge up to 150 g	None	See above	None	None	None	None
	27	Manufacturer	Many, amongst others AHT (A), Caravel (DK), Fricon (P), Frigoglass (GR), Liebherr (D), Norcool (N), Vestfrost (DK)	Liebherr (D), Vestfrost (DK)	Vestfrost (DK) and others	Amongst others AHT, Carrier, Elcold, Hauser, ISA, KMW, Metalfrio Solutions, Novum, Oscartielle	AHT (A), Frost-trol (ES), Liebherr (D)	Amongst others Frost-trol (ES), Novum (IRL)	See above	Amongst others Epta, Hauser (A), KMW, Oscartielle (I), Frost-trol (ES) and Novum (IRL) also with R744	Carrier, Criocabin, Epta, Fogal, Hauser (A), Oscartielle (I) and others	Frigoglass (GR)	e.g. Cibin, Isobar, KBS Kältetechnik and others
	28	Eventual importer	Mammut and others	-	-	Mammut and others	-	Not known	See above	Mammut and others	Mammut and others	-	many
	29	Component manufacturer	Many	Expansion valves: Danfoss, Compressors: Danfoss, Embraco	Compressors: Daikin, Danfoss, Embraco, Sanden, Sanyo	Expansion valves: amongst others Danfoss, Compressors: amongst others Danfoss, Embraco	Amongst others Danfoss	Compressors: Daikin, Danfoss, Embraco, Sanden, Sanyo	See above	Many	Many	Compressors: Danfoss, Embraco, Sanyo, Expansion valve: Danfoss	Standard components
	30	Operating company	All	Carlsberg	Coca-Cola	Esp. discounters	Esp. discounters	Nestlé is considering use	See above	Not known	Many	Coca-Cola	All supermarket chains

5.9 Individual equipment with external condensing unit

Individual equipment with external condensing unit was standard in German retail stores until 1985, later, however, they were subsequently replaced by multi-compressor refrigeration systems, see section 5.5 [Höpfer2007]. Today, condensing units are still applied for small self service groceries (so-called „Tante Emma Läden“), convenience stores, gas stations, butcher shops, bakeries, etc. [Höpfer2007]. The size of current supermarket stores (without small self service stores, see chapter 2) normally requires refrigeration capacities above 20 kW and hence parallel operation of multiple compressors [ASHRAE2002]. Systems with several parallel switched compressors are designated as multi-compressor refrigeration systems which are described in section 5.5.

In supermarkets of the size being examined within this study, i.e. above app. 400 m^2 sales area, see chapter 2, condensing units are mainly used for capacity expansion when the capacity of the multi-compressor refrigeration system is not sufficient for an expansion [Schnase2007]. As a rule, the condensing units are operated external to the cooling point, located on the roof, in the cellar, in an adjacent room or outside on the building envelop. Modern condensing units do not experience any problems concerning corrosion due to the materials applied, when installed outdoor. In most cases, the components are installed in weather protection housing and they contain the entire electric/electronic installations [Höpfer2007]. Condenser, compressor (normally hermetic compressors, but there are also semi-hermetic compressors) and receiver are pre-fabricated on a frame by the manufacturer. On site the refrigeration loads, smaller cooling cells, and groups of refrigeration/freezing units are connected by the refrigeration technician. In Europe, there are approximately 1 million of such multi-compressor refrigeration systems [DKV2002]. In South and East European supermarkets with their compared to Germany significant smaller sizes, condensing units are often used as sole refrigeration system of the store.

Usually, new refrigeration systems based on condensing units are designed for direct evaporation of HFC. For medium temperature partially R134a is used, and R404A as a standard for low temperature. R290 condensing units presented in the middle of the

1990s by some smaller companies had no success on the market. Currently, all compressor manufacturers keep to the maximum charge of 150 g flammable refrigerant used as an upper limit for household appliances. As long as the refrigerant charges remain below 150 g, no specific requirements relating to the installation place are to be met according to IEC 60335 (International Electrotechnical Commission). Yet, the appliance manufacturer is required to meet special requirements concerning e.g. surface temperatures and gas tightness. 150 g refrigerant charge are clearly to low for condensing units requiring typical charges of HFC between 3 kg and 43 kg, see technology data sheets B as well as summary in table 9.

In Great Britain at the end of the 1990s individual approaches were made to install hydrocarbons in condensing units for sale equipment. Here, the hydrocarbon charge was below 1.25 kg [Colbourne2007]. In connection with different attempts to establish hydrocarbons as refrigerant for condensing units, normally the investment costs will increase by reason of the requirements, e.g. steady monitoring, ventilation, gas tightness, (explosion-protected) components, etc.. At the same time, there is a reluctance regarding flammable refrigerants at the user companies; refrigeration systems traditionally do not contain flammable refrigerants. Larger amounts of a flammable refrigerant (e.g. 1 up to 10 kg) are classified as dangerous. A camping gas cylinder with its 5 or 11 kg charge is however not seen as a threat. Up to now, the real additional costs and “felt” safety concerns have prevented the distribution of hydrocarbons as refrigerants in condensing units.

Specifically designed for convenience stores and gas stations, a Japanese manufacturer offers combined condensing units for air-conditioning, heating (heat pump), and refrigeration with R407C [Zeller2006]. For April 2007, the installation of this technology was planned by a German discounter [Vogelbacher2007]. Within the second meeting of the project associated panel the decision was made to classify this solution marketed as „Conveni-Pack“ under the multi-compressor refrigeration systems, see technology data sheet C 16.

Table 9: Summary of technology data sheets part B, condensing units

		B1 **Individual systems with external condensing unit**
Refrigeration data	1 Intended Use	Condensing unit with air-cooled condenser and semi-hermetic condenser for air-conditioning, MT and LT applications
	2 Cooling capacity	AC 2.5 kW; MT 1.8 kW-45 kW; LT 0.75 kW-25 kW
	3 Type of heat transfer	direct
	4 Refrigerant	R404A, R134a, R507A, R407C
	5 Refrigerant charge	10 up to 20 kg
Leakages	6 Typical refrigerant losses	With smaller number of solder joints lower than multi-compressor systems
	7 Source of leakage information	Bitzer
	8 Type of discharge	Into the store
	9 Refrigerant after decommissioning	Disposal
Energy	10 Energy consumption	Similar to multi-compressor system with same compressor technology, i.e. on/off or rotation speed control
	11 Possibility for heat recovery	Possible on system side
	12 Further possibilities for energy savings	Many of the technologies described in ch. 6, e.g. rotation speed control, hot gas defrosting or condenser pressure reduction
	13 Conditions of climate and use from which data were extracted	Worldwide
Life cycle costs	14 Investment / component costs	Lower than multi-compressor system
	15 Installation costs	Lower than multi-compressor system
	16 Operational costs	Similar to multi-compressor system
	17 Maintenance intervals	Cleaning condenser as required, otherwise according to F-gas regulation, e.g. 1 (up to 30 kg) or 2 times (over 30 kg) per year
	18 Maintenance costs	Low
Market share	19 Number of units/systems installed	Many units worldwide
	20 Regional distribution	Germany since 1985 withdrawal, still common in smaller South-European stores
Operational experience	21 Duration of operational experience	Over 10 years with HFC, previously CFC
	22 Reliability	Very reliable
	23 Eventual special issues	None
	24 Special characteristics	Large selection of refrigerants, robust, durable, flexible
	25 Usability in connection with supermarket refurbishing	Ideal for expansions and systems with one or more cooling points; flexible choice of refrigerant; observe cleaning when replacing refrigerant
	26 Safety requirements	With larger markets redundancy and distribution of leakage risk through use of individual systems
Source of supply	27 Manufacturer	Bitzer, Bock, Copeland, Danfoss, Frigopohl and other
	28 Eventually importer	Many
	29 Component manufacturer	Bitzer, Bock, Copeland, Danfoss, Dorin, Frigopohl and other
	30 Operating company	Several, in Germany, mainly for chilled rooms or expansions

5.10 Central multi-compressor refrigeration systems

Today one can find central multi-compressor refrigeration systems[12] in nearly any supermarket [Jakobs2006]. In large consumer markets and hypermarkets only multi-compressor systems are used for refrigeration. They are also used by discounters, however, usually only for the MT range. The refrigeration systems are characterized by using the parallel switching of several compressors in order to create a composite system. The compressors operate with a common condenser which provides the different points of consumption with the refrigerant. Points of consumption are refrigerated counters, refrigerated shelves, refrigerated islands, refrigeration rooms, and freezer rooms. From the point of view of a multi-compressor refrigeration system, a subdivision according to these points of consumption makes little sense because each user is supplied by the same compressor system. The refrigeration capacity ranges from 1,200 up to 1,800 W per front meter refrigerated shelve [Schneider2007].

The different central multi-compressor refrigeration systems offered on the market are to distinguish according to the choice of the refrigerant(s) and also the type of refrigerant distribution, as well as with several systems according to the cooling of the condenser. Further there is a distinction between systems with direct and indirect evaporation. Table 10 shows the different variations (see technology data sheets, part C, for further details). Due to (safety) technology reasons, not any combination makes sense or is acceptable. Thus ammonia by reason of its high toxicity is excluded from the consumer area and it will never be used in direct evaporation systems in the sales area of a supermarket.

[12] Multi-compressor refrigeration systems are also known as multiplex systems, parallel compression systems or composite systems. All four phrases are used in this publication.

Table 10: Combination alternatives for central multi-compressor refrigeration systems

Condenser	air cooled; ambient air	water cooled; water cooling in ambient air cooled heat exchanger	water cooled; heating service water or store (heat recovery)	air cooled; heating store (heat recovery)
Refrigerant MT	HFC (R404A / R507A / R134a)	HC (R290 or R1270)	R717	R744
Cold Distribution MT	Direct evaporation	Liquid secondary refrigerant, single phase	Evaporating secondary refrigerant	Melting secondary refrigerant
Refrigerant LT	HFC (R404A / R507A)	HC (R290 or R1270)	R717	R744
Cold Distribution LT	Direct evaporation	Liquid secondary refrigerant, single phase	Evaporating secondary refrigerant	Melting secondary refrigerant

Multi-compressor refrigeration systems realized in practice to date use the following technologies, which are described in section C of the technology data sheets:

C1 HFC direct evaporation: R404A supermarket multi-compressor refrigeration system with direct evaporation – currently, this system is the industrial standard for supermarket composite systems. Variants of it use heat recovery. Apart from R404A, also R507A (rarely) and R134a for MT are used.

C2 HFC indirect: R404A compact system with liquid heat transfer fluid (HTF). Besides air-cooled condensers sometimes water-cooled condensers are operated in order to keep the refrigerant charge low.

C3 HFC indirect liquid HTF/CO_2: R404A compact system with liquid HTF for medium temperature and evaporating CO_2 for low temperature. Besides air-cooled condensers sometimes water-cooled condensers are operated in order to keep the refrigerant charge low.

C4 HFC ice slurry: R404A compact system with ice slurry as HTF for medium temperature and direct evaporation for low temperature. Besides air-cooled condensers sometimes water-cooled condensers are operated in order to keep the refrigerant charge low.

C5 HFC/R744 cascade system: R404A direct evaporation for medium temperature together with R744 cascade system for low temperature.

C6 HFC indirect/R744 cascade system: R404A compact system with liquid HTF for medium temperature together with R744 cascade system for low temperature. Besides air-cooled condensers sometimes water-cooled condensers are operated in order to keep the refrigerant charge low.

C7 HFC/R744 cascade system – MT evaporating carbon dioxide: R404A compact system with evaporating HTF (CO_2) for medium temperature combined with R744 cascade system for low temperature. Besides air-cooled condensers sometimes water-cooled condensers are operated in order to keep the refrigerant charge low.

C8 R717 indirect: ammonia (R717) with liquid HTF, variants use water-cooled condensers and/or evaporating HTF.

C9 R717/R744 cascade system: R717 in cascade system with R744 – MT cold distribution with liquid secondary refrigerant

C10 R717/R744 cascade system: R717 in cascade system with R744 – MT cold distribution with evaporating carbon dioxide.

C11 Hydrocarbon indirect: hydrocarbon with liquid HTF, variants use water-cooled condensers and/or evaporating HTF.

C12 HC/R744 cascade system: hydrocarbon in cascade with R744 – refrigerant distribution for MT with liquid or evaporating HTF.

C13 R744 direct evaporation: carbon dioxide in the entire market. Instead of refrigerant condensing, in summer – depending on ambient temperature – no condensing, but only gas cooling takes place. During such operation the pressure levels are usually above 100 bar on the high pressure side. Often used in combination with heat recovery.

C14 R744 direct evaporation in cascade with HFC or HC: carbon dioxide in the entire market. Subcritical operation of MT and LT with condensing by means of a HFC or HC compact unit.

C15 Distributed Systems („Hussmann Protocol“, presented 1993 by the company Hussmann): compact compressor systems with water-cooled condensers. The compressor systems are located in sound-proof housings which can be installed in the sales area. As refrigerant R404A is always used by the company Hussmann.

C16 Conveni-Pack – combined refrigeration, air-conditioning and heating for small up to medium store dimensions.

The evaporator of direct evaporation systems is located in the refrigeration units. Condensers can be arranged in air-cooled machine rooms in the building or outside of the building. Heat recovered from the condenser can be used for room or water heating. Direct evaporation systems are worldwide the dominating technology for supermarkets. The refrigerants for new systems are R404A and to a smaller extent R134a for medium temperature applications, as well as R507A in some countries, e.g. Norway. Direct evaporation systems will always have a refrigerant-carrying part inside of the sales area which the public may enter. Therefore, the refrigerant will normally require the utmost safety class (i.e. L1 according to EN-378).

Indirect systems include a secondary cycle which transports the heat energy by means of a HTF from the refrigerated cabinet to the evaporator. Refrigerant-carrying parts can be located in a secured machine room, i.e. isolated with no public access. The refrigerant charge of the primary system can be essentially reduced. Indirect systems are operated with HFC refrigerants as well as with R717 or hydrocarbons. Machine rooms with sufficient safety installations represent an additional cost factor in connection with systems using R717 or hydrocarbons. Energy consumptions of well installed and adjusted indirect supermarket refrigeration systems are quite able to compete with R404A direct evaporation systems – see technology data sheets C2, C3, C8, and C11.

In recent time, also the use of secondary fluids with phase change has become more common, ice slurry for medium temperature (see technology data sheet C4) or CO_2 for low temperature (C3), but also for medium temperature (C7 and C10) [Møller2003]. Even if ice slurry previously has only been used for medium temperature in supermarkets, there are developments within an EU project to use ice slurry also for the low temperature range [Hägg2005]. Through the selection of the correct additive, ice slurry can outperform a single phase HTF in the medium temperature range as well as in low temperature range [Hägg2005, Lagrabette2005].

Indirect systems allow designing the primary refrigeration system in a very compact manner. One can use prefabricated units and the systems' assembly can be simplified on site. Indirect systems applied for supermarket refrigeration systems allow also providing for more stable temperatures and increased humidity at the points of refrigeration, even if the control becomes a little bit slower [Bucher2007]. The energy consumption is susceptible for a decrease of up to 10 % below a comparable direct evaporation system, especially in connection with ice slurry, because a direct evaporation system often requires lower evaporation temperatures by reason of the refrigerants' superheating in the evaporators. These, in turn, cause a stronger frosting of the evaporator and hence associated defrosting losses. Also the suction piping in direct evaporation systems of supermarkets are often very long. Long distances piping cause pressure drops and hence require an increased capacity of the compressor [Rivet2007].

Secondary refrigeration systems, however, also include some disadvantages. At least one additional pump and one additional heat exchanger are required. In order to prevent the increase of energy consumption it is also important to select the appropriate HTF.

Table 11 shows in two parts a summary of the technology data sheets for multi-compressor refrigeration systems (part C). Partially, the information within the table has been strongly abridged. More detailed information as well as the corresponding literature can be found in the technology data sheets of the German version of the report.

Table 11: Summary of technology data sheets part C, multi-compressor refrigeration systems, part 1

			C1	C2	C3	C4	C5	C6	C7	C8
			Central multi-compressor refrigeration systems							
			HFC Direct evaporation	HFC Indirect	HFC Indirect liquid HTF/CO_2	HFC Ice slurry	HFC/R744 Cascade system	HFC Indirect/R744 cascade system	HFC/R744 Cascade system – MT indirect with CO_2	R717 Indirect
Refrigeration data	1	Intended use	Central multi-compressor refrigeration systems	Central multi-compressor refrigeration systems	Central multi-compressor refrigeration systems	Central multi-compressor refrigeration systems	Central multi-compressor refrigeration systems	Central multi-compressor refrigeration systems	Central multi-compressor refrigeration systems	Central multi-compressor refrigeration systems
	2	Cooling capacity	40 up to 1000 kW	40 up to 1000 kW	40 up to 1000 kW	10 up to 100 kW, partly up to 800 kW	40 up to 1000 kW; LT off-the-shelve production up to 120 kW	All ranges possible	All ranges possible	All ranges possible
	3	Type of heat transfer	Direct	Indirect	Indirect	MT: indirect; LT: direct	Direct	MT: indirect; LT: direct	MT: indirect; LT: direct	Indirect
	4	Refrigerant	R404A, more rarely R134a (MT), R507A and R410A	R404A, R507A, for MT also R134a	R404A, as HTF for low temperature R744	R404A, rarely R717	MT: R404A, rarely R134a; LT: R744	MT: R134a or R507A; LT: R744	MT: R134a or R404A; LT: R744	R717 Indirect
	5	Refrigerant charge	60 (discounter) up to 1500 kg (consumer market)	Approx. 60 % less than with direct evaporation	Approx. 60-70 % less than with direct evaporation	MT: 70 - 80 % less than C1, LT same as C1	Consumer market 5000 m^2: 1150 kg R404A, 70 kg R744	MT system approx. 60 % less HFC than C1	MT: 70-80 % less HFC than C1	Approx. 300 - 800 g/kW cooling capacity
Leakage	6	Typical refrigerant losses	4 to 10 %, with R134a less as pressure is lower	Lower than C1	Lower than C1	Lower than C1	HFC leakage lower than C1	HFC leakage lower than C1	HFC leakage lower than C1	Low due to smell of ammonia
	7	Source of leakage information	Manufacturer and user	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
	8	Type of discharge	Leading outdoors	Leading outdoors	Leading outdoors	Leading outdoors	Leading outdoors	Leading outdoors	Leading outdoors	Leading outdoors
	9	Decommissioning	Disposal	Disposal	Disposal	Disposal	HFC: Disposal; R744 sometimes blow-off – but then capture oil!	HFC: Disposal; R744 sometimes blow-off – but then capture oil!	HFC: Disposal; R744 blow-off – but then capture oil!	Disposal
Energy	10	Energy consumption	Approx. 3400 kWh/a/m – average value per front meter MT and LT	Between 10 % less and 20 % more than C1	MT: approx. 10 % more than C1, LT: up to 6 % more than C1	MT: up to 3 % less than C1; LT: same as C1	Same as C1	Approx. 5 to 15 % less than C2	Approx. 15 % less than C2	Approx. 0 - 10 % more than C1
	11	Possibility for heat recovery	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	12	Further possibilities for energy savings	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6
	13	Conditions of climate and use from which data were extracted	D, F, CH	USA, CAN, EU	CH, D, F	F	D	CH, N	N	Central Europe and Brazil
Life-cycle cost	14	Investment / component costs	Industry standard, cheaper than R744 or R717	Up to 25 % higher than C1	Up to 20 % higher than C1	Higher than traditional HTF systems (C2)	Same as C1	LT similar to C1, MT: similar to C2	Up to 20 % higher than C1	Approx. 20 - 35 % higher than C1
	15	Installation costs	Cheapest composite technology	Depending on used piping material and installation company partially lower than C1	Depending on used piping material and installation company partially lower than C1	Lower than C2	Depending on size of system between 0 and 10 % higher than C1	Depending on size of system between 0 and 10 % higher than C1	Depending on size of system between 0 and 10 % higher than C1	Approx. 2 % higher than C1
	16	Operational costs	Reference system / technology	Between 15 % lower and 15 % higher than C1	Similar to C1, lower than C2	Lower than C2	Between 0 and 5 % lower than C1	Between 5 and 10 % lower than C1	Between 10 and 15 % lower than C1	Between 0 and 10 % higher than C1
	17	Maintenance intervals	Depending on HFC charge up to 4x per year	Depending on HFC charge up to 4x per year	Depending on HFC charge up to 4x per year	Depending on HFC charge up to 4x per year	Depending on HFC charge up to 4x per year	Depending on HFC charge up to 4x per year	Depending on HFC charge up to 4x per year	Once a year
	18	Maintenance costs	Reference system / technology	Up to 50 % lower than C1	Up to 50 % lower than C1	Higher than C2	Same as C1	Lower than C1	Lower than C1	Up to 50 % lower than C1
Market share	19	Number of units / systems installed (estimate)	Many	Esp. In CAN, CH, L and S, approx. 500 in USA	Approx. 100	10 to 50 in supermarkets	More than 100 by Carrier/Linde, in total in EU several hundred	Between 20 and 50 (estimate)	Few	Approx. 60 by Carrier/Linde
	20	Regional distribution	Entire EU	CAN, CH, L, N, S, USA	Amongst others CH, S	CH, F, JP	CH, DK, D, I, L, N, S	CH, N	DK, N	Brazil, CH, D, DK, L, N, S
Operational experience	21	Duration of operational experience	R404A since 1998, R134a (MT) since 1998, R410A since 2006	Since mid-nineties	Since mid-nineties	Since 1995	Since 2001	Since late nineties	Few	Since1995
	22	Reliability	Very reliable	Very reliable	Very reliable	Reliable	Very reliable	Very reliable	Very reliable	Very reliable
	23	Eventual special issues	None	Air in HTF circuit leads to corrosion	High pressure levels in CO_2 LT circuit	Depending on design ice slurry generator requires high levels of maintenance	High standstill pressure levels with R744 lead to blow-off during downtime	High standstill pressure levels with R744 lead to blow-off during downtime	High standstill pressure levels with R744 lead to blow-off during downtime; MT return pipe needs to be inclined	R717 is toxic
	24	Special characteristics	High flexibility	Very flexible, unpacked products are less likely to dry out, use of plastic pipes possible	In LT range use of traditional units possible	High flexibility, possibility of cooling storage, use of plastic pipes possible	LT evaporation temperature higher than with HFC; very small pipes with R744	High flexibility, unpacked products are less likely to dry out, LT evaporation temperature higher than with HFC; very small pipes with R744	Unpacked products are less likely to dry out, LT evaporation temperature higher than with HFC; very small pipes with R744	GWP almost 0, use of plastic pipes possible
	25	Usability in connection with supermarket refurbishing	Yes	Yes, but replacement of heat exchangers advisable	yes	Limited	MT: no problems; LT: replacement of all components required/advisable	Limited	Limited	Very limited
	26	Safety requirements	Pressure levels with R410A higher, up to 28 (40) bar	High safety	High pressure levels in CO_2 LT circuit, safety valves and CO_2 sensors are necessary	High safety	Maximum pressure in R744 stage is 40 bar, safety valves and CO_2 sensors necessary	Maximum pressure in R744 stage is 40 bar, safety valves and CO_2 sensors necessary	Maximum pressure in R744 stage is 40 bar, safety valves and CO_2 sensors necessary	R717 is toxic
Supply chains	27	Manufacturer	All	Many	Many	Few	BKT, Carrier/Linde, Epta, Knudsen Køling, Norild, Superkøl	Carrier/Linde, Goetz (CH)	Carrier/Linde	Carrier/Linde
	28	Importer	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	29	Component manufacturer	Many	Many	Many	Ice slurry generator e.g. Axima, Sunwell, Müller, Heatcraft	Many	Many	Many	Many
	30	Operating company	R404A all, R134a (MT) Rewe, R410A Ökoring (refrigerated storage)	All Swedish companies, many in CAN, CH, L, N, USA	Some in CH, DK, F, S	Migros (CH), Carrefour (F)	Many	Coop (CH, N), ICA (N), Migros (CH)	Coop (N), Hurtigrutenterminal (N)	ICA (S), Migros (CH)

Table 11: Summary of technology data sheet, part, C, multi-compressor refrigeration systems, part 2

			C9	C10	C11	C12	C13	C14	C15	C16
			Central multi-compressor refrigeration systems							
			R717/R744 Cascade system MT with liquid HTF	R717/R744 Cascade system – MT CO_2 as HTF	Hydrocarbon indirect	HC/R744 Cascade system – MT CO_2 as HTF	R744 Direct evaporation	R744 Direct evaporation in cascade system with HFC or HC	Distributed system	Conveni-Pack
Refrigeration data	1	Intended use	Central multi-compressor refrigeration system	Central multi-compressor refrigeration system	Central multi-compressor refrigeration system	Central multi-compressor refrigeration system	Central multi-compressor refrigeration system	Central multi-compressor refrigeration system	Distributed (composite) system	Simultaneous provision for air-conditioning and MT refrigeration units (optionally LT) with integrated heat recovery (HP)
	2	Cooling capacity	All ranges possible, downwards limited by available compressors	All ranges possible, downwards limited by available compressors	Designed for up to 90 kW MT and 50 kW LT	All ranges possible	All ranges possible, so far designed for 40 to 140 kW	All ranges possible, in DK common in discounters MT: 24 kW, LT: 10 kW	Each individual compressor system 15 to 40 kW	MT 15.8 kW; LT: 2.0 kW, Air conditioning 14.5 kW; HP 30 kW
	3	Type of heat transfer	MT: indirect; LT: direct	MT: indirect; LT: direct	Indirect	MT: indirect; LT: direct	Direct	Direct	Direct, but locally limited	Direct
	4	Refrigerant	R717/R744	R717/R744 cascade – MT CO_2 as HTF	R290 or R1270	R290 and R744	R744	HFC/R744 oder HC/R744	R404A	R407C
	5	Refrigerant charge	Approx. 230 g/kW R717 and 2500 g/kW R744	Approx. 1 kg R717 per kW cooling capacity, R744 not known	From 120 g per kW cooling capacity	From 120 g per kW cooling capacity	Approx. 1 kg per kW cooling capacity	HFC approx. 70 - 80 % lower than C1	Approx. 25 - 33 % lower than C1	10 - 25 kg
Leakage	6	Typical refrigerant losses	Low due to smell of ammonia	Low due to smell of ammonia	Not known, but probably low due to gas sensors	Not known, but probably low due to gas sensors	Approx. 10 %	HFC under 5 %, R744 approx. 10 %	Lower than C1	Probably lower than composite system
	7	Source of leakage information	Estimate	Estimate	Estimate	Estimate	Danish estimate	Danish estimate	USA	Daikin
	8	Type of discharge	Leading outdoors	Leading outdoors	Leading outdoors	Leading outdoors	Leading outdoors	Leading outdoors	Individual circuits in the market	In the market
	9	Decommissioning	R744 blow-off – but then capture oil!	Disposal or blow-off – capture oil!	Disposal	Blow-off – capture oil!	Blow-off – capture oil!	Disposal; R744 also blow-off – capture oil!	Disposal	Disposal
Energy	10	Energy consumption	Lower than C1	13 - 18 % lower than C1	Air-cooled condenser 5 % more than C1, indirect cooling of condenser 20 % more than C1	Similar to C1	In North Europe approx. 10 % lower than C1, in South Europe approx. 10 % more than C1	Similar to C1	Approx. 5 to 10 % lower than C1	Similar to composite systems
	11	Possibility for heat recovery	Yes	Yes	Very good, esp. with heat carrier fluid circuit at condenser	Yes	Very good	Yes	Very good	Built-in
	12	Further possibilities for energy savings	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Most of those described in chap. 6	Many of the technologies described in chap. 6, e.g. hot gas defrosting
	13	Conditions of climate and use from which data were extracted	Denmark – test system and supermarket in Norway	NL	Not known	DK	CH, D, DK, N, S	DK	USA	B, D, GB, JP
Life-cycle cost	14	Investment / component costs	LT part in large markets comparable to C1	28 % higher than C1	Approx. 15 to 25 % higher than C1	Approx. 20 % higher than C1	Approx. 50 % higher than C1, in future approx. 20 % higher than C1	Up to approx. 20 % higher than C1	For small supermarkets up to 30 % higher than C1, for large supermarkets cheaper than C1	Similar to composite system
	15	Installation costs	Not known	Higher than C1	Approx. 20 % higher than C1	Approx. 10 to 20 % higher than C1	Slightly higher than C1	Slightly higher than C1	Probably lower than C1	Installation costs slightly lower than composite system with air-conditioning unit
	16	Operational costs	Not known	Lower than C1	Lower than C1	Same as C1	At the moment still slightly higher than C1	Similar to C1	Approx. 10 % lower than C1	For whole market up to 30 % lower, as no furnace installed
	17	Maintenance intervals	Once a year	Once a year	Once a year	Once a year	Several times per year for cleaning of gas cooler	Once a year	Depending on HFC charge up to 4x per year, but more rarely than C1, as charge is lower	As required, assessed by system and automatically requested
	18	Maintenance costs	Not known	Lower than C1	Lower than C1	Same as C1	Approx. 20 higher than C1	Approx. 20 to 50 % higher than C1	Similar to C1	Probably lower than C1
Market share	19	Number of units / systems installed	Very few	Less than 10 in EU	Carrier/Linde approx. 17	1 in DK	Approx. 60 in EU	More than 100 in DK	Market share among newly installed systems in USA in 2006: 15 %	Approx. 4000 in JP in convenience stores as well as approx. 130 in EU
	20	Regional distribution	N, S	NL	CH, D, DK, GB, I, S	DK	B, CH, D, DK, GB, I, L, N, S	DK	USA, a few in A and CH	D (10), B (20), GB (100), JP (4000)
Operational experience	21	Duration of operational experience	Since 1995 test system in DK	3 to 4 years	Since 1996	Since 2000	Since 2001	Since 2002	Since mid-nineties	Since 2002
	22	Reliability	Very reliable	Very reliable	Very reliable	Very reliable	Very reliable	Very reliable	Very reliable	Very reliable
	23	Eventual special issues	R717 is toxic, high downtime pressures of R744 lead to blow-off during downtime	R717 is toxic, high downtime pressures of R744	HCs are flammable, gas sensors required	R290 is flammable, high downtime pressures of R744, gas sensors required	High downtime pressures	High downtime pressures of R744	None	None
	24	Special characteristics	GWP near 0, unpacked products are less likely to dry out, LT evaporation temperature higher than with HFC; very small pipes with R744	GWP near 0	GWP near 0, very flexible, unpacked products are less likely to become dry, use of plastic pipes possible	GWP near 0, very flexible, LT evaporation temperature higher than with HFC; very small pipes with R744	Steadier temperatures in refrigeration shelves, smaller piping diameter with R744	Steadier temperatures in refrigeration shelves, smaller piping diameter with R744	Very flexible	Integrated heat recovery
	25	Information about usability in connection with supermarket refurbishing	Very limited	Possible, but limited	Possible, but limited	All components new	Many components new	Many components new	Yes, very good	Possible, requires comprehensive cleaning of all parts with refrigerants
	26	Safety requirements	R717 is toxic, high downtime pressures with R744, safety valves and CO_2 sensors required	R717 is toxic, high downtime pressures with R744, safety valves and CO_2 sensors required	HC are flammable, gas sensors and fan/ventilation required	R290 is flammable; R744 high downtime pressure, safety valves and CO_2 sensors required	R744 high downtime pressure, safety valves and CO_2 sensors required	R744 high downtime pressure, safety valves and CO_2 sensors required	None	In larger markets separated refrigerant circuits with shared control
Supply chains	27	Manufacturer	Johnson Contols/Sabroe/York (DK), Norild (N)	Not known	Carrier/Linde (D), Johnson Controls (DK)	SuperKøl (DK), J&E Hall (GB)	Epta, Goetz, Green and Cool, Knudsen Køling, Linde/Carrier, Trondheim Kulde	Tempcold (DK)	Hussmann	Daikin
	28	Potential importer	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Hussmann	Daikin
	29	Component manufacturer	Many	Many	Many	Many	E-valve: Danfoss; compressor: Bitzer, Dorin; Units: Costan, Linde; heat exchanger: Güntner, Luve	E-valve: Danfoss; compressor: Bitzer, Dorin; Units: Costan, Linde; heat exchanger: Güntner, Luve	Many	Daikin
	30	Operating company	Coop (N) and some in S	Not known	Some in S	Fakta in DK (MT with HTF)	Today more than 70 markets of different chains in EU	Rema 1000 und others in DK	In EU only three markets in A known, very popular in USA – 15 % market share and still rising	Aldi (GB), Penny (D), Spar (B) and others

The installation costs of a central multi-compressor refrigeration system are specifically determined by the selection of the refrigerant. Pressure level, volumetric refrigeration capacity and material compatibility are issues influencing the installation costs. Figure 9, e.g., shows the necessary piping cross sections for a refrigeration capacity of 100 kW, together with appropriate insulation for different refrigerants. Through smaller piping dimensions with R744 large supermarkets are able to save as much money as additional costs will arise due to complementary safety technology and corresponding high pressure components [Post2007]. In connection with smaller refrigeration systems, e.g. at the discounter, the cost advantages from piping do not outweigh the additional costs [Görner2007].

Refrigeration system	Suction/ return line	Liquid/ supply line	Ratio of area
Direct expansion, R404A refrigerant	76/102mm	35mm	100%
Indirect, brine as secondary refrigerant	76/140mm	76/140mm	337%
Indirect, CO_2 as secondary refrigerant	54/118mm	35/73mm	166%
Direct expansion, CO_2 refrigerant	42/68mm	22/48mm	60%

Figure 9: Comparison of the piping diameter with insulation for different refrigeration systems (refrigeration capacity 100 kW) [Heinbokel2005].

It is difficult to provide precise information about the energy efficiency of multi-compressor refrigeration systems because the energy consumption is influenced by many factors:

- Gradient of ambient temperature; this is subject to variations depending on daytime and season and varies between North and South Europe,
- Solar radiation on the condenser,
- Amount of dirt on the condenser,
- Solar radiation in the sales room or directly on the refrigerated cabinets,

- Air temperature and humidity in the sales room; these are normally higher in summer than in winter,
- The cooling loads are higher in daytime operation than over night, at the same time are the ambient temperatures higher during day than during night,
- The building materials of the supermarket and possible air-conditioning influence the air humidity and temperature,
- The different sales volume of chilled goods,
- The different shopping-hours of the store – each extended shopping-hour increases the energy consumption by approximately 4 % [Pries2008],
- Loading of the refrigerated cabinets,
- The number and size of the refrigerated rooms.

Consequently, comparisons include therefore large uncertainties. The comparison of largely identical supermarket refrigeration systems within a narrow geographical region might show variations in energy consumption larger than one would have to expect according to the use of different model technologies. Figure 10 illustrates the energy consumption of 226 Penny markets from 2001, which approximately have the same refrigeration system and are nearly of the same size. Similar variations are also to find in other publications concerning other store dimensions. Figure 11 shows measurements carried out in Swiss supermarkets [Heinbokel2005].

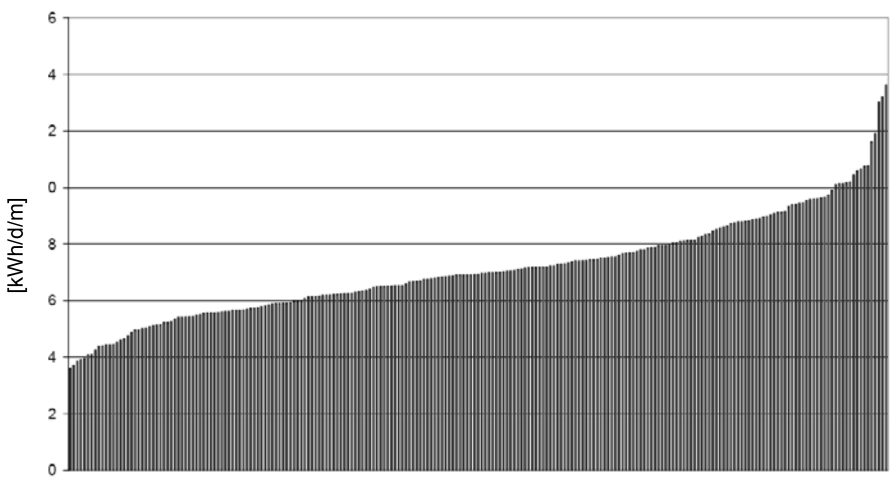

Figure 10: Daily normalised power consumption for refrigeration related to front meter of refrigerated cabinet in 226 Penny markets in 2001 [Ecofys2003].

The annual energy consumption illustrated in figure 11 is related to the number of refrigeration units and rooms installed in the individual store in order to enable a comparison of the energy efficiency of the different store installations. The different refrigeration units and rooms are assigned corresponding correction factors in order to evaluate their different refrigeration need related to front length of refrigeration unit. The diagram includes direct and indirect systems with refrigerant R404A as well as the data of a pilot store in Wettingen with R744 [Heinbokel2005].

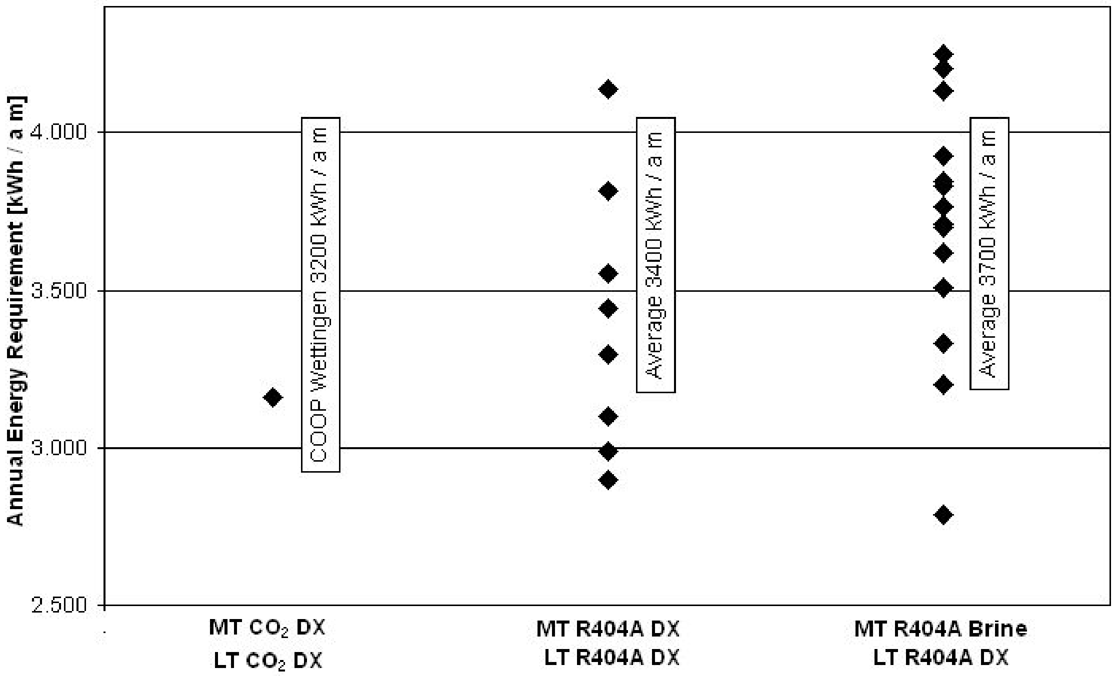

Figure 11: Energy need per front meter refrigeration unit in Swiss supermarkets. Measured values: COOP Basel, Carrier Kältetechnik Schweiz AG, former LKS Schweiz AG [Heinbokel2006]. Average is based upon best 75 % stores.

However, the analysis of the energy consumption of individual refrigeration units is rather unproblematic and can be carried out in accordance with European standards (e.g. DIN EN 441-9). In order to define the energy efficiency one has to define a reference value first (e.g. sales volume of refrigeration units, product sales area, meter refrigerated shelve, meter refrigerated chest freezer, shop sales area, turnover) whose selection can have essential impact on the result.

In future, one may expect advantages in relation to material costs for HTF systems. A HTF may be carried in plastic piping – refrigerants require copper or steel/stainless steel. Especially the copper price has strongly increased in the last 5 years. Another type of system that reduces the length of the piping to a large extent are the so-called "Distributed Systems", in the USA also known as "Hussmann Protocol." These systems are characterized by a water loop which is installed in the market in order to remove the heat of the condenser at the individual compressor stations. The (composite) compressors are arranged in silenced refrigeration aggregates next to the points of consumption in the sales area, see technology data sheets C 15 „Distributed Systems". Through such systems the HFC refrigerant charges can be reduced by 25 up to 33 % compared to R404A direct evaporation refrigeration systems. At the same time, the energy consumption of large stores is diminished by 5 up to 10 % due to reduced suction pipe losses [Garry2007, Walker1999].

In Germany, the market for the construction of central multi-compressor refrigeration systems is dominated by four large companies with supra-regional operations responsible for the construction of approximately 85 % of multi-compressor refrigeration systems for the supermarket area. These are according to their turnover: Carrier UTC (Linde), EPTA (BKT), Hauser, and Dresdner Kühlanlagenbau [Bucher2007, Schauer2008]. Beside them, there are a couple of smaller refrigeration companies which equally build and maintain supermarket refrigeration systems, partially as contractor of one of the large firms and in particular for such stores not belonging to the large retail chains. The other European countries do not know a comparable domination of the market [Bucher2007].

5.11 Alternative Technologies

Apart from the refrigeration systems previously described which are based on the vapor compression process, there are several approaches in research institutes and universities to use alternative technologies also for the supermarket sector. These alternative technologies include:

- Magnetic refrigeration
- Pulse tube / sound waves
- Peltier elements
- Cold-air cycle

Magnetic refrigeration means that a magneto caloric material, e.g. gadolinium, is alternately brought into a magnetic field and then removed. In the magnetic field the material is getting warm whereas outside it cools down. Researchers make the prognosis that magnetic refrigeration will be able to achieve a higher degree of efficiency than that one produced by a vapor compression process. Yet, with magneto caloric materials of today one can only achieve temperature differences of 15 K during demagnetization [Warthmann2006].

Refrigeration via sound waves (Pulse tube) is a gas process. The achieved COP is usually lower than that of vapor compression systems.

Peltier elements mean that heat is transported via electric current. When an electric current flows through a circuit consisting of two different conductors or semi-conductors, a heating or chilling of the points of contact will arise according to the direction of the current. At one point of contact heat is absorbed from the environment and discharged at the other. Today, Peltier elements are used for, e.g., cooler bags for the use in vehicles. The refrigeration COP of such Peltier elements drops very strongly with increasing temperature difference between the warm and the cold end. With a temperature difference of 5 K the COP of present-day Peltier elements that consist of semi-conductors is approximately 10, but it drops already at a temperature difference of 10 K to values below 1 [Radermacher2007]. Hence, it would be conceivable to use Peltier elements for liquid subcooling after the condenser or for the improvement of the efficiency of the fins of air-refrigerant heat exchangers [Radermacher2007].

The cold-air cycle is based on the compression of air. The compressed air, which is warmer than before the compression, is cooled and expanded in a machine producing work. For example, this expansion machine can be a continuous flow machine as used by an exhaust gas turbocharger. The work gained by expansion can be induced to the compressor. Today, such cold-air refrigeration systems work in almost every airplane because they are lighter than comparable vapur compression systems and because in the engines of airplanes large volumes of compressed air are produced anyway.

The cold-air cycle, however, is only energetically competitive at temperatures below approximately -30 °C compared to a vapor compression system [Kauffeld1993]. In the supermarket it would therefore only be appropriate for low temperature. The great advantage of a cold-air refrigeration system is that the refrigerant (air) is everywhere available in large volumes free of charge and neither combustible, nor toxic, nor harmful to the environment.

Currently, none of the alternative technologies described can be considered as a real alternative for efficient refrigeration systems used in the supermarket.

6. Opportunities for energy savings

Since the beginning of the 1990s household refrigerators and freezers have become more energy-efficient by more than 30 %. Concerning commercial refrigeration units and freezers one still cannot observe a similar development [LZD2005]. Nevertheless, refrigeration units/freezers are the main power consumers in a supermarket, with a share of 40 up to 60 % [BEK2007a] of 500 kWh/(m^2 a) on average related to a supermarket with more than 2,000 m^2 sales area [Manz2008]. Table 12 shows the typical distribution of electrical power consumption in a German supermarket [BEK2007a]. In total, the German food retail industry consumes more than 24 billion kWh per year for refrigeration [Jakobs2006]. In a German discounter, the refrigeration system consumes approximately 0.6 kWh/m^2 sales area per day [Jakobs2007]. For large Canadian supermarkets Minea indicates 1.37 kWh/m^2 sales area per day [Minea2007]. Certainly, a portion of the difference is caused by longer shopping-hours in North America. Based on the current shopping-hours in Germany from 8 to 20 h from Monday until Saturday, one German retailer expects an additional consumption of electric energy of 3.5 % per hour of extended opening time [Schmidt2007b].

Table 12: Typical electricity consumption in a German supermarket [BEK2007a].

Refrigeration	**48 %**
Light	26 %
Office equipment	11 %
Electrical small appliances	9 %
Power	6 %

Figure 12 shows the typical costs related to the different energy consumers of a supermarket. The costs for energy consumption may exceed the profit of the supermarket – typically 1.2 % of the turnover. In spite of, the refrigeration systems are exclusively chosen by reason of investment costs [Faramarzi2004].

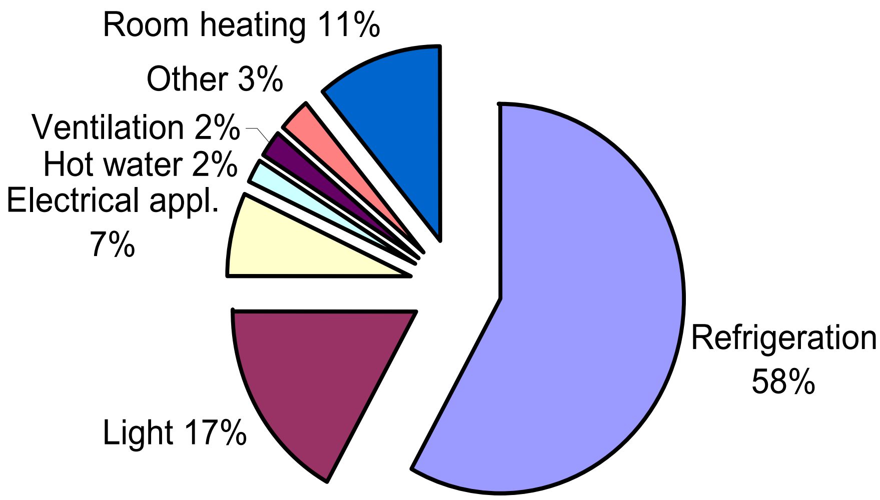

Figure 12: Energy costs in German retail [KBW1996].

Energy saving is important in relation to the supermarket's contribution to the greenhouse effect because, depending on refrigerant, leakage rate, and refrigeration system, the corresponding share for energy related emissions varies between 50 and 80 % (R404A multi-compressor refrigeration system [IPCC/TEAP2005]) and almost 100 % (R290 plug-in chest freezer or R744 multi-compressor refrigeration system).

There are a lot of initiatives for energy saving of supermarket refrigeration systems, especially provided by the different utilities. Furthermore, there is an EU project which encourages further development of energy-efficient plug-in refrigeration units and freezers for commercial application: ProCool is an international project supported within the promotion program LIFE of the European Commission. ProCool is aiming at the development of high-quality units for the food and drink retail sector which are both energy-efficient and environmentally friendly. The core of the project is a competition offering manufacturers the possibility to launch innovative and environmentally friendly refrigeration units. User companies of refrigeration units and freezers are also entitled to participate in the project so that they may benefit from the information and presentation platform under development. In Austria, ProCool is processed by the Österreichische Energieagentur and the Verein für Konsumenteninformation. In

Germany the Deutsche Energie-Agentur and the Wuppertal Institut für Klima, Umwelt und Energie are responsible for the project.

The measures for energy saving described in this chapter are applicable in nearly any case to the model technologies described above. The following opportunities for energy saving are described:

- Design / installation
    - Glass lids / glass doors
    - Fan motor outside the unit
    - Improved evaporator-fan and/or -fan motor
    - Improved airstream in open refrigerated shelves
    - Infrared reflecting shades or baldachins
    - Edge heating / dew point control
    - Siphon in defrosting drain of the refrigeration unit
    - Hot gas defrosting
    - Rotation speed control of compressor, pump, fan
    - Two-stage compression with intermediate cooling
    - Improved expansion valves
    - Expansion machines
    - Improved evaporator
    - Flooded evaporator
    - Defrost on demand
    - Improved lighting
    - Reduction of condenser temperature
        - Adjustment of the condensing to ambient temperature
        - Evaporative cooling of the condenser
        - Heat emission to the soil
        - Subcooler
    - Internal heat exchange
    - Free cooling
    - Heat recovery
    - Cold storage system

  - Intelligent system control involving several of the aforementioned measures
- Operation
  - Correct filling of the refrigeration / freezer units
  - Air humidity in the sales room
  - Cleaning of evaporator and condenser

6.1 Glass lids / glass doors

Southern California Edison indicates a reduced cooling load of 13 % for refrigerated shelves with overnight shields. During the examination a characteristic American refrigerated shelve for meat was closed from 12.00 a.m. until 6.00 a.m. with aluminium coated night shields [Faramarzi2004]. The use of glass doors closed all day if no chilled goods are taken out provides a reduced cooling load of 68 % according to Faramarzi [Faramarzi2004]. In this case too, the supermarket was open from 6.00 a.m. until 12.00 p.m.. The comparison was based on a refrigerated shelve without night shields. In German supermarkets in most cases automatic night shields have already been installed. According to the company Linde (now Carrier), new markets are only build with night shields. Consequently, only via use of all-day glass doors there would be further energy saving. The energy saving with glass lids on chest freezers would be around 40 % and with glass doors on MT shelves around 70 % [Brouwers2007 and Kröger2007a]. If possible, the glass doors / lids should be coated with a thin metal layer susceptible to reflect effectively the heat radiation (infrared radiation). This may reduce the energy consumption once again [Quack2007]. If the retrofit refrigerated shelves are such ones with night shields and optimized air ventilation, e.g. via CFD simulations, the energy saving achieved will presumably be lower. Nevertheless, energy saving ranging from 25 up to 40 % should be possible to realize. A German retail store chain reports a reduction by 50 % for the 5 meter refrigerated shelves for fresh meat by means of glass doors [Schmidt2007b].

Measurements by the company KWN at a cash and carry market in Austria, performed on open refrigerated shelves with night shields after retrofit to coated glass doors resulted in energy savings of 86 % [KWN2004]. The measurements were based on a comparison of the cooling load of the open refrigerated shelves with that of the same shelves retrofitted with sliding glass doors. During overnight operation the refrigerated shelves with glass doors should equally reduce their energy consumption compared to such ones with aluminium coated shields because the glass doors have insulation glassing. The thermal conductivity of standard insulation glass is at approximately 2.64 W/(m^2 K), that of specifically layered energy glass is at app. 1.28 W/(m^2 K) [Kauffeld2000].

Beside the reduced cooling load also a reduced energy consumption for defrosting will result because less room air and hence humidity is getting into the refrigeration unit. Via glass lids or glass doors the energy consumption for defrosting will be reduced by up to 35 % [Enova2006].

Differences in energy saving that are to achieve by glass doors can result from, e.g., the fact that some sources indicate measurements on closed doors whereas other ones relate to measurements with door openings. Thus, based on LT shelves, the opening of the door in 100 s intervals will cause an additional energy consumption of 28 % [Li2007].

In communications, all retailers pointed out the disadvantage of a loss in sales. There are no examinations known related to the influence of glass doors on the turnover of a supermarket. Retailers were not able to evidence losses in sales after the retrofit of individual markets. The air temperature in the aisle before the refrigerated shelves with glass doors is higher than in such ones with open refrigerated shelves. According to information from the USA, customers tend to stay longer in the area in front of refrigerated shelves with glass doors by reason of the convenient temperature and hence sales increase from using glass doors [Artwohl2008].

Some countries have legal provisions for the use of glass doors or lids, respectively. In Switzerland, e.g., 90 % of all freezers of a supermarket must be equipped with glass lids [Minergie2007]. By reason of a reduced infiltration of ambient air, the energy saving for freezers by means of glass lids is not as large as with the use of glass doors for refrigerated shelves. In a supermarket without air conditioning energy savings of 30 % were measured through the use of glass lids for low temperature [Post2007]. In this context the glass lids on freezers did not lead to a reduction of the sales [Post2007]. In the Netherlands in any supermarket within the municipal area of Amsterdam at least 90 % of the entire length of LT cabinets and refrigerated shelves, or 90 % of the entire length of refrigerated shelves, respectively, if these make up 90 % of the refrigeration units of the store, are to retrofit with by-day lids as of 31st December 2009 [Amsterdam2007].

The temperature distribution is more homogenous in refrigerated shelves with glass doors and the temperature of the chilled goods can be better controlled within a close temperature margin. Therefore, e.g., in 1,500 stores of a German discounter the refrigerated shelves for fresh meat were retrofitted with glass doors [Sturm2008].

There are also large energetic differences with glass doors. In order to prevent fogging standard doors need a glass and possibly edge heating. Via innovative surface layers, recent developments get along without any glass heating [Sturm2008] and partially even without edge heating [Artwohl2008]. In this way one can save up to 200 W energy for each full-size door (height 180 or 190 cm) compared to heated doors [Sturm2008]. The energy saving is composed of the electrical heating energy not consumed as well as the correspondingly reduced cooling load in the refrigerated shelve which results in reduced energy of the entire refrigeration system.

6.2 Fan-motor outside the unit

Conventionally, the fan-motor of the evaporator is installed in the cooled part of the refrigeration unit. The entire electrical energy absorbed by the motor is hence transferred to the air flow to be cooled by the evaporator. When the fan-motor is placed outside the part of the refrigeration unit to be cooled, only a significantly smaller part of the proper fan performance is fed to the air to be cooled and the cooling load will accordingly decrease.

6.3 Improved evaporator fan and/or fan motor

In connection with multi-compressor refrigeration systems the evaporator fans need approximately 6 % of the aggregate energy spent for cooling [BEK2007b]. By using energy saving motors and aero dynamical optimization of the fan blades, the energy consumption of the fans can be reduced. At the same time, the energy consumption of the refrigeration system will be reduced because it will have to remove less heat.

Within a Danish research and development project effective direct current motors were used for a bottle cooler. Consequently, the energy consumption of the bottle cooler could be reduced by app. 10 % [Kauffeld2000].

Ebm-papst, a manufacturer of fans, motors, and control equipment, has won an industrial award in 2005. In England, the “Refrigeration and Air Conditioning Magazine“ awarded its “The most environmentally friendly product of the year” prize to the company for its new energy-saving motors (ESM) and EC-fans. The jury agreed that the prize sponsored by the supermarket giant ASDA should be awarded to the company in Mulfingen because its EC motors and fans had broken new soil in energy efficiency including significant cost advantages for the end customers and a positive effect for the environment [ki Produktnews 22.5.2005]. The fans consume approximately 70 % less energy than conventional ones [Goetjes2007].

6.4 Improved compressor

In particular plug-in units with their relatively small hermetic compressors offer numerous opportunities for optimization. Measurements carried out with a plug-in LT chest freezer resulted in energy consumption reduced by 9.5 %, analogous measurements with a MT refrigerated shelve by 17 % [Salem2007].

6.5 Improved airstream in open refrigerated shelves

Up to 80 % of the cooling load of an open refrigerated shelve can result from air exchange with the sales room [SCE2007]. By means of appropriate measurement methods (DPIV – Digital Particle Image Velocimetry) [Foster2007] and modern methods of airstream simulation (CFD – Computerised Fluid Dynamics), the airstream can be optimized in such a way that the exchange with the ambient air is minimized. A complete reduction, however, is only possible by the use of glass doors, see 6.1.

The optimization of an open refrigerated shelve for fresh meat led to an energy consumption reduced by approximately 6 % coupled with improved temperature stability and variation [Schuster2007].

6.6 Infrared reflecting shades and baldachins

Figure 13 shows that approximately 15 % of the cooling load of an open refrigerated shelve result from heat radiation in exchange with the ambient air [Johansen2006]. Regarding open chest freezers, this share should be even larger. Infrared reflecting shades or baldachins can effectively shield the heat radiation and hence reduce its impact.

The temperature of goods packed with transparent film is reduced when shielded against radiation. The transparent films permeate short-wave light radiation into the interior of the package, while long-wave heat radiation cannot escape [Kaufmann1994].

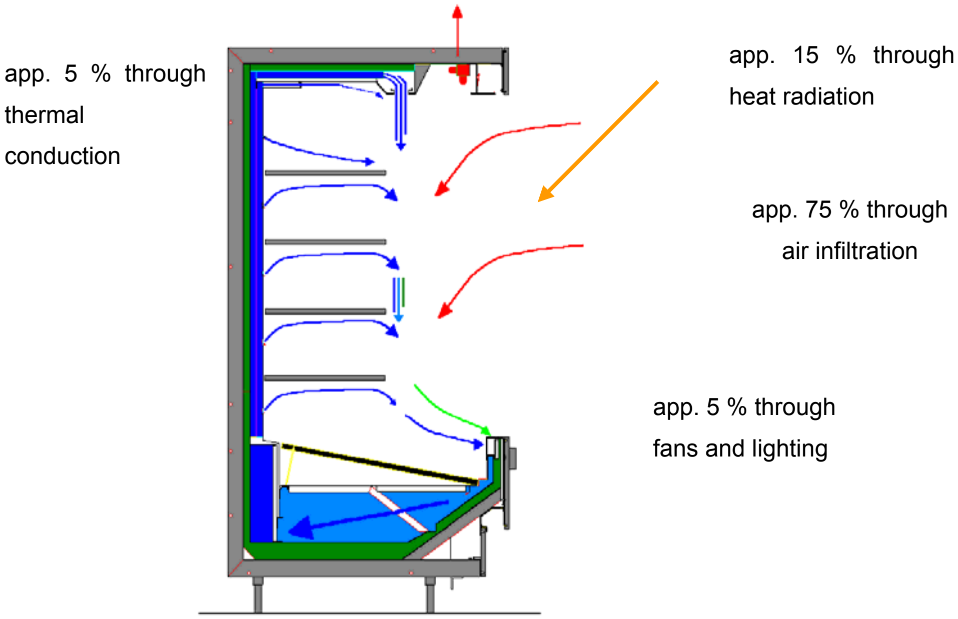

Figure 13: Pro rata cooling load of an open refrigerated shelve [Johansen2006].

6.7 Edge/rim heating / dew point control

In particular for a portion of chest freezers edge heating is used. On one part, it prevents the condensation of air humidity, and on the other part, it serves for the convenience of the customer through increased edge temperature when touching the refrigeration unit. Normally, the edge heating is electric. The energy consumption used for edge heating ranges from 8 up to 18 % of the aggregate energy consumed in a retail store for refrigeration [BEK2007b]. By means of heat conduction along the wall, a portion of the heat is conducted into the refrigeration unit where it must be removed by the evaporator, additionally. The possible reduction of the cooling load through demand controlled edge heating is given by Faramarzi at 5 % [Faramarzi2004]. Demand controlled means that the surface temperature is adjusted to the dew point temperature of the surrounding ambient air.

6.8 Siphon in defrosting drain of the refrigeration unit

Most refrigeration units are provided with a water drain enabling the condensate to flow out. Without a siphon this pipe may lead to an air exchange and hence to an increased cooling load for the refrigeration unit [Johansen2006].

6.9 Hot gas defrosting

Air coolers (evaporators and such ones with HTF), having a surface temperature below 0 °C, freeze on their air side part of the water which is in ambient air. This frost must be defrosted periodically or, from the energetic point of view more favorable, according to need. The following procedures are possible:

- Defrosting with re-circulated air (only medium temperature range),
- Electrical defrosting,
- Hot gas or hot brine defrosting via waste heat of the refrigeration system.

For any cooling point with temperatures exceeding +2 °C defrosting with re-circulated air is the most economic method. Refrigeration units and rooms for fresh meat as well as the entire low temperature sector allow only electrical defrosting or defrosting with hot gas or hot brine. Regarding electrical defrosting, the points of consumption are defrosted in groups at periodic intervals in order to avoid undesired power peaks. Measurements at HTF systems have shown that the defrosting time which is necessary for the heating of the brine increases by 10 to 20 % compared to direct evaporation systems [Haaf1998].

Even if electrical defrosting can easily be managed, from the energetic point of view it is unfavorable because the system is heated and this generated heat must be removed afterwards. Energetically, it is by far more favorable to use the hot side of the refrigeration system for defrosting. Generally, one applies hot gas after the compressor which is fed “backwards” through the evaporator for defrosting.

In connection with HTF systems, instead of hot gas normally the heat which is caused by subcooling of the refrigerant after the condenser is used for heating up the HTF.

Consequently, the temperature of the HTF is high enough for a quick defrosting of the ice on the air cooler surfaces and low enough in order to not affect the corrosive protection of the HTF. Typical temperatures for the HTF used for defrosting are at 22 to 25 °C [Kaltenbrunner2007].

Regarding hot brine defrosting, two different methods are possible:

a) Section-wise defrosting of individual groups of points of consumption by means of stored warm brine of +30 to +40 °C.
b) Heating of the entire brine network at a temperature of approximately +5 °C with simultaneous defrosting of all points of consumption and subsequent re-cooling of the brine network.

From the energetic point of view, method a) is favorable and causes short defrosting times, but it requires a significant extra expenditure especially for switch fittings. Regarding method b), the defrosting time and the energy expenditure necessary for re-cooling the brine is dependent on the total length of the piping. Calculations as well as measurements carried out for an indirect R717 refrigeration system have shown that this method is still energetically more favorable than electrical defrosting, as well as it helps to achieve acceptable defrosting times [Haaf1998].
Regarding R744 LT cascade refrigeration systems, the use of hot gas defrosting is not cost-efficient. The gas temperatures at the compressor outlet of the R744 LT stage are much lower than those of conventional R404A refrigeration systems. Hot gas defrosting with R744 therefore needs much more time with a R744 LT cascade refrigeration system and it requires 20 % more energy than electrical defrosting [Sawalha2007].

6.10 Rotation speed control of compressor, pump, fan

Via rotation speed control of the compressor the cooling performance of the refrigeration system can be adjusted continuously variable according to need. Consequently, the driving power is more reduced than the cooling capacity because, due to equal heat transfer surfaces at the evaporator and condenser, lower temperature differences arise which reduce the pressure ratio at the compressor and hence improve the specific refrigeration COP [Adolph1999]. Furthermore, the frost formation on the evaporator is reduced and longer defrosting intervals will result

[Bouchareb2003]. In addition, the quality of the chilled goods is improved by reason of reduced loss of humidity, as the variations of temperature are reduced and air humidity is achieved on a higher and more stable level [Bouchareb2003]. The rotation speed control, however, is limited toward the bottom by reason of increasing inhomogeneity (reciprocating piston compressor), oil supply, and increasing leakages (screw compressor and partially also scroll compressor) [Adolph1999].

A rotation speed control of the compressor yields depending on the system or unit, respectively, 12 to 18 % energy saving [Jürgensen2004, Sieber2006, Zeller2006]. Bouchareb et al. inform of energy savings of even 16 to 25 % for multi-compressor refrigeration systems [Bouchareb2003]. Regarding the latter, the additional costs amount to approximately 1 % of the installation costs [Sieber2006].

In earlier times (until the second half of the 1990s), electronic rotation speed control of the compressor was relatively expensive. Therefore, an adaption of the performance, at least stepwise, was achieved by switching on and off individual compressors or, as the case may be, cylinders in a compressor. Toscano et al. have shown that on calculatory grounds with a 1 : 2 : 4 staging of the compressors annual energy saving of 15 % (for R502) up to 26 % (for R12) can be expected [Toscano1982]. Measurements at a laboratory supermarket led to energy savings of 10 up to 12.5 % for R12. The comparison was made to a system having the same cooling capacity and three equally large parallel compressors.

At present, the price for electronic rotation speed controllers for compressors is in a range that enables a cost-neutral installation of electronic rotation speed controllers in multi-compressor refrigeration systems as it offers the possibility to increase the compressor speed to 60 Hz for piston compressors and 75 Hz for screw compressors instead of 50 Hz and hence a reduction of the total number of compressors used in the system can be achieved [Bouchareb2003].

Regarding the pumps of HTF systems or the possibly existing water or glycol cycle on the condenser side, one may obtain energy savings through rotation speed control of the pumps. No measurements are known for HTF systems. For the water cycle of the heating system of a one-family house energy savings of 50 up to 60% are possible through demand controlled rotation speed control, according to the Stiftung Warentest [test2007].

Demand controlled rotation speed control of the fans of condensers and evaporators is also able to save energy. At Walmart in the USA, in the period from 2006 to 2008, a corresponding test is carried out at two supermarkets [MacDonald2007, Deru2007].

6.11 Two-stage compression with intermediate cooling

The use of two-stage compression with intermediate cooling is especially favorable for LT systems. With such type of compression one may save approximately 6 % energy consumed by a composite MT/LT system [Zeller2006]. Regarding some systems, e.g.. R744 multi-compressor refrigeration systems, the two-step compression is also used for keeping the compression end temperatures below the maximum admissible values, as per example oil coking may be caused by too high compression end temperatures.

6.12 Improved expansion valves

Thermostatic expansion valves, as they are normally used for direct evaporation systems, work on the basis of linear control characteristics. Consequently, the superheat portion in the evaporator might be unnecessary high both at low and at high cooling load, from which a poor exploitation of the evaporator will follow, see also 6.15 flooded evaporators. Electronic expansion valves allow an adaptive adjustment of the control characteristics during operation. The inclusion into a network of all electronic expansion valves and asynchronous control, i.e. avoidance of load peaks which may be caused through simultaneous opening of many valves, prolongs the life time of the compressor and possibly decreases the energy consumption [Larsen2007].

Further, thermostatic expansion valves need a certain minimum pressure difference to comply with the required cooling performance. Electronic expansion valves are capable to operate with a significantly lower pressure difference so that they allow the decrease of the condensation temperature [Bobbo2005], see 6.18 reduction of the temperature of the condenser. Yet, in consequence the possibility of heat recovery is diminished, see 6.21 heat recovery. In a large (4,430 m^2 sales area) Italian supermarket (Milan) one was able to save energy according to season between 20 % (summer) and 35 % (winter) by using electronic valves for the MT and LT evaporators, in comparison with a comparable supermarket equipped with thermostatic valves [Bobbo2005]. The energy saving with MT evaporators proved 6 % larger than with LT evaporators [Bobbo2005].

In addition, electronic expansion valves allow a demand based increase of evaporation temperature. When the control of the electronic expansion valves also includes the corresponding load-dependent suction rate and the associated pressure losses, approximately 4 % energy can be saved [Zeller2006].

Regarding thermostatic expansion valves, a nozzle for pulldown[13] and a smaller nozzle for normal operation may lead to energy savings. According to Faramarzi, the superheat decreases by 2 Kelvin through application of a smaller nozzle [Faramarzi2004]. The use of internal heat exchangers (suction gas to liquid line heat exchanger) equipped at each evaporator allows a significant smaller superheating with thermostatic expansion valves [Schaller2008]. Thus optimal selected and adjusted thermostatic expansion valves can be operated at minimum condensing temperatures of 15 up to 18 °C [Schaller2008]. The energetic advantage between electronic and thermostatic expansion valves is accordingly reduced to approximately 4 up to 6 % [Schaller2008].

6.13 Expansion machine

Instead of using an expansion valve, the reduction of pressure in a refrigeration system can also be carried out by an expansion machine. It allows gaining work during the expansion. At the same time, the cooling performance is increasing because less vapor is generated in the expansion machine during the expansion process and the vapor fraction after the expansion machine is lower than after an expansion valve. To date, there are no expansion machines produced on a commercial basis. Also, the improvement of the COP with an expansion machine is rather small reaching a magnitude of 8 up to 10 % with conventional refrigerants. However, the situation alters

[13] „Pulldown“ designates the initial cooling from room temperature to operational temperature.

significantly with transcritical R744 refrigeration systems as the COP may increase by up to 40 % and the energy consumption may correspondingly decrease [Quack2004]. When the R744 refrigeration system is operated in subcritical range, e.g. in winter, the gain through using an expansion machine is still at app. 15 % so that according to Swiss climate conditions the annual average energy savings would make up approximately 20 % [Quack2007]. Corresponding expansion machines for R744 are in the development pipeline but they are (still) not available in series production.

Another type of expansion machines are ejectors. With this combination of expansion organ and compressor it is possible to, e.g., improve the COP of a transcritical R744 cycle by 7 %, the cooling performance will increase at the same time by 8 % [Elbel2007]. Other researchers report even a COP that is 20 to 30 % higher due to the use of an ejector for a transcritical R744 MT refrigeration system [Boulawz2007].

6.14 Improved evaporators

Through improved evaporators the evaporation temperature may be raised as a smaller temperature difference is required for the transfer of equal cooling capacity. Regarding refrigeration units, a higher evaporator temperature may lead to fewer or none at all defrost cycles. Faramarzi reports evaporator temperatures 3.3 K higher with an optimized evaporator whose U•A value (former k•A value) was increased by 68 % [Faramarzi2004]. Evaporation temperature increased by one Kelvin reduces the energy consumption by approximately 3 % [Bouchareb2003 and Johansen2006]. Improved evaporators are for example installed at two Wal-Mart supermarkets. The results are announced for 2008 [MacDonald2007].

The energy saving achievable with an improved evaporator with larger surfaces or improved heat transfer is limited by the superheat necessary for a safe operation of the compressor which is adjusted by the expansion valve. Through the transfer of the superheat into an internal heat exchanger installed after the evaporator the evaporation temperature may be further increased. In the ideal case, there should remain 2 to 5 % liquid refrigerant at the evaporator outlet [Tambovtsev2007]. In order to achieve a stable control behavior, Tambovtsev proposes a parallel flow arrangement of the refrigerant vapor leaving the evaporator for being superheated, and the refrigerant condensate leaving the condenser for being subcooled [Tambovtsev2007]. Subsequently, the evaporation temperature could be increased by 2 K leading to an energy saving of approximately 5 % [Tambovtsev2007].

Also with HTF systems energy can be saved by means of improved heat exchangers. A change to mini-channel heat exchangers resulted in 14 % energy saving in the MT range [Hoglund2007].

6.15 Flooded evaporators

Instead of the common operation method including superheating of the refrigerant (control of superheat through as a rule the thermostatic expansion valve), the evaporators may also be operated flooded. This operation mode, which often is used in industrial refrigeration systems, requires a refrigerant accumulator and normally a refrigerant pump. Particularly, with R744 supermarket refrigeration systems it is possible to save 30 up to 40 % energy [Johansen2006]. These savings result from improved use of the evaporators and a higher coefficient of heat transfer during evaporation, compared to superheating.

Another possibility to approximate flooded evaporation is the use of a thermostatic flow control in combination with a two-step expansion and a suction gas heat exchanger. With a plug-in LT chest freezer 16 - 17 % energy could be saved [Zimmermann2007].

6.16 Defrost on demand of the evaporator

Frequently, evaporators are defrosted by means of a time switch. Yet, often the defrosting is not necessary at the time preset by the timer. For example, defrost on demand can be detected by observation of the evaporation temperature (when frosting, the evaporation temperature sinks) or by increased energy consumption of the evaporator fan and then it can be defrosted according to need. In a standard supermarket between 3 % [Schaller2008] and 5 % [BEK2007b] of the total energy consumed by the refrigeration system is used for defrosting.

A further possibility of energy saving during defrosting are adequate defrosting flaps controlled by motors which interrupt the air exchange with the refrigeration room during defrosting. In this way, the necessary energy for defrosting can be reduced further by 50 % [Summerer2007].

6.17 Improved lighting

For good presentation of the chilled and frozen goods many refrigeration units and freezers have a lamp installed in the unit. A large portion of the electrical energy from the lamp is converted into heat which is partially discharged into the ambient, whereas the other part reaches the evaporator as additional cooling load. Via energy saving lamps one therefore obtains the opportunity to save energy twice. On one hand, through reduced need for energy by the lamp and on the other hand, through reduced cooling load. The expenditure for lighting amounts to approximately 6 % of the aggregated energy used for refrigeration [BEKb2007].

The present standard for lighting of refrigerated/freezer units and refrigeration/ freezing rooms are fluorescent tubes. The energy consumption of such tubes is composed of the energy consumption of the tube itself and that of the ballast. Pursuant to EU directive 2000/55/EC, as of 21st November 2005 electronic ballasts of energy class C are not permitted for distribution any longer. In this class, the ballast absorption performance was up to 35 % compared with the aggregated energy consumption. Modern electronic ballasts need only a small fraction of the performance – the best ones around 5 %. The exploitation of light from a fluorescent tube is at app. 80 lm/W. Lights based on diodes are developed at present. In the last ten years, LEDs were able to increase their brightness for nearly ten times and at present they achieve efficiencies of up to 100 lm/W. Walmart has installed LEDs in the refrigerated shelves of a supercenter in Aurora, Colorado, which consume approximately half of the energy compared to fluorescent tubes with adequate product lighting [Deru2007]. An advantage of LED technology against fluorescent tubes is that LEDs work the better the cooler they are kept, whereas fluorescent tubes consume more energy at low temperatures. Via replacement of LEDs for T8 fluorescent tubes one can save energy with a full-size refrigerated shelve between 50 and 70 W per opening [Sturm2008].

Apart from the use of appropriate energy-saving lights, it is also possible to place the lighting outside of the refrigerated zone or one may install reflectors or light conductors. Within a Danish project one was able to save energy with a bottle cooler of approximately 8 % through placement of the light source outside of the refrigeration unit [Kauffeld2000]. Another possibility consists in demand controlled switching on/off of the product lighting. In a supercenter in Aurora, Colorado, Walmart has switched the product lighting of one aisle via motion sensors [Deru2007]. Of course, the switching off of the lighting makes only sense where the customer frequency at certain days or times is low as this is the case during the night hours in the USA.

6.18 Reduction of the temperature of the condenser

The temperature of the condenser is often artificially maintained on a high level in order to secure the fault-free operation of the thermostatic expansion valves. When the temperature of the condenser is reduced, with each Kelvin lower temperature of the condenser approximately 3 % energy is saved [Bouchareb2003]. The temperature of the condenser is reducible by, e.g., larger surfaces of the heat exchanger, optimized air flow, shading of the condenser, spraying of the condenser (see 6.18.2) and more periodical cleaning.

6.18.1 Adjustment of the condensing to the ambient temperature

Via adequate electronic control of the condensing temperature according to ambient temperature and hence also of the condensing pressure one may save up to 3 % energy [Zeller2006]. Within a test at a Swedish supermarket one was able to save approximately 20 % energy through the adjustment of the condensing temperature [Arias2006]. Normally, reducing the condensing temperature requires electronic expansion valves because thermostatic expansion valves require a certain driving pressure difference for the refrigerant flow and capacity required.

6.18.2 Evaporative cooling of the condenser

Through spraying or wetting of the condenser with water it is possible to cool the air temperature down to approximately the wet bulb temperature. Via evaporation of the water one may further increase the performance of the condenser twice or three times [Raetz2003]. In this context, one should observe the water preparation in order to prevent, e.g., mineral deposits. When improperly operated, also health issues may arise (e.g. Legionella).

6.18.3 Heat discharge to the soil

Especially in summer the soil is cooler than the ambient air. Instead of the ambient air also a heat transfer fluid could be used, which discharges the heat of the condenser to the soil as geothermal energy. Such systems are especially appropriate when they combine dumping of waste heat to the ground in summer and heat recovery (geothermal heating) via heat pump for the supermarket's heating system in winter. Such procedures are only appropriate for soils which provide good heat conductivity. These are especially humid grounds. One has to observe that the characteristics of the ground will eventually not alter by reason of the construction of the supermarket or the parking lot, which normally will happen in direction of less favorable heat conductivity of the ground. Detailed information about geothermal heating can be found in i.e. [Loose2006]. The energy saving achieved by waste heat discharged as geothermal energy in summer is dependent on the possible reduction of the condensing temperature and it is approximately at 3 % per Kelvin reduced condensing temperature.

Usually, the waste heat of a supermarket refrigeration system is so high that the area of soil required for the heating system in winter in connection with adequate design of the building and the engineering technology available today is rather small. However, in summer this area is then not sufficient in order to discharge the entire condensing heat as geothermal energy. As one possibility, there is subcooling of the refrigerant after the condenser by means of the dischargeable heat conducted into soil [Schaller2008]. Experience with approximately 50 such systems evidence up to 20 % lower energy consumptions coincident with 20 % smaller compressors with 20 % reduced rated power [Schaller2008].

6.18.4 Fluid subcooling

Beside the reduction of the condensing temperature, one has also the possibility of subcooling the refrigerant fluid after the condenser. Consequently, the cooling capacity will increase. At the same time, the work of the compressor remains unaltered. The COP increases or the energy consumption of the system is minimized according to the necessary cooling capacity. From the energetic point of view it would be more reasonable to decrease the condensing temperature because this includes a decrease of energy expenditure and the COP would increase to a higher level compared to subcooling of the fluid with retained high condensing pressure. The energy saving following from a decreased condensing temperature would thus be higher than that which is achieved through subcooling of the refrigerant fluid.

Fluid subcooling seems favorable where a heat sink with low temperature level but limited capacity is available or where the condensing pressure and hence the condensing temperature may not sink below a certain value necessary for a fault-free operation of the thermostatic expansion valves, but where the ambient temperature would allow further cooling. The first case, i.e. a heat sink coupled with limited capacity, is connected with thermal ground probes or earth collectors. Via condensing by means of fluid subcooling which is switched according to the ambient temperature one may achieve energy savings between 18 and 22 % following from heat transfer into the soil [Schaller2008]. In the second case, i.e. the use of an additional air-cooled subcooler, the savings are between 8 to 12 % [Schaller2008].

One may also realize fluid subcooling through the heat exchange with an evaporating partial refrigerant flow that has been branched off. This fully evaporated partial refrigerant flow used for subcooling of the condensate is connected to the compressor on a pressure level that lies between the condensing and evaporating pressure levels. For such refrigerant flow the compressor must be designed on medium pressure level. A fluid subcooler of such type is also designated as economizer. Depending on the refrigerant used, energy savings might be achieved.

6.19 Internal heat exchange

Liquid subcooling can also be obtained through heat exchange between the refrigerant vapor leaving the evaporator and the refrigerant condensate leaving the condenser. In accordance with the refrigerant and its thermodynamic properties such internal heat exchange may lead to an increase or decrease in energy consumption. According to Förster [2008], in particular the isentropic exponent of the refrigerant at the evaporator outlet has to be regarded as criterion. Consequently, additional energy consumption will normally arise in connection with the use of a suction line heat exchanger for R717. Energy savings will be obtained with, e.g., R290 and R404A [Förster2008].

Considerable energy savings of 45 % are possible with R404A, when a so-called economizer, see 6.18.4, is combined with a subsequent suction line gas heat exchanger [Förster2008].

6.20 Free cooling

In Norway there are systems which completely switch off the compressors of the refrigeration system in winter and directly condense the evaporated refrigerant on the same pressure level. This type of system switching is called in Scandinavia “free cooling“. It functions significantly simpler when used with HTF systems and therefore it is often used in North European countries where numerous HTF systems are installed [Hellsten2007].

Another type of free cooling consists in blowing in the cold ambient air directly into the refrigeration unit used within MT range. Corresponding investigations with refrigerated MT shelves in China resulted in up to 80 % energy savings [Chen2007].

6.21 Heat recovery

When the waste heat is consequently used for heat recovery (HR), a large part of the energy necessary for the heating of the supermarket can be saved. Usually, direct use of the heat of the condenser for heating of the room air is more efficient than an intermediate water circuit. Nevertheless, systems with interconnected water circuit are more flexible and easier to control [Johansen2006]. HR systems with an additional air-cooled condenser in the supply duct of the ventilation system need an additional refrigerant charge between 50 and 100 kg [Görner2007]. There are also systems which combine heat recovery from the refrigeration system with reversible air-conditioning systems. This is using heat from the ambient air during heating operation. In this way one may save 23 % energy compared to a separate heating system [Zeller2006].

In order to keep the condensing temperature of the refrigeration system low, even under heat recovery mode, a heat pump can be used to transform the heat of the condenser to a temperature level that is required for heating [Minea2007]. Besides Canada [Minea2007], also in Austria such system has been installed [Kaltenbrunner2007]. The condensing temperature, however, can also be maintained on a low level during heat recovery without using an additional heat pump. The multi-compressor refrigeration system is divided into individual circuits, some are serving for the required heating level of the supermarket, with an increased condensing temperature, while, in winter, the other circuits operate with reduced temperature of the condenser [Arias2006]. Despite heat recovery, the energy consumption of the refrigeration system could be reduced by approximately 20 % [Arias2006]. At the same time, the energy expenditure for the heating system was reduced by 70 % [Arias2006]. According to Arias, heat recovery makes only sense when the entire condenser heat (of the corresponding circuit) can actually be used.

Meanwhile there are lots of supermarkets in Europe which cover their entire need for heating from the refrigeration system, as well as individual systems [Manz2008, Nüssle2008], which in addition to the coverage of their own heating water and service water supply also provide the heating for adjacent buildings.

6.22 Cold storage

Supermarket refrigeration systems have a strongly varying refrigeration load during the course of the day. During closure time, normally the otherwise open refrigerated shelves are closed with corresponding shades. The energy consumption of these refrigerated shelves decreases to 10 to 20 % of the need during opening hours. Furthermore, special peaks of cooling load arise in the morning when new, partially warm goods are delivered[14], and in the afternoon during the principal hours of sale. The refrigeration system must have a design adequate for these peaks and over the day it mostly operates under part-load condition. According to the type of refrigeration system, losses occur in the part-load operating mode that is more or less large. From the energetic point of view it would be more reasonable to design the refrigeration system for an average refrigeration load and to operate it with this steady load all over the day for 24 hours. In order to achieve this, cold storage would be necessary which however represents itself an energetic loss, e.g. via heat flux through the surface.

With cold storage a large part of the refrigeration can be deferred into the night hours in which the ambient temperature normally is cooler. With air-cooled condensers with adequate control (see there), one could achieve significantly reduced condensing temperatures in the night and hence a lower energy consumption.

6.23 Intelligent system control involving a plurality of the aforementioned measures

By means of computer-aided control concepts many of the previously described measures can be adequately integrated into the operation of the system. In such way, low condensing and high evaporation temperatures are viable which realize between 12 up to 20 % energy saving [Schauer2008]. Furthermore, the switching frequency of the compressors is reduced in favor of their life cycle which is augmented [Schauer2008].

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[14] Warm goods can mean goods that are prepared in the supermarket such as liver pie. In spite of HACCP, delivered goods may have to wait a longer time so that they heat up. HACCP is the acronym for **H**azard **A**nalysis **C**ritical **C**ontrol **P**oints and it relates to any step of preparation, processing, packaging, storage, dispatch, distribution, handling, and sale of chilled goods.

6.24 Correct filling of the refrigeration/freezer units

Correct filling of refrigerated shelves and cabinets does not only ensure a correct temperature of the goods, but it also aids to save energy. According to Faramarzi, overfilled, open refrigerated shelves need up to 6 % more energy [Faramarzi2004]. Coincidentally, the temperature of the warmest products increases by 6 K. The maximum staple heights are to comply with and the air channels are to keep free.

6.25 Air humidity in the sales room

Faramarzi has shown that as regards open refrigerated shelves a reduced air humidity (35 instead of 55 % relative air humidity) in the sales room can lead to up to 18 % energy saving by reason of reduced latent heat (62 % less condensation of air humidity) at the evaporators of the refrigerated shelves [Faramarzi2004]. When the room air is dehumidified by an air-conditioning system, the energy consumption of this system will increase due to the larger dehumidification. Yet, the water that is contained in the air is only condensed on the evaporator of the air-conditioning system instead of frozen in the refrigeration unit. The energy need for dehumidification of the air-conditioning system should therefore be approximately 15 % lower than that of the refrigeration system.

6.26 Cleaning of evaporator and condenser

Air cooling and air cooled heat exchangers are prone to contamination, in particular the condensers of plug-in units. Periodical cleaning of any heat exchanger surfaces reduces the energy consumption. Also applicable is the following: Evaporation temperature lower and condensing temperature higher by 1 Kelvin, respectively, will increase the energy consumption by approximately 3 %.

Any of the measures 6.1 up to 6.23 are to consider or to install during planning, whereas the measures 6.24 up to 6.26 can be influenced by the operator of the supermarket itself. Experts estimate that 10 % to 15 % of the energy consumption of refrigeration units could be saved through better filling, servicing, and maintenance [Kaufmann1994].

Figure 14 shows a comparison of the individual energy savings according to measure. Some measures exploit the same potential, e.g. electronic expansion valves and flooded evaporator. Yet, most of the measures can be combined and will hence result in an extended scope of energy saving.

Within a study carried out over several years (2005 up to 2007) for two identical multi-compressor refrigeration systems at two EC-centers located in the same climate zone, in one store 22 % energy were saved due to increase of evaporation temperature, decrease of condensing temperature depending on the ambient air down to a minimum condensing temperature level of 15 °C, use of electronic expansion valves, rotation speed control of the compressors as well as use of intelligent interactive control systems, compared with the conventional multi-compressor system with standard control in the reference store [Wendelborn2008].

In the description of the individual model technology, see technology data sheets of German version, in each case the possibility for application of the various energy saving measures are explained.

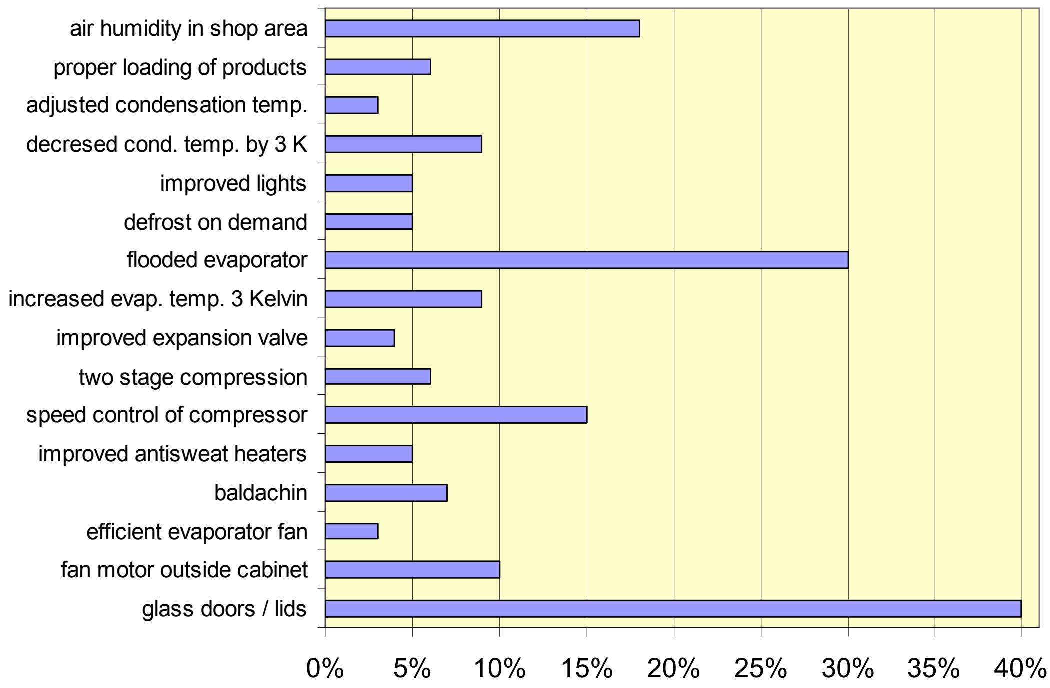

Figure 14: Energy saving in percent of aggregate energy consumption of the refrigeration system through different measures to the extent that they are proven by literature. Sources see text. Concerning wide-spread data a realistic value was assumed.

7. Losses of refrigerant

Losses of refrigerant occur with almost any refrigeration system. The amount of refrigerant loss depends on the complexity of the system, the operating conditions, the maintenance and many other factors. Thus systems ex factory are less prone to leakages than those which are assembled at site from different components. This is especially applicable when the latter rely upon screwed connections. During an examination of the Forschungsrat Kältetechnik with 62 commercial refrigeration systems in Germany (of these 19 multi-compressor refrigeration systems and 43 decentralized refrigeration systems, construction years 1990 up to 1999, refrigerant charges from 0.7 up to 360 kg) 83 % of the leakages occurred in connection with assembly joints [FKT2003], see figure 15. The average specific refrigerant loss was at 3.2 %. 99 % of the aggregated refrigerant loss resulted from „large“ leaks with leakage rates of over 30 g/a [FKT1999].

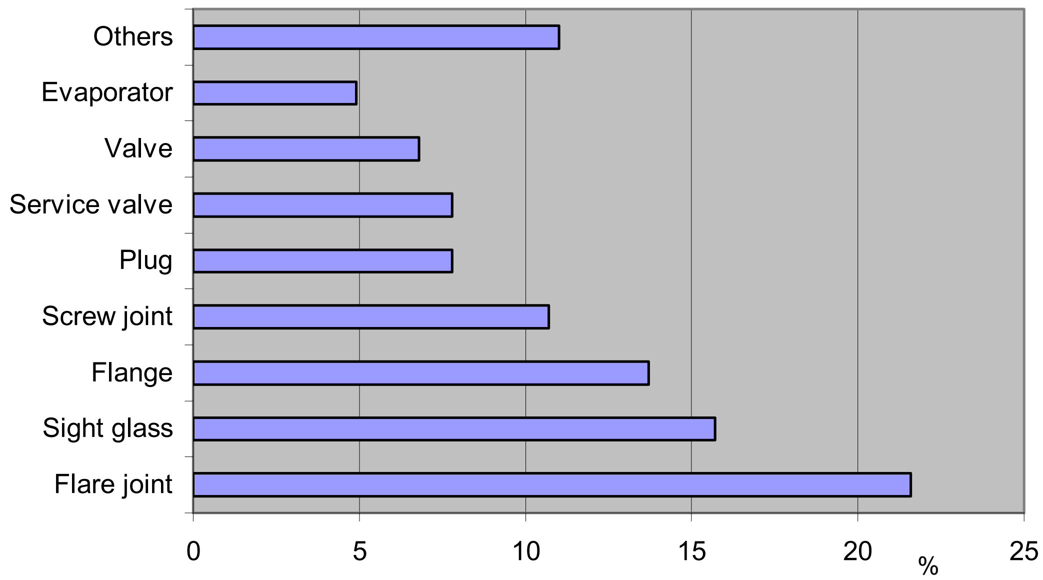

Figure 15: Locations of refrigerant losses (according to leakages, not volume!) at 62 commercial refrigeration systems in Hesse and Saxony in the year 1999 [FKT1999].

The number of screw joints is largely reduced in new multi-compressor refrigeration systems and locations susceptible for problems with vibration cracks have been eliminated [Görner2007, Huchet2007]. According to a French study, valves, especially the servicing valves, are the main places where leakages occur [Huchet2007]. In this context 40 % of the aggregate leakage places have a leakage rate of less than 5 g refrigerant per year and 45 % of the aggregate leakage places have a leakage rate of 5 up to 10 g refrigerant per year [Huchet2007], i.e. the majority of emissions is due to many, but only very small leakages.

Refrigerant losses of multi-compressor refrigeration systems in Germany (inventory) have at present a magnitude of 5 up to 10 % [Görner2007, Bucher2007]. A study carried out for 21 American supermarkets proved a leakage rate of approximately 8 % on average for 2006 [Perti2007]. Newer systems (1 to 4 years old) normally were (clearly) below that value. Exceptions were systems with pipe fractures; one system (5 years old) therefore evidenced 27 %, another (2 years old) 25 % refrigerant loss. Yet surprisingly, also ten and eleven years old systems proved a leakage rate of 5 % [Perti2007]. Hence, one cannot conclude that the age of the system is necessarily synonymous with increasing leakage rate.

A Swedish investigation of approximately 450 supermarkets carried out over the period from 1996 to 2003 shows annual leakage rates of 12.2 % (1996) up to 11.2 % (2003), see figure 16 [Engsten2004].

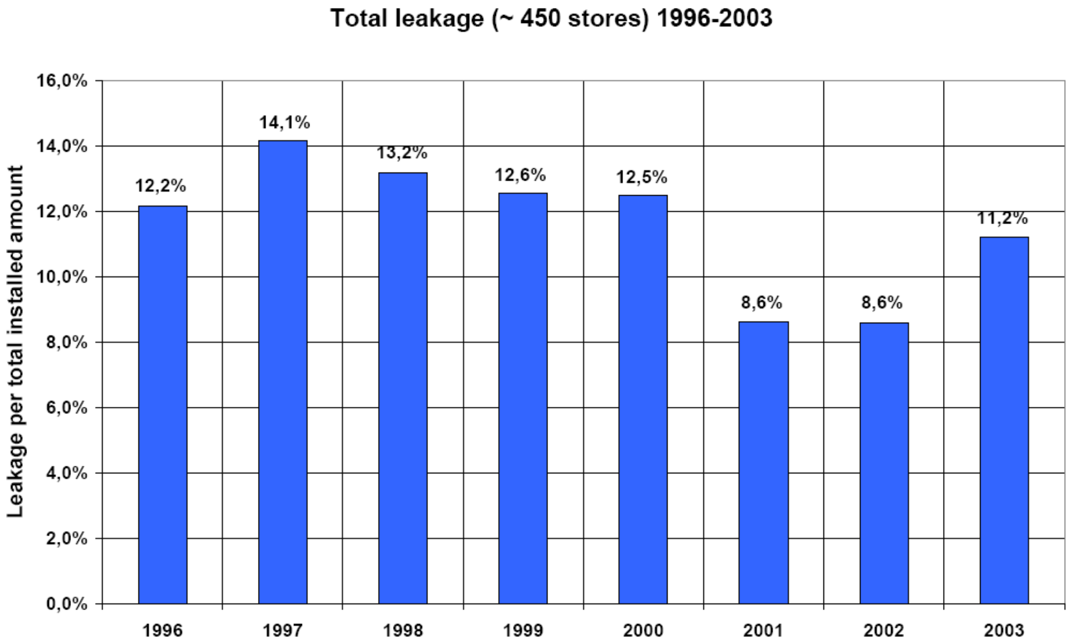

Figure 16: Refrigerant leakage rates of central supermarket refrigeration systems of two Swedish retail store chains [Engsten2004].

According to an English study, figure 17 shows leakage places aligned with leakage frequencies for multi-compressor refrigeration systems in supermarkets [Colbourne2004] where in principle the results are similar to those of the study of the Forschungsrat Kältetechnik [FKT1999]: The predominant number of leakages occurs at mechanical joints. “The main reason for the fact that mostly flare joints were not fully tight should be that the flares were not produced properly and in many cases the leakage test was not sufficient” [FKT1999].

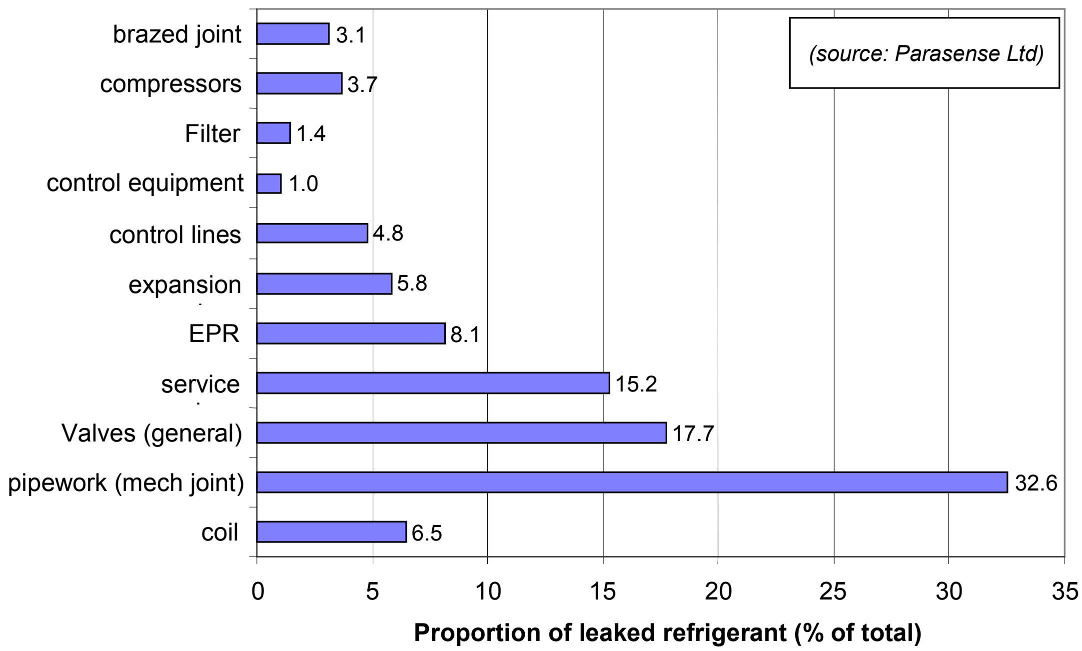

Figure 17: Refrigerant leakages in central supermarket refrigeration systems in Great Britain [Colbourne2004].

Figure 18 shows leakage places together with leakage frequency for supermarket multi-compressor refrigeration systems according to an American study.

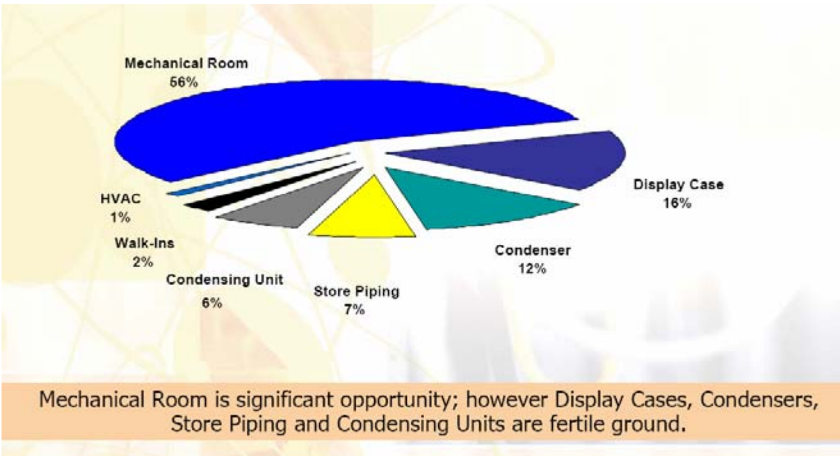

Figure 18: Refrigerant leakages in central supermarket refrigeration systems in the USA [Hoglund2006].

Figure 19 is showing again and more precisely where the leakages occur. It becomes obvious why pursuant to EN378 brazed joints are to be used as far as possible for assembly. Also for American systems more than 30 % of the detected leakages are caused by defective mechanical joints (loose fitting: approximately 55 % of 64 %).

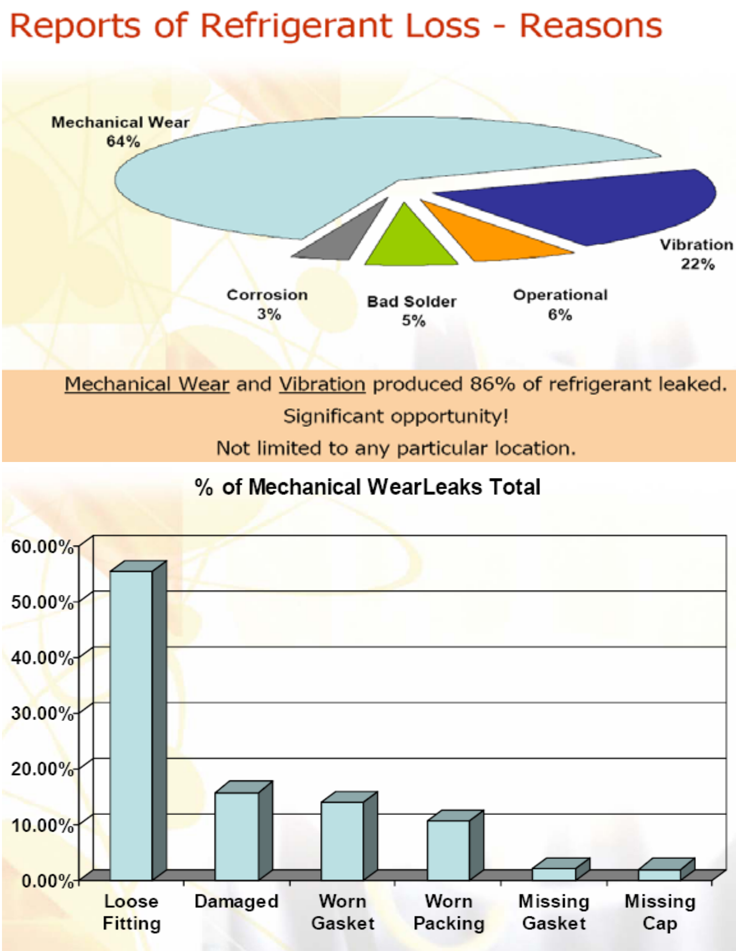

Figure 19: Refrigerant leakages in central refrigeration systems in the USA [Hoglund2006]. 86 % of the leakages are caused by mechanical wear and vibrations. Under mechanical wear the main part are loose screw joints. Loose fitting consist of flare fittings, Schraeder caps, rotolock valves, service port caps, and others.

As refrigerant leakages are earlier to notice at systems with reduced refrigerant charge and lower amount of refrigerant may escape in connection with a system's breakdown, where the system contains less refrigerant, the reduction of the refrigerant charge has large importance in respect to the reduction of greenhouse gas emissions. For instance, the reduction of refrigerant charges is possible through the use of mini-channel heat exchangers or plate heat exchangers. A test system with plate heat exchangers achieved specific refrigerant charges of 18 g per kW cooling capacity [Litch1999], whereas for systems in series production 28 g/kW has been reported [Behnert2003]. Initial evaluations of the refrigerant R290 in connection with mini-channel condenser and evaporator led to a refrigeration system with 1 kW cooling performance and 120 g refrigerant charge, coupled with the projection of an optimized system of 50 g per kW for systems with small capacity [Hoehne2004].

8. Renovation of existing systems

According to definition, in Germany there are approximately 40,000 up to 50,000 supermarkets, see chapter 3. After a period of 7 to 10 years a supermarket is rebuild, at the same time the refrigeration system obtains a renovation, too. After about 14 years or with every second rebuilding the supermarket obtains a completely new refrigeration system [Schmidt2007a, Schneider 2007]. Older supermarkets use R22 in connection with direct evaporation refrigeration systems. According to an estimate, R22 is contained in about 25 % of all existing supermarket refrigeration systems [Kröger2007b] – equivalent to approximately 10,000 systems. For a couple of years, the use of R22 has not been allowed for new systems in Europe. Alternatives for existing systems are so-called drop-in refrigerants, such as R417A (46.6 % R125, 50 % R134a, 3.4 % R600) or R422D (65.1 % R125, 31.5 % R134a, 3.4 % R600a), which can be installed without larger retrofit. Both refrigerants have a GWP of 2,300 or 2,700 [UNEP2006], i.e. higher than that of R22 (GWP = 1810 [UNEP2006]) which is replaced by them. Through a small portion of hydrocarbon in the refrigerant such as 3.4 % R600 with R417A or 3.4 % R600a with R422D these drop-in refrigerants may also be operated with mineral oil. The retrofit of a refrigeration system requires approximately five [Kröger2007b] up to fifteen hours [Schauer2008], according to the size of the system. Yet, the service technician has now to deal with another refrigerant. Therefore, when a comprehensive renovation is carried out, the system is usually converted to the refrigerant R404A. Any components with elastomeric gaskets have to be exchanged. Further, the refrigerant oil must be replaced and the expansion valves are to be adjusted. Consequently, such renovation will cost almost as much as a complete new installation [Görner2007]. Due to the significantly higher pressure levels following from the use of R744, a conversion (retrofit) to this refrigerant is not possible.

Equally, it is not possible to convert the existing system into a well functioning HTF system. The evaporators should be replaced by heat exchangers specifically designed for secondary refrigerants. Normally, the piping is too small and the liquid refrigerant pipes are not insulated. A HTF system, however, requires the insulation of the entire piping system. Also the use of ice slurry in existing direct evaporation refrigeration systems, sometimes promoted in technical journals, does not imply an energetically optimal solution to the extent that only the expansion valves are replaced by control valves and an additional pump is assembled.

Individual measures aiming at the reduction of energy consumption can be applied when retrofitting an existing refrigeration system. Glass slide covers on chest freezers and/or glass doors for refrigerated shelves are such measures with short payback times. But also the retrofit of electronic expansion valves or the electronic rotation speed control of compressor and/or heat exchanger fan motors are such measures which can be managed quite easily during renovation. For further details see chapter 6 “Opportunities for energy savings” in relation to saving potentials as well as the corresponding sources.

The EU F-gas regulation seeks to increase the tightness of existing refrigeration systems with the help of stricter tightness control, see chapter 4 “Legislation on F-Gases“. Another approach was selected by the countries Denmark and Norway imposing partially very high greenhouse gas taxes on refrigerants. Further details are contained in chapter 4.

9. Initiatives from retail store chains

Environmental topics are “fashionable”. Consumers pay more and more attention to environmentally friendly products. An international study of Weber Shandwick Worldwide from 2000 provides evidence: The behavior of a company in relation to society and environment becomes more and more important for the consumers when a decision has to be taken for or against any product or brand. Apart from price and quality, a growing number of consumers pay attention to the fact that the company behaves correctly in relation to the society and the environment when purchasing a product. Accordingly, far more than half of the German consumers decide to buy another product because the producer of their favored product lacks ecological awareness, maltreats his employees or admits child work [Weber2000].

In the meantime, now 2007, 70 percent of the consumers want to know how much carbon dioxide is caused for the production and transport of a product. Thus sustainability is also becoming the focus in the supermarket sector. That was the result of a survey carried out by Accenture nation-wide among 1,000 German persons between 14 and 70 years in May 2007 [Accenture2007]. Correspondingly, the information how many climate-damaging CO_2 is emitted for production, logistics, and packaging is an important criterion for 70 % of the Germans when buying food [Accenture2007]. 75 percent prefer retailers who presumably comply with environmentally friendly behavior. Persons over 60 years are especially distinctive regarding the awareness of sustainability. 79 percent of them would welcome a label that informs about the CO_2 balance of a product. Almost every one of the so-called best-agers appreciates food stemming from the neighborhood (97 %). The environmental image of the retailer influences almost 80 percent of the respondents within this age group [Accenture2007].

Already 1999, Paul Spoonley made the prognosis that in future the consumer will set the direction [Spoonley1999]. Especially companies which produce for the end consumer have acknowledged that trend and attempt to assume a “green” image.

In the supermarket sector, therefore, almost every retail store chain has established at least one HFC-free or greenhouse gas reduced store or it uses energy-saving concepts. By means of examples carried out in one's own company, the impact on lasting improvements, the energy consumption, the greenhouse gas emissions, the purchasing behavior of the consumers, the costs of specific technologies, etc. are evaluated [MacDonald2007]. As soon as a technology has proved its value both under the perspective of environment and costs, it will be adopted voluntarily on large scale, such as plug-in chest freezers with rotation speed-controlled compressors, glass lids, and R290 as refrigerant [Schneider2007].

Examples for voluntary commitment in the area of environmental protection related to avoidance of CO_2 emissions are provided by, e.g.: Aldi Süd, Edeka (individual Edeka retailers), Lidl, Marks & Spencer (food mainly as order good, besides food retailer under the brand Simply Food), Metro, Migros, Tesco and Wal-Mart.

Aldi Süd has played a prevailing role in the development and market launch of plug-in LT chest freezers with glass slide lids, rotation speed-controlled compressors, and R290 as refrigerant. By means of the replacement of the condenser fan which was triggered by Aldi Süd the energy consumption of the LT freezer was further reduced. To date, Aldi Süd has installed 8 transcritical R744 MT refrigeration systems in different discount stores and entered a cooperation and development agreement with Carrier/Linde related to R744 refrigeration systems. Refrigerated shelves of Aldi Süd are equipped with energy saving fans and an energy saving lighting for which Aldi Süd is holding a patent and which introduces less heat into the refrigerated area. Condensers of the refrigeration systems are designed with larger heat exchanger surfaces in order to reduce the energy consumption. All information about energy saving measures at Aldi Süd are from Aldi Süd.

Coop Swiss intends to reduce its own CO_2 output from heating, transport, etc. by 16 % until 2010, those of the affiliate shops even by 30 % [source: WWF CL!MATE GROUP[15]].

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[15] In the WWF Climate Group are associated companies which intend to make a contribution for the protection of the climate. They commit to keep the CO_2 emissions of their company and products low and agree individually with the WWF, in which areas they intend to implement climate protection measures [www.wwf.ch].

In 2006, Koch Edeka Aktiv markets were awarded the "Umweltpreis" of the state Baden-Wuerttemberg for their 2,781 m^2 food retail store because the market:

- is operated economically without combustion of fossil fuels (hence emission-free and climate-neutral),
- reduces the energy consumption by 25 % through intelligent linkage of cooling and heating sources as well as cooling and heating energy consumption and the implication of a geothermic pendulum storage without any impact on the performance of the system,
- achieves an energy saving of annualized 30,000 liters heating oil through an intelligent composite cooling/heating system and this technology is simple and cost-effective as regards its production and operation, and hence the system can be applied in full scale [Koch2007].

In addition, in 2007, all chest freezers were retrofitted with glass slide lids [Koch2007].

Since 2001, Lidl has already used several heat pump technologies for heating and cooling in numerous markets. In a market opened on 8th October 2007 it was possible to completely avoid a gas connection due to the installation of a composite geothermal energy system. Six geothermic ground probes 100 m below the ground serve as source for cooling/heating. The adjustment of room temperature (heating and cooling) relies upon a thermoactive concrete core system. Further, geothermal energy is used for subcooling of the refrigerant. A composite system including a R404A/R744 cascade system is used for chilling of the goods. In comparison with the standard, the CO_2 emissions of this market are reduced by almost 35 %. Since the second half of 2006, Lidl has been operating a MT multi-compressor refrigeration system with R744 (LT via plug-in chest freezers with R290) as pilot system. At present, further projects with pilot technologies are developed which will be commissioned until the second half of 2008. In central warehouses which were rebuild from 2003 on, Lidl is feeding the waste heat of the refrigeration systems into an industrial floor heating so that the gas consumption is reduced by 50 %. At the moment, the decision was also made to use only natural refrigerants for large scale refrigeration systems in the whole company. In the segment "photovoltaics", Lidl is operating a couple of systems where the largest individual system produces a performance according to installation of approximately 1.3 MWp. Any information relating to Lidl is taken from [Schadt2007].

200 “Simply Food” supermarkets of Marks & Spencer in England and Wales are supplied exclusively with electricity from renewable energy [M&S2007]. Until 2008, all Marks & Spencer stores shall save 20 % CO_2 emissions [M&S2007]. Marks & Spencer is a member of the °Climate Group[16].

According to its own environmental report, Metro is testing the use of natural refrigerants at a couple of locations, and the „previously used refrigerants shall be replaced step-by-step through environmentally friendly alternatives [Metro2007].” In the meantime, most of the LT freezer cabinets and shelves have been provided with covers and doors [Metro2007]. The energy consumption per square meter sales area could be reduced from 2002 until 2005 by 10 %. Since the start of 2007, 250 locations of Metro in Germany have been supplied with electricity from energy-friendly sources [Metro2007].

Migros (CH) is committed strongly to energy optimization and climate protection [Migros2007]. Thus, e.g., all freezer cabinets were equipped with glass slide covers, many markets were refurbished by energy saving concepts for lightings, and several labels are used for marking of sustainable goods [Migros2007]. On 1st July 2007, the company Migros has entered the WWF CL!MATE GROUP[17], an association of companies which are committed to active participation in the protection of the climate. In collaboration with the Energieagentur der Wirtschaft (EnAW) Migros has engaged itself to reduce the output of CO_2 of its affiliates and industrial plants by 16 % until 2010. As partner company of the WWF Climate Group the wholesaler also intends to enlarge strongly its offer for energy efficient appliances, lamps, and lightings [Migros2007].

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[16] The °Climate Group is an independent, internationally operating non-profit organisation seated in Australia, Great Britain, and the USA, whose members are public and private organisations which are committed positively to CO_2 reduction in the area of climate change. The °Climate Group was founded in 2004 by a group of different companies, governmental and non-governmental organisations in order to create new internationally striving impulses for the limitation of climate change. Members from FRI are Marks & Spencer and Tesco [www.theclimategroup.org].

[17] At present, the “WWF CL!MATE GROUP“ exists in Switzerland and Austria. In other countries the program is known under the name „*climate savers*“. Members in Austria are IKEA and in Switzerland e.g. Coop, IKEA, and Migros. In the WWF Climate Group are associated companies which intend to contribute to the protection of the climate. They commit themselves to keep the CO_2 emissions of their companies and products low and agree individually with the WWF, in which areas they intend to implement climate protection measures [www.wwf.at and www.wwf.ch].

For its new city markets (500 to 1,000 m^2 sales area) Rewe intends to use only R744 for the LT range [Rewe2007], in cascade to an R134a MT refrigeration system [Schmidt2007a].

Tesco has equipped three supermarkets with natural refrigerants in order to test alternatives for HFCs [Tesco2007]. The intention is that Tesco wants to reduce the energy consumption of all markets by 50 % compared to 2000 until 2010. To this end, the reduction of energy consumption for any new market will exceed 50 % compared to a typical supermarket from 2006. Tesco's options are elements such as LEDs as lighting source, solar panels, and wind generators [Tesco2007]. Tesco is a member of the international °Climate Group.

Walmart has built two test markets in the USA. They are so-called supercenters with an area of 19,000 m^2 each [MacDonald2007]. The two markets were located in two places different in their climate: one market in McKinney, Texas (hot), and the other in Aurora, Colorado (cold). A lot of innovative technologies were installed into the stores, such as glass doors, enlarged/improved heat exchangers, and rotation speed-controlled fans on or in any refrigerated shelves, respectively, glycol circuits for MT refrigeration units, LED lighting in refrigerated shelves, evaporative condenser or cooling tower, absorption refrigeration systems, wind generators, solar panels, and gas turbines for combined heat and power generation [MacDonald2007, Deru2007]. For technical measurement the two supercenters are surveyed by two independent institutes from 2006 until 2008. Concerning the refrigeration system, as yet there are no clear results [MacDonald2007]. Walmart is planning to consume 20 % less energy until 2012 in all existing supermarkets and already as of 2009 up to 30 % less energy in any new one [Wal-Mart2007]. An important element is demand controlled LED lightings for any refrigerated shelve. Until 2008, these will be installed in 500 Wal-Mart supermarkets [Wal-Mart2007]. On the long term, Wal-Mart will option for 100 % renewable energies [Wal-Mart2007].

The same direction has the initiative „Refrigerants, Naturally!“ of Coca-Cola, McDonald, and Unilever which was created by Greenpeace within the Olympic Games 2000 and implemented in 2004 to use only HFC-free refrigerants in the future. In the meantime, the companies Carlsberg, IKEA, and PepsiCo have joined the initiative which is supported by the UNEP. In 2005, the initiative has been awarded a prize by US EPA. According to the environment report 2006 of The Coca-Cola Company, the company was using 6,000 bottle coolers with R744 until the end of 2006, of a total of over 9 million units [Coca-Cola2006]. In 2003, MacDonald has opened the first restaurant in Vejle, Denmark, where all cooling and air-conditioning systems are working without HFC [McDonald's2004]. The central air-conditioning system is operated with R744.

As laudable as the mentioned initiatives of individual retail store chains are in relation to the greenhouse effect, there are still some retail store chains which, even today, operate or build new supermarkets with R22 on the large scale in countries with corresponding legislation such as China, India, USA. R22 has a GWP of 1,810, thus approximately half of R404A, but is has also an ozone depleting potential of 0.04. In the EU it is therefore prohibited for new systems and it may only be used for servicing of existing systems, see chapter 8 "Renovation of existing systems."

10. Summary

The following points are a summary of the findings worked out in this part of the study. Several items relate to the detailed information of the technology data sheets which as an excerpt are provided by table 8, 9, and 11. The full version of the technology data sheets is only published in German.

- Only in very few cases (e.g. the Netherlands)[18] the manufacturers and operating companies of F-gas equipment were as yet successful to demonstrate that measures for tightness of F-gas systems can be efficient in refrigeration technology – partially connected with very high system costs.
- Even if HFCs are at present the basis of most technical solutions available on commercial grounds in the supermarket sector, they can in the meantime be replaced by refrigerants with very low or zero GWP at generally acceptable costs and for almost any application. In order to evaluate the technologies, a comprehensive analysis by means of TEWI, see part 2 of this study, or better LCCP is imperative, apart from the global warming potential of the refrigerants.
- According to the current state of art, there is no need of being afraid of losses of energy efficiency when fluorinated refrigerants are substituted by natural refrigerants.
- Some of the technologies described are as yet only installed in few supermarkets with special technical servicing. The evidence by means of adequate field tests as to whether such systems prove themselves also in rough every-day operation (e.g. retrofit in short time) and lead to similar good results as the pilot systems so far constructed is still open.
- In countries with corresponding legislation, such as Denmark, Norway, and Sweden, in the meantime many systems are built with significantly reduced F-gas charges or are using natural refrigerants only. These systems achieve energy efficiencies comparable to conventional direct evaporation refrigeration systems with F-gases.

[18] And even in the Netherlands the figures are partially disputed.

- Many retail store chains have commissioned individual supermarkets with alternative technologies in order to examine the use of such technologies. A couple of retail store chains have announced CO_2 emission avoidance strategies within voluntary environmental obligations, which partially are very ambitious.

- Plug-in units are, at least for cooling capacities up to 1,000 W, compared with units with HFC energetically better solutions relying upon refrigerants with very low GWP. When the limitation of refrigerant charge for flammable refrigerants is extended, such as from 150 g at present to 500 g, all plug-in units could be equipped with this technology.

- Refrigeration technology applications in present supermarkets include significant potentials for energy savings (up to far over 50 %) at affordable costs. Depending on the measure, amortization periods of only a couple of years result.

- Transcritical systems based on R744 have a very good potential for heat recovery because R744 shows a temperature and enthalpy change similar to the water to be heated in the transcritical range. Also, significantly more heat is available in transcritical operation at high temperature level compared to the de-superheating of, e.g., R404A. Hence the water amount which can be heated to the level of service water (about 60 °C) is larger with R744.

- Possibly, there are individual applications where HFC based solutions in connection with finally optimized systems and at comparable costs achieve better TEWI values on the long term. In the reality of the German food retail, however, it is very improbable that the degree of optimization is achieved in full scope. The same holds for expensive alternative solutions from which follows that on the long term simple solutions with good environmental compatibility are required.

- A prohibition of HFC in supermarkets is an option that is viable both from the technical and economical point of view (see Denmark), even if at present it is (still) not an ecologically compulsory option. Losses of theoretically feasible energy efficiency do not offer in practice a salient argument against such prohibitions of HFC use.

11. Literature

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Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment” (FKZ 206 44 300)

Final Evaluation and Assessment

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Table of Abbreviations

COP	Coefficient of Performance
CO_2E	Carbon Dioxide Equivalents
FRI	Food Retail Industry
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC	Hydrocarbon
HFC	Hydrofluorocarbon
kWh	Kilowatt hour
LCCP	Life Cycle Climate Performance
LT	Low Temperature
MT	Medium Temperature
R290	Propane
R717	Ammonia (NH_3)
R744	Carbon Dioxide (CO_2)
R125	Pentafluorethane (C_2HF_5)

R134a	1,1,1,2-Tetrafluorethane ($C_2H_2F_4$)
R143a	1,1,1-Trifluorethane ($C_2H_3F_3$)
R404A	Blend from R125 (44 %), R134a (4 %) and R143a (52 %)
t	Metrical tons
TEWI	Total Equivalent Warming Impact

1. Introduction

The final evaluation and assessment is carried out for three defined store categories and different refrigeration systems. Both the store categories and the model technologies under consideration were reconciled with experts from the retail industry and refrigeration technology during an initial project meeting. The target of this section is to set out a comparative overview of the climate relevance of different cooling concepts used in the retail industry. For this purpose the so-called “Total Equivalent Warming Impact” (TEWI) is calculated according to different refrigeration systems. A refrigeration system’s TEWI value describes the system’s indirect emissions from energy consumption and its direct emissions which result from using refrigerants with impact on the climate. Within the project, special abatement costs are mapped onto these values in order to provide selected emission reduction measures.

At the beginning of October 2007, the entire set of the TEWI analyses’ input data and the calculation of abatement costs were reconciled during a second project meeting with those experts who had also attended the first meeting in Berlin, as well as further representatives from refrigeration technology and the retail industry.

The emissions from German food retail industry (FRI) in connection with power consumption and refrigerant emission are currently accountable for up to approximately 1% of the German greenhouse gas emissions (see ch. 5.2). Apart from high energy consumption of refrigeration technology systems (about 50 % of the aggregate energy consumption of a market [Bremer2006]), a large part of the emissions is stemming from the use of HFC refrigerants including their greenhouse potential.

2. Store categories and procedures

The structure of the food retail industry in Germany is heterogeneous. The market ranges from the little downtown supermarket up to spacious hypermarkets in the open countryside. The refrigeration technology installed in the different store categories differs accordingly. In order to gain a perspective of the greenhouse gas emissions as representative as possible in accordance with the supermarket refrigeration technology, the considerations of this study are carried out for three customary store categories. These were reconciled with representatives from the retail industry during the first expert meeting in Berlin at the end of February 2007 (see Table 1).

Table 1: Selected store categories

Store categories	Sales area	Food segment	Linear meters refrigeration equipment MT	Linear meters refrigeration equipment LT
Discounter	800m^2	ca. 95%	22.5 m	40 m
Supermarket	1,500m^2	ca. 95%	50 m	40 m
Hypermarket	6,000m^2	ca. 70%	95 m	150 m

2.1 Layout alternations concerning the store categories

In order to demonstrate the climate relevance of the different store categories according to their refrigeration technology used, for each store category the use of different refrigeration systems is taken into consideration.

Discounters are to separate from other categories of the food retail industry, due to a not only smaller range of products but also due to an almost standard refrigeration technology, especially for the low temperature segment.

Normally, centrally located direct evaporation systems with HFC are used for plus cooling and freezing rooms.

For LT in the sales area hermetic plug-in chest freezers are used. In recent years, R290 (propane) has become the most customary refrigerant for such freezers used by discounters. Table 2 illustrates the relevant refrigeration systems for the examinations of this study.

Table 2: Refrigeration systems for discounters

I.	Direct evaporation system with R404A for normal cooling (MT) + plug-in R290 chest freezers for freezing (LT)
II.	Direct evaporation system with R134a for MT + plug-in R290 chest freezers for LT
III.	Indirect refrigeration system with hydrocarbon (R290) and liquid cooling medium for MT + plug-in R290 chest freezers for LT
IV.	R744 (CO_2) direct evaporation system for MT + plug-in R290 chest freezers for LT

Classical supermarkets and hypermarkets normally offer a larger range of refrigerated products than discounters. Accordingly, the refrigeration systems have a wider scope and are more complex. The current standard of the German retail sector consists in direct evaporation multi-compressor refrigeration systems which in most cases use R404A as refrigerant. The cold is generated outside of the sales area in the proper refrigeration plant and afterwards transported to the cooling units of the sales area by means of an often largely distributed piping system.

Table 3 contains a summary of the corresponding refrigeration systems for supermarkets and hypermarkets whose climate relevance has been analyzed in this study.

Table 3: Refrigeration systems for supermarkets and hypermarkets

Ia.	R404A direct evaporation systems for MT and LT
Ib.	Direct evaporation systems with R134a for MT and R404A for LT
IIa.	R404A direct evaporation for MT and R744 cascade system for LT
IIb.	R134a direct evaporation for MT and R744 cascade system for LT
III.	Ammonia indirect with liquid cooling medium
IVa.	R717 (Ammonia)/CO_2 cascade system with distribution of MT by means of evaporating CO_2
IVb.	HC/CO_2 cascade system with distribution of MT by means of evaporating CO_2

2.2 Development of policy scenarios as an illustration of different leakage rates

Losses of refrigerant exist at any of the refrigeration system. The degree of losses generated by leakages is depending upon the complexity of the refrigeration system, the operating conditions, maintenance intervals and many other factors. Systems ex factory tend to have a lower leakage rate than those assembled on site by several components, especially when the last ones include mechanical joints (screw connections). In connection with new multi-compressor refrigeration systems the number of screw connections has been largely reduced and critical points for vibration cracks eliminated [Görner2007].

Beside leakages, a breakdown of the system is happening again and again with especially large multi-compressor refrigeration systems, which lead to a total loss of the refrigerant. A system breakdown is caused per example by improper treatment of systems or material fatigue of components, in particular of old systems.

Within the policy scenarios the loss of refrigerant caused by a breakdown of the system has been accounted for so that in the following the term leakage rate includes also the losses through breakdowns.

Studying the leakage rates observed in literature, one finds values from 3-22 % for different countries. An overview of the leakage rates observed in different countries can be found in "*IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System.*" Accordingly, in Germany annual refrigerant losses of 5 – 10 % are recorded [IPCC/TEAP2005]. A Danish study from 2003 reports refrigerant losses of 10% for supermarket refrigeration systems [Pedersen2003]. From Norway 14 % are reported [Bivens2004]. 14 % as well represent Great Britain and numbers from the United States vary between 13 % and 22 % [IPCC/TEAP2005].

In 1999, 62 commercial refrigeration systems, especially in supermarkets, were examined in Hesse and Saxony on behalf of the Forschungsrat Kältetechnik e. V. concerning their specific loss of refrigerant. In this case, an average specific loss of refrigerant of 10.5 % per year was evaluated [FKT1999].

Regarding their values, the Netherlands are especially conspicuous with a reported leakage rate of 4.5 % per year. In comparison with the other values, it is the result of a program for the regulation of refrigerants named STEK which is applied in the Netherlands since 1992 [Yellen2002].

However, the effectivity of STEK and the leakage rates reported are not indisputable. According to the interpretation of the specific losses of refrigerant reported, the rates increase from 4.5 % up to 12.6 % [Anderson2005].

A completely tight system does not exist. Principally, leakage rates of an individual system from below 1 % up to largely above 100 % are possible, because in connection with a breakdown the whole refrigerant may escape. The target therefore must be to keep potential leakages as low as possible and to avoid a breakdown as far as possible.
Due to large differences of the literature data, in this study plausible assumptions are made concerning the leakage rates of refrigerants. However they are not empirically re-evaluated in respect of Germany.

2.2.1 Scenario 1 – Current situation in the year 2006

Scenario 1 mirrors the reference situation in Germany before the successful implementation of the new EU framework. The annual leakage rates of refrigeration equipment with HFC are lying about 10 % of the refrigerant charge.

An awareness concerning the responsible operation of refrigeration equipment does already exist. Regular maintenance is made maximally once a year due to which possible leakages are detected only very late.

The loss during disassembling the equipment for disposal is estimated about 15 % of the initial refrigerant charge (corresponding to an annual loss of 1.5 % with an average life time of 10 years). During the filling of the systems low leakages may exist which however should not exceed 1.5 %. In relation to a life time of 10 years 0.15 % per year will result there from. Annual leakage rates, disposal losses, and small refrigerant losses during the filling are equivalent to an annual leakage rate of **11.65 %** of the initial refrigerant charge.

For plug-in systems concerning any of the three policy scenarios a leakage rate of 1.5 % per year is assumed. These systems are delivered ex factory and they are principally very tight. Normally, larger losses only happen in connection with damaging the piping in consequence of improper treatment. Also during disposal of the equipment further losses may occur.

2.2.2 Scenario 2 – Improved forthcoming situation with optimum tightness due to EU F-Gas regulation enacted on 4th July 2006

Within scenario 2, this study establishes the assumption that due to the consequential implementation of the EU regulation No. 842/2006 on certain fluorinated greenhouse gases from 17th May 2006 (F-gas regulation) the annual leakage rates of refrigeration systems using HFC will decrease from 10 % to date to 5 % in the near future.

The lower annual leakage rate is the result of the mandatory tightness examination required by the F-gas regulation for equipment with 3 kg refrigerant charge of fluorinated greenhouse gases. Applications of 30 kg fluorinated greenhouse gases or more will be subject to control for tightness at least once per six month. Applications of 300 kg fluorinated greenhouse gases or more will be subject to control for tightness at least once per quarter (art. 3, sect. 2-4) and provided with a leak detector. In addition, it has to be ensured in future that maintenance work is executed by certified and qualified personnel (art.5).

Further, the operating companies of the equipment with a refrigerant charge of >3 kg are obliged to keep so-called “logbooks” pursuant to art. 3, sect. 6, as of 4th July 2007. In the logbooks the operating companies are to document the amount and type of refrigerant, amounts refilled as well as recovered during maintenance, upkeeping or disposal. Further they keep records concerning the identification of the company or the technical personnel having carried out the maintenance or upkeeping. In addition, records on the dates and outcomes of control measures are kept pursuant to section 2, 3, and 4 of the regulation.

Art. 4 of the regulation prescribes the recovery of refrigerant by means of certified personnel. Hence the loss of disposal during disassembly of the equipment decreases to 10 % of the initial refrigerant charge (annually 1.0%) according to our assumptions. Filling emissions during installation of the equipment remain on the same level with 1.5 % of the initial refrigerant charge (0.15 % per year). According to the assumptions mentioned above, an annual leakage rate of **6.15 %** will result for scenario 2.

2.2.3 Scenario 3 – Improved Situation with optimum tightness pursuant to VDMA standard sheet 24243-1

Within a two step schedule, the VDMA standard sheet 24243-1 recommends admissible specific refrigerant losses for new refrigeration equipment according to DIN EN 378-1 with HFC refrigerants. The standard sheet provides for a reduction of admissible annual losses as follows:

First step mandatory since 30.06.2005

- Refrigerant charge < 10 kg – admissible specific refrigerant loss ≤ 6 %
- Refrigerant charge 10-100 kg – admissible spec. refrigerant loss ≤ 4 %
- Refrigerant charge >100 kg – admissible spec. refrigerant loss ≤ 2 %

Second step mandatory as of 30.06.2008

- Refrigerant charge < 10 kg – admissible specific refrigerant loss ≤ 3 %
- Refrigerant charge 10-100 kg – admissible specific refrigerant loss ≤ 2 %
- Refrigerant charge >100 kg – admissible specific refrigerant loss ≤ 1 %

Due to the recommendation of VDMA standard sheet, this study assumes that the annual leakage rate will be further reduced onto a level of about 2 %.

Even if VDMA standard sheet 24243-1 does not impose any specific requirements regarding the disassembly of the refrigeration systems, scenario 3 assumes a further reduction of disposal losses up to 5 % (annually 0.5 %). Emissions during charging the systems remain however on the same level and are assumed with 1.5 % (annually 0.15 %). Summing up, for scenario 3 will result an annual leakage rate of **2.65 %** according to the assumptions.

The defaults of VDMA do not specifically deal with unforeseeable refrigerant losses by reason of breakdown. In principle, one cannot avoid them completely (see ch. 2.2). The present scenario, however, makes the assumption that following a scenario with optimum tightness the risk of possible breakdown is reduced to a minimum because due to improved system construction, regular preventive maintenance in short intervals, and responsible treatment by qualified personnel a system breakdown will only happen in rare cases. In order to achieve the very ambitious leakage rate target of 2.65 % per year, a high degree of effort and technical know how is indispensable for any operating company, refrigeration technician, and the maintenance personnel.

2.3 TEWI calculations – methods

The so-called **T**otal **E**quivalent **W**arming **I**mpact (TEWI) of a refrigeration technology system describes the aggregate sum from indirect emissions of the systems due to energy consumption and direct emissions caused by loss of refrigerant. Contrary to a Life Cycle Climate Performance (LCCP) analysis which also involves emissions from energy expenditures for production of the system and further greenhouse gas emissions caused during the production of the refrigeration system, the focus of a TEWI analysis consists in the emissions following from the operation of the system. Yet in most cases the difference between LCCP and TEWI is only low because the climate relevance of the system's production against emissions during its operation is only very small. The calculations are made pursuant to DIN 378-1 as follows:

$$TEWI = GWP * L * n + GWP * m * (1 - \alpha_R) + n * E_a * \beta$$

with:	GWP	: Global Warming Potential	[-]
	L	: leakage rate	[kg/a]
	n	: operating time	[a]
	m	: refrigerant charge	[kg]
	α_R	: recovery portion in connection with disposal	[-]
	E_a	: annual energy consumption	[kWh/a]
	B	: CO_2 emissions from energy consumption	[kg/kWh]

The calculated value is divided by the system's operating time and thus given as its annual value. Within this study any data are related to a system life time of 10 years. Frequently however in German markets refrigeration systems are used for a by far longer period. The GWP values applied relate to a time horizon of 100 years (see table 4).

Table 4: Applied GWPs Source: [IPCC1996, UNEP2006]

Refrigerant	IPCC 1996	UNEP 2006
R404a	3,260	3,900
R134a	1,300	1,430
R744 (CO_2)	1	1
R717 (Ammonia)	<1	<1
R290 (Propane)	~20	~20

The values from 1996 are exclusively applied for calculations within this study because these are used in the Kyoto Protocol and thus are politically mandatory. However one has to acknowledge that the application of the old and low GWP values has a favorable effect on the TEWI results of conventional equipment with HFC-containing refrigerants. Table 4 shows that according to new scientific output the GWPs for R404A and R134a are up to 20% higher.

Annual leakage rates and the recovery portion correspond to the annual refrigerant loss values described in the policy scenarios.
Contrary to conventional supermarket systems with HFC (essentially R404A and R134a) the FRI segment up to now does not provide reliable empirical data for system technologies with natural refrigerants due to their low market share. Thus, when better data are not available, percentaged values are applied relating to conventional systems with HFC. In connection with any store category a direct multi-compressor refrigeration system with R404A was selected as “reference system“.

2.4 Uncertainty analysis

The energy consumption in particular, but also the refrigerant charge of refrigeration equipment used in the retail sector are subject to large variations (see ch. 3). In order to involve these variations within the TEWI analyses in an appropriate manner, the outcome of the TEWI analyses is determined by means of so-called Monte-Carlo simulations as probability distributions.

With the help of Monte-Carlo simulations it is possible to simulate the effects of the combination of uncertainties within complex calculations. A Monte-Carlo simulation is a method borrowed from stochastic and based upon random experiments very often performed. Within the simulation applied, random figures are generated that correspond to the input variables for “energy consumption” and “refrigerant charge.” The random variables “energy consumption“ and “refrigerant charge“ are considered as normally distributed because they follow from the interference of a large number of influences (equipment location, system size, cooling performance, consumer behavior, ambient temperature, age of equipment, etc.).

Due to Monte-Carlo simulations, one can show in which range the TEWI value of a model technology has a possible variation margin. The aggregate uncertainty of the TEWI value is defined by means of the so-called coefficient of variation of the corresponding Monte-Carlo simulation. The coefficient of variation is defined as quotient from the standard variation and the average value of the series of measurement and normally is given in percent.

Regarding large variation margins of the input values, it seems not reasonable to provide one single TEWI value for some specific model technology without the addition of variation margins. Consequently the results from TEWI analyses are represented on one part as curves of distribution. On the other part, uncertainties following from the simulation and when represented as a TEWI value are transferred into a bar chart where error bars correspond to two standard variations symmetrically around the average value and hence include 95 % of all possible values.

3. Data base

As far as possible, TEWI calculations should apply empirical data which are provided by different representatives from the retail industry, refrigeration system manufacturers, as well as refrigeration technicians. When empirical data do not exist, the study is referring to data from the first part of the study worked out by Prof. Kauffeld and literature data.

A critical factor for the robustness of the calculated TEWI values is especially a large data basis of the real energy consumption from the retail industry. The following retail store chains have generously provided empirical data for elaboration:

- Rewe-Group, Köln
- Metro-Group, Düsseldorf
- Tengelmann-Group, Mülheim an der Ruhr
- Tegut, Fulda
- Lidl, Neckarsulm
- Aldi Süd, Mönchengladbach

The average values of the data provided are illustrated by table 5 and were confirmed as representative for German energy consumptions by retail representatives attending a second expert meeting at the beginning of October 2007 in Bonn.

Table 5: Average values of energy consumption data provided by the retail industry

R404A reference system [kWh/m]	
	Average
Discounter (MT)	**3,263**
Supermarket (MT + LT)	**2,992**
Hypermarket (MT+LT)	**3,292**

For any of the three store categories, the majority of the German retail industry is using R404A direct evaporation systems. Therefore measured data available on a sufficient large scale normally exist only for this technology. For the other technologies taken into consideration often the measurement values of only very few or individual equipment are available.

Consequently, the different model technologies for the TEWI analyses are correlated with the corresponding average energy consumption values of the R404A reference system. The tables 6, 8 and 10 show how energy consumptions of model technologies according to store category correspond in percent with the R404A reference system[19].
Further, the corresponding refrigerant charges of the technology are set out in table 7, 9, and 11.

3.1 Data base discounter

Table 6: Annual energy consumption of different refrigeration systems at the discounter

Energy consumption			
Layout option	**Relation to R404A**	**Energy consumption [kWh/m]**	**Uncertainty[20] [%]**
I R404A dir. MT	**0 %**	**3,263**	**+/- 17.5**
II R134a dir. MT	-10 %	2,937	+/- 17.5
III ind. R290 MT	+10 %	3,589	+/- 17.5
IV dir. 744 MT	0 %	3,263	+/- 17.5
R290 plug-in LT		2,400	+/- 17.5

[19] The percentage values stem from the extended literature research of Prof. Kauffeld in the chapter market overview.
[20] Energy consumption margins were calculated on the basis of retail data. See chapter 3.1.2

Table 7: Refrigerant charges of different refrigeration equipment at the discounter

Refrigerant charge		
Layout option	**Refrigerant charge RC [kg/m]**	**Uncertainty[21] [%]**
I R404A dir. MT	**2.9**	**+/- 5.0**
II R134a dir. MT	3.3	+/- 5.0
III ind. R290 MT	1.0	+/- 5.0
IV dir. 744 MT	2.0	+/- 5.0
R290 plug-in LT	< 0.1	-

Layout option I MT:

Data from four large German retail store chains are considered for the energy consumption. In each case the average energy consumptions of a different number of German markets with **R404A** systems were transferred by the retailers. Table 6 shows the average energy consumption based on these values. The uncertainties and margins of energy data are explained in chapter 3.1.1.

Solid average refrigerant charges (see table 7) concerning the R404A reference system were only obtained from one retail chain. Nevertheless, R404A direct evaporation systems at the discounter are comparatively uniform so that the uncertainty in respect of the refrigerant charges obtained is only at approximately 10 %.

Layout option II MT:

Following the measurements on **R134a direct evaporation systems** of a large German retail chain, the annual energy consumption of this technology is about 10 % lower than that of comparable R404A systems. The cause is that R134a as an one-component-refrigerant offers a better heat transfer than any refrigerant blend such as R404A. Thus the coefficient of performance (COP) is better and the result is an energy consumption on a lower level.

[21] Energy consumption margins were calculated on the basis of retail data. See chapter 3.1.2

Medium refrigerant charges of the R134a direct evaporation system were obtained from the same retail store chain.

Layout option III MT:

Within the MT range, the energy consumption of an **indirect refrigeration system with R290** is about 10 % higher than the R404A reference system. When also the LT range is supplied by the R290 refrigeration system, the energy consumption is about 20 % higher than that of the R404A reference system. Therefore the LT is as well provided by plug-in chest freezers with R290.

Layout option IV MT:

Since some time the first **R744 direct evaporation systems** have been installed in German discount markets for MT. Unfortunately, measured values regarding the energy consumption of individual equipment are only available for very short periods. The first experience is that the energy consumption evidences considerable variation in connection with the ambient temperature. Regarding German climate conditions, the energy consumption of the R404A system is lower from May until September; while from October to April the energy consumption of the R744 system is lower (see technology data sheet C13).

These experiences were confirmed through the measurement of energy consumption of two discount chains. Based on the series of measurements of a large German discount chain from November 2006 until October 2007, the energy consumption of a CO_2 system was analysed. During the winter months the energy consumption was clearly lower than that of a comparable R404A system. In the summer months, however, it was slightly above. Over the annual average the result was an energy consumption 3 % lower than for the reference system with R404A. Due to these first experiences and measurement data, the operating company expects that by means of a CO_2 system applied to discount stores over the whole cycle of the year it will be able to save 5-6 % on the long term in comparison with conventional systems with R404A.

A second series of measurements of another German discount chain has been obtained for the summer months from April until September 2007. In this series of measurements the CO_2 system shows on average a clearly higher energy consumption for the assessed period.

Due to the different measurement results, the identical energy consumption of the R404A system is stipulated for the following calculations, in favor of the HFC technology.

Plug-in chest freezers with R290:

Any of the four layout options uses plug-in, hermetic chest freezers for LT. This sort of LT supply has become the prevailing form in recent years for the retail segment. The advantages include, above all, lower sales area consumption (omission of machine rooms) and a high flexibility for the use at the discounter.

Temporarily, R134a and R404A were the prevailing refrigerants of plug-in freezers. In recent years, though, R290 (propane) has become dominant. Beside the clearly lower GWP due to propane, new freezer on propane base also show a lower energy consumption than conventional freezers with HFC.

According to information of a large German retailer the annual energy consumption of R290 freezers is about 2,400 kWh/m. The annual consumption of R404A freezers is about 20 % higher at 3,000 kWh/m. Within the scenarios shown here, only R290 freezers are taken into consideration.

A feature of plug-in freezers is the transfer of waste heat which, contrary to multi-compressor systems, is delivered into the interior of the supermarket. Yet on annual average the additional need of ventilation and air conditioning during the summer months should be overcompensated by saved heat energy during the winter months. The corresponding data were not available, in the following, however, it is not further dealt with.

3.1.1 Uncertainty analysis of energy data

Following from energy consumption data of a retailer in an earlier UBA study [Harnisch 2004] it becomes clear that energy consumptions of similar system technologies used at the discounter may largely vary by multiple reasons.

As a representative value for energy consumption has to be considered for the TEWI analysis, it is important to take account for the variation margins in an adequate manner. Accordingly, the variation margin of the series of measurements has to be analysed first. When taking into account the values of the preceding series of the energy consumption measurements for R404A systems, a variation margin of 47 % would result. Extreme deflections at the upper and lower margin of the series of measurements, however, were not taken into account by means of which a variation margin of 35% was analysed. The extreme deflections may have different causes such as defective connections of the electricity meter or a temporary shutdown of individual systems.

Figure 1 shows the energy consumption variation margin relating to different model technologies by means of the orange uncertainty bar. The 404A reference system is represented as green bar.

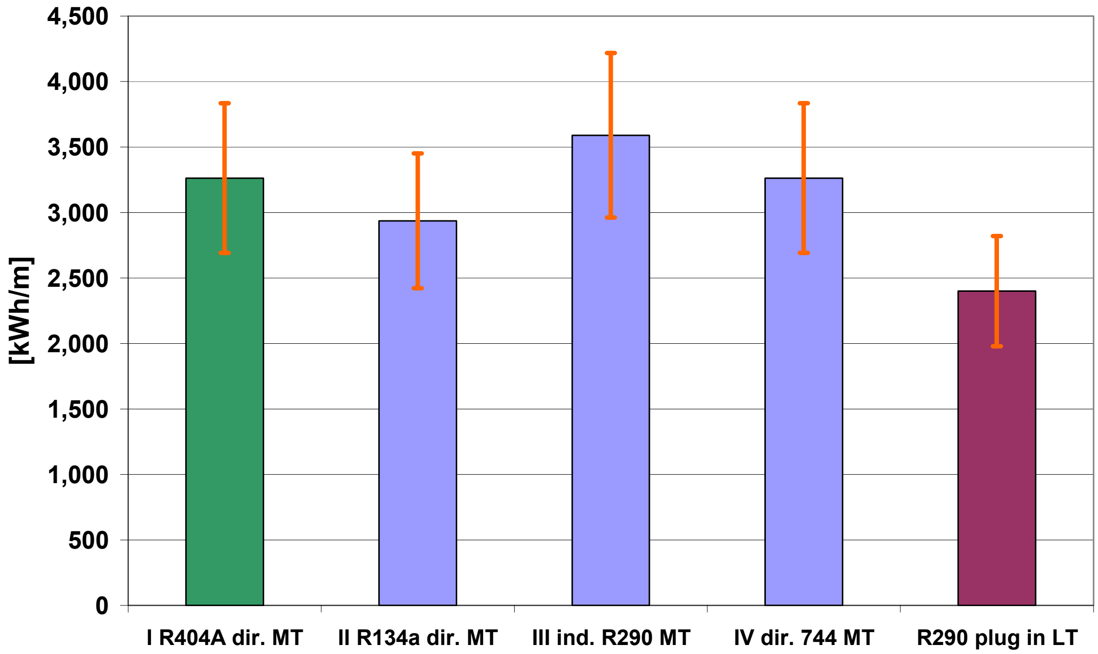

Figure 1: Annual energy consumption of the different refrigeration systems at the discounter – data from table 7

3.2 Data base supermarket

As already initially explained, today central direct evaporation systems with R404A are mainly used in the retail sector. For the remaining technologies shown in this study, regarding energy consumption and refrigerant charge there are partially only individual values from literature to obtain. Above all, this includes the layout options IVa and IVb. In this respect an increased uncertainty of 25 % for energy consumption is assumed for these two technologies (see chapter 3.2.1).

Table 8 and 9 show the values for energy consumption and refrigerant charge of different technologies at the supermarket.

Table 8: Annual energy consumption of different refrigerant systems at the supermarket

Energy consumption			
Layout option	**Relation to R404A**	**Energy consumption [kWh/m]**	**Uncertainty[22] [%]**
Ia dir. R404A MT+LT	**0 %**	**2,992**	**+/- 7.5**
Ib dir. R134a MT+ R404A LT	-7 %	2,783	+/- 7.5
IIa R404A MT + R744 LT	0%	2,992	+/- 7.5
IIb R134a MT + R744 LT	-7 %	2,783	+/- 7.5
III ind. R717	+15 %	3,441	+/- 7.5
IVa R717/R744 MT+LT	-13 %	2,603	+/- 12.5
IVb R290/R744 MT+LT	0 %	2,992	+/- 12.5
V dir. R744	0 %	2,992	+/- 7.5

Table 9: Refrigerant charges of different refrigeration systems at the supermarket

Refrigerant charge		
Layout option	**Refrigerant charge RC [kg/m]**	**Uncertainty [%]**
Ia dir. R404A MT+LT	**2.5**	**+/- 8.0**
Ib dir. R134a MT+R404A LT	2.4 kg R134a + 0.8 kg R404A	+/- 8.0
IIa R404A MT + R744 LT	2.7 kg R404A 0.5 kg R744	+/- 8.0
IIb R134a MT + R744 LT	2.45 kg R134a 0.5 kg R744	+/- 8.0
III ind. R717	0.75	+/- 8.0
IVa R717/R744 MT+LT	0.5 kg R744 0.15 kg R717	+/- 13.0
IVb R290/R744 MT+LT	1.1 kg R290 0.8 kg R744	+/-13.0
V dir. R744	3.0	+/- 8.0

[22] Energy consumption margins were calculated on the basis of retail data. See chapter 3.1.2

Layout option Ia:

The energy consumption of **direct evaporation R404A systems** are based upon average values of supermarkets of three large German retail store chains. Current series of measurements from individual systems are not available. In each case the operating companies transferred representative average values for the corresponding store category. The uncertainties and variation margins are explained in chapter 3.2.1. Refrigerant charges of the R404A system have only been obtained from one retail store chain.

Layout option Ib:

According to information of a large German retail chain and in the technology data sheet, the energy consumption of **R134a systems** is approximately 10 % lower than that of a system with R404A. The LT supply of central multi-compressor systems with R134a is operated with R404A. Consequently, the aggregate energy consumption for MT and LT is app. 7 % lower than the energy consumption of a market which is providing both MT and LT by means of a R404A multi-compressor refrigeration system. Average refrigerant charges were received by one retail chain.

Layout option IIa:

According to the results of Prof. Kauffeld, the energy consumption of the **R404A/R744-cascade system** is equivalent to the R404A reference system (see technology data sheet C5). The refrigerant charges represent values referred to literature from an eco-efficiency survey of the company Solvay [Diehlmann2006].

Layout option IIb:

By using R134a as refrigerant for MT, the energy consumption of **R134a/R744 cascade systems** is 7 % more favorable compared to the R404A reference system. This value matches also with the results of the eco-efficiency survey of the company Solvay. The refrigerant charges used stem from the eco-efficiency survey of Solvay [Diehlmann2006].

Layout option III:

The 15% higher value for energy consumption used here for the **indirect R717 system** is lying at the upper end of the margins referred to in the technology data sheet. The margin given there covers 8-15 % additional consumption in comparison with the R404A reference system (see technology data sheet C 8). In the following, the calculation is based upon 15 % because this corresponds more with the experience of German operating companies, according to representatives of a large German retail chain. In order to improve the energy consumption of an indirect ammonia system, the already very expensive systems would become even more expensive by 20-30 %.

Layout option IVa:

The energy consumption of a **R717 cascade system with R744** is about 13–18 % lower than that of a comparable R404A reference system. Here is used a 13 % lower energy consumption in the following. The outlined refrigerant charges refer to the eco-efficiency survey of Solvay [Diehlmann2006].

Layout option IVb:

The energy consumption of a model system at a Danish discounter with **10 kg R290, 6 kg R744** and 140 kg propylene glycol/water-mix as the cooling medium, corresponds to a R404A system (see technology data sheet C 12). When instead of the propylene glycol/water-mix evaporating CO_2 is used as cooling medium, the energy consumption of a corresponding system is 5 % lower than that of the R404A reference system.

Layout option V:

The retail industry did not provide measured data of the energy consumption for a **R744 direct evaporation system** used in the supermarket. First experience shows that the energy consumption varies considerably according to the ambient temperature. Under German conditions the energy consumption of the R404A system is lower from May until September; while from October until April the energy consumption of the R744 system is lower (see technology data sheet C13). The calculations here are based on the same energy consumption as that of the R404A system (see also chapter 3.1).

3.2.1 Uncertainty analysis of energy data

Corresponding with the data set of a German retailer already used in [Harnisch2004], the energy consumptions of equal system technologies vary considerably. For illustration of variation margins of energy consumptions in the TEWI analyses the variation of energy consumption was defined by means of published series of data measured in 2001. After elimination of deflections a variation margin of 15 % was analysed for the R404A reference system. In figure 2 the energy consumption of the individual technologies is represented by graph. The R404A reference system is shown in green colour. The corresponding variation margins are represented by means of orange error bars. One should observe that for variants IVa and IVb a larger uncertainty factor of 25 % has been assumed because their input data rely upon merely punctual values from individual equipment. Unfortunately, further data to this technology are not available.

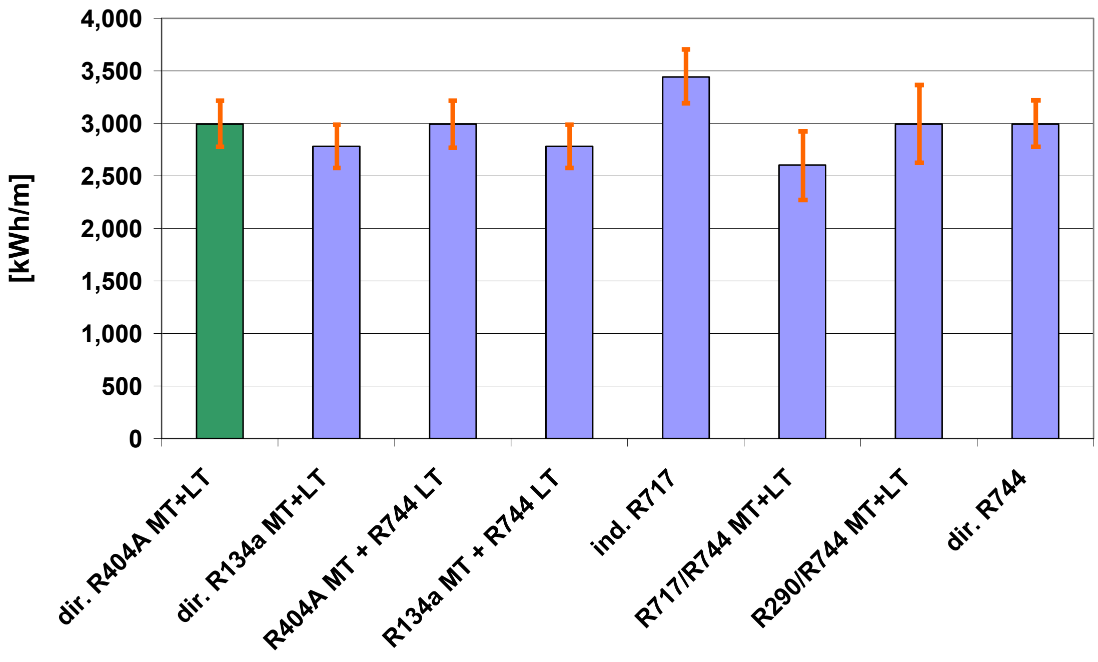

Figure 2: Annual energy consumption of different model technologies at the supermarket– data from table 8

3.3 Data base hypermarket

The prevailing refrigerant in large hypermarkets with sales areas of 6.000 m² and more is R404A as well. Due to the insufficient data base (see table 10 and 11) related to alternative technologies at the hypermarket, only the layout options Ia, III, and V are taken into consideration in this study.

Table 10: Annual energy consumptions of different refrigeration systems at the hypermarket

Energy consumption			
Layout option	**Relation to R404A**	**Energy consumption [kWh/m]**	**Uncertainty[23] [%]**
Ia dir. R404A	**0 %**	**3,292**	**+/- 9.0**
III indir. R717	+10 %	3,621	+4.5/-20.0
V dir. R744	0 %	3,292	+/- 9.0

Table 11: Refrigerant charges of different refrigeration systems at the hypermarket

Refrigerant charge		
Layout option	**Refrigerant charge RC [kg/m]**	**Uncertainty[3] [%]**
Ia dir. R404A	**4.6**	**+/- 5.0**
III indir. R717	1.0	+/- 5.0
V dir. R744	4.8	+/- 5.0

[23] Energy consumption margins were calculated on the basis of retail data. See chapter 3.1.1

Layout option Ia:

The average energy consumption of the **R404A** reference system is the result of an analysis from six hypermarkets of a large German Retailer. An extended data base would considerably increase the reliability of the data. Even if only a few measurement values are present, the value applied has been confirmed as representative within given uncertainties by retail agents and system manufacturers during an expert meeting in October 2007.

A comparable value was obtained from Swiss hypermarkets. Here the average energy consumption of R404A direct evaporation systems is lying at 3,400 kWh per linear meter of refrigeration unit [Linde2007]. Refrigerant charges were adopted from data of the six hypermarkets provided.

Layout option III:

Large **indirect store refrigeration systems with R717** have an approximately 10 % lower energy consumption compared to R404A systems, according to a system manufacturer who is looking back on long experience with ammonia system manufacture. Nevertheless, other manufacturers and retail representatives indicate a 10 % higher energy consumption compared to R404A. In the present study the calculation is based on a 10% higher energy consumption following the outcome of an expert meeting in October 2007 in Bonn. In connection with optimal system conception and the highest optimization degree this type of system will have an at least equal energy consumption as any R404A system.

Due to the toxicity of ammonia, the system’s tightness has had priority since ever, following that the systems as a rule have essentially lower leakage rates [Harnisch2004]. Even if leakage rates do not have an influence on TEWI analyses due to the low GWP of ammonia, any of the three policy scenarios is based on a calculation of a leakage rate as low as 2.65%.

Layout option V:

The same energy consumption as for the R404A reference system is assumed for the **R744 direct evaporation system**. Values reported from a model system at a Swiss hypermarket with 3,200 kWh per linear meter of refrigeration unit are lying approximately in the range of energy consumption indicated here. The refrigerant charge has been adopted from the Swiss hypermarket [Haaf 2005].

3.3.1 Uncertainty analysis of energy data

The data of the R404A reference system are based on measurement values of only six different hypermarkets. Nevertheless, one can re-evaluate once more considerable variation margins on energy consumption (see figure 3).

Annual energy consumption per linear meter of refrigeration units at 6 hypermarkets (R404A)

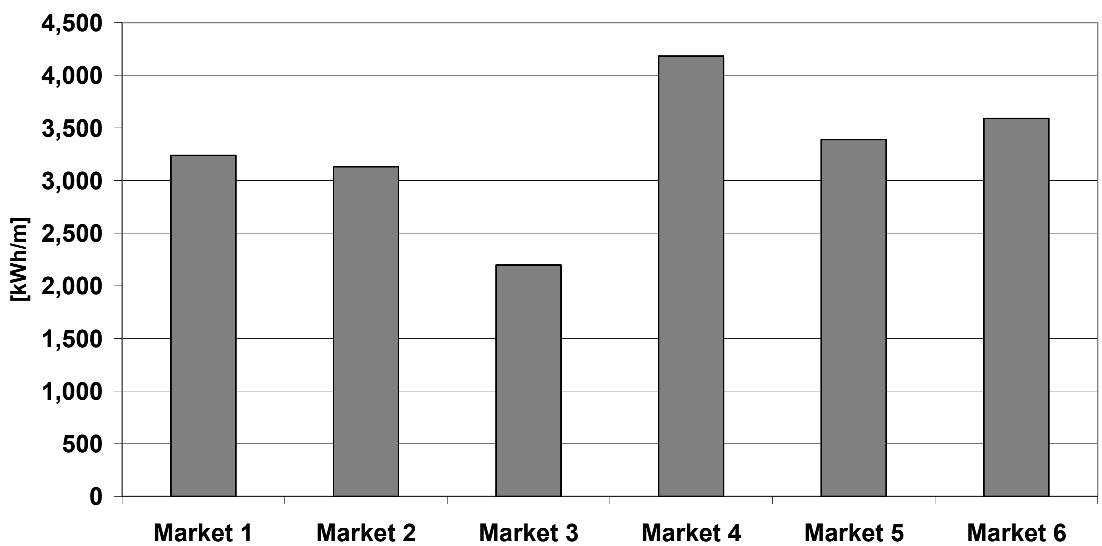

Figure 3: Measured energy consumption at hypermarkets – multi-plex refrigeration system with HFC (*Source: Retail chain*)

The analysed margin of the R404A reference system is lying at 18 % for the hypermarket. Following both preceding market categories, figure 4 represents the energy consumptions in contrast to their respective margins. In order to make the variation margin more reliable, a data series of considerably more markets would be very favorable.

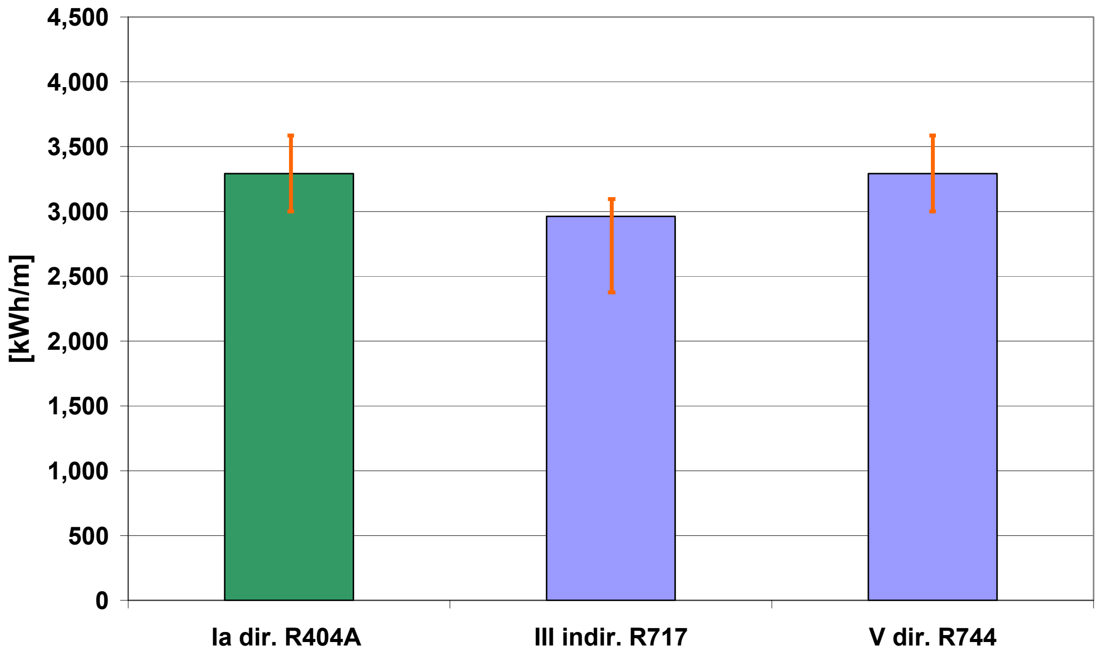

Figure 4: Annual energy consumption of different model technologies of the hypermarket – data from table 10

4. Costs data

Here the specific abatement costs for the three market categories are to calculate. The abatement costs are given in costs per ton of avoided CO_2 equivalent and relate to the abatement measure in comparison to the reference technology. The calculations of abatement costs are based on the costs data of table 12 to 17. Any costs data relate to **policy scenario 1** with an annual leakage rate of 11.65 %. How the costs will vary under changed policy conditions according to expectations is described in table 18 and figure 5.

Investment costs are according to the technology data sheets given in relation to the R404A reference system. The energy costs were determined by means of the energy consumption figures in chapter 3 and calculated with an electricity price of € 0.13 per kWh. “Full maintenance costs” were only received for the R404A reference system from retailers. As “full maintenance costs” here are defined the maintenance costs including examination costs for regular tightness as well as repair costs.

Table 12: Specific technology costs for discounter 1 (only MT)

Investment costs			
	Incremental cost against R404A reference system [%]	Investment costs [€]	Uncertainty [%]
I R404A dir. MT	**0 %**	**70,000**	**+/-15.0**
II R134a dir. MT	+13 %	79,000	+/-15.0
III ind. R290 MT	+20 %	84,000	+/-15.0
IV dir. 744 MT	+20 %	84,000	-10.0 / +40.0

Table 13: Specific technology costs for discounter 2 (only MT)

Annual costs		
	Energy costs (0.13 €/kWh) [€/a]	Full maintenance costs [€/a]
I R404A dir. MT	**9,550**	**2,000**
II R134a dir. MT	8,590	2,000
III ind. R290 MT	10,500	2,500
IV dir. 744 MT	9,550	2,500

Table 14: Specific technology costs for supermarket 1

Investment costs			
	Incremental cost against R404A reference system [%]	Investment costs [€]	Uncertainty [%]
Ia dir. R404A MT+LT	**0 %**	**370,000**	**+/-15.0**
Ib dir. R134a MT+R404A LT	+12 %	416,000	+/-15.0
IIa R404A MT+R744 LT	0 %	370,000	+/-15.0
IIb R134a MT+R744 LT	+12 %	416,000	+/-15.0
III ind. R717	+27 %	472,000	+/-15.0
IVa R717/R744 MT+LT	+28 %	474,000	-10.0/+40.0
IVb R290/R744 MT+LT	+15 %	426,000	-10.0/+40.0
V dir. R744	+20 %	444,000	-10.0/+40.0

Table 15: Specific technology costs for supermarket 2

Annual costs		
	Energy costs (0.13 €/kWh) [€/a]	Full maintenance costs [€/a]
Ia dir. R404A MT+LT	**39,000**	**6,500**
Ib dir. R134a MT+R404A LT	36,000	6,500
IIa R404A MT+R744 LT	39,000	7,500
IIb R134a MT+R744 LT	36,000	7,500
III ind. R717	45,000	8,000
IVa R717/R744 MT+LT	34,000	8,000
IVb R290/R744 MT+LT	39,000	6,500
V dir. R744	39,000	7,800

As already described above, for hypermarkets only few data is available. Therefore in table 16 and 17 are only represented the costs data for the layout options I, II, and V. Principally, the percentage values from the supermarket may also be transferred to the hypermarket.

Table 16: Specific technology costs for hypermarket 1

Investment costs			
	Incremental cost against R404A reference system [%]	Investment costs [€]	Uncertainty [%]
Ia dir. R404A MT+LT	**0 %**	**800,000**	**+/-15.0**
III ind. R717	+28 %	1,024,000	+/-15.0
V dir. R744	+20 %	960,000	-10.0/+40.0

Table 17: Specific technology costs for hypermarket 2

Annual costs		
	Energy costs (0.13 €/kWh) [€/a]	Full maintenance costs [€/a]
Ia dir. R404A MT+LT	**105,000**	**16,000**
III ind. R717	115,000	20,000
V dir. R744	105,000	20,000

The abatement costs calculation (see chapter 5.3) is carried out for any of the three policy scenarios because the assumptions underlying the scenarios have considerable influence upon the full maintenance costs and the range of HFC emissions of the reference technology. In order to mirror the situation according to policy scenario as precise as possible, the investment and maintenance costs for the reference technology are adjusted in accordance with the values of table 18. The adjustment of maintenance costs by +30 % in scenario 2 and by +50 % in scenario 3 represented by figure 5 is the consequence of increased maintenance requirements for HFC systems pursuant to the EU-F-Gas regulation (EC) No. 842/2006 and the requirements pursuant to VDMA standard sheet 24243-1.

In order to comply with the tightness requirement pursuant to VDMA standard sheet, the investment expenditures for R404A reference systems within scenario 3 will correspondingly increase. For calculation of the abatement costs the values in table 18 are applied on any HFC containing technology.

Table 18: Development of costs of HFC technology according to modifications of the political framework

	Scenario 1	Scenario 2	Scenario 3
Investment costs	current values in table 12, 14, and 16	According to scenario 1	+15 %
Full maintenance costs	current values in table 13, 15, and 17	+30 %	+50 %

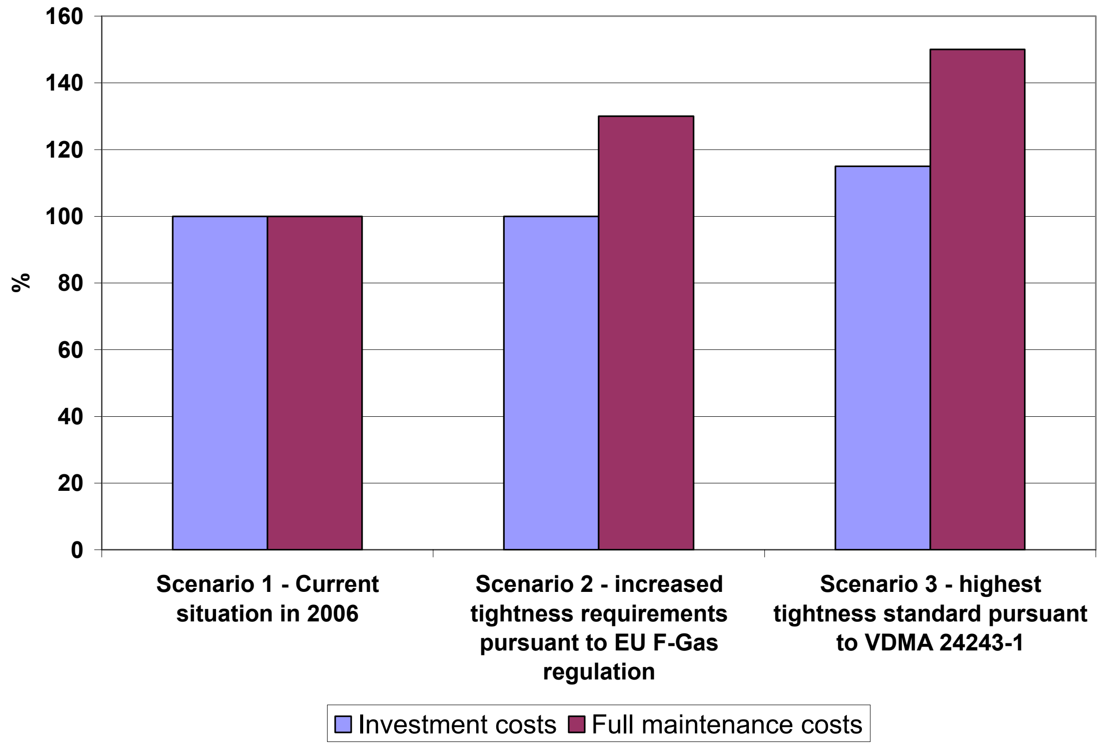

Figure 5: Development of costs of HFC technology according to modifications of the political framework

5. Results

5.1 TEWI analyses

The results form the calculation of the TEWI analyses are presented in the following. First in figures 6-8, 13-15, and 19-21 are represented the probability distribution of annual greenhouse gas emissions per meter of refrigeration unit in relation to any of the shop categories. The distributions were determined by means of Monte-Carlo simulations whose method has been described in chapter 2.4.

Subsequently the annual GHG emissions of the individual technologies are represented as a bar chart in figures 9-11, 16-18 and 22-24. The variation margins analysed within the Monte-Carlo simulations are represented in the bar chart by orange error bars.

5.1.1 Discounter

The following figures 6-8 are the results from the Monte-Carlo simulations for policy scenarios 1, 2, and 3. The differences become clearly smaller with the increasing strength of provision, while the sequence of probability curves for the individual layout option remains almost unaltered. One may observe also that the curves become steeper and hence the emission values of the individual systems more homogenous.

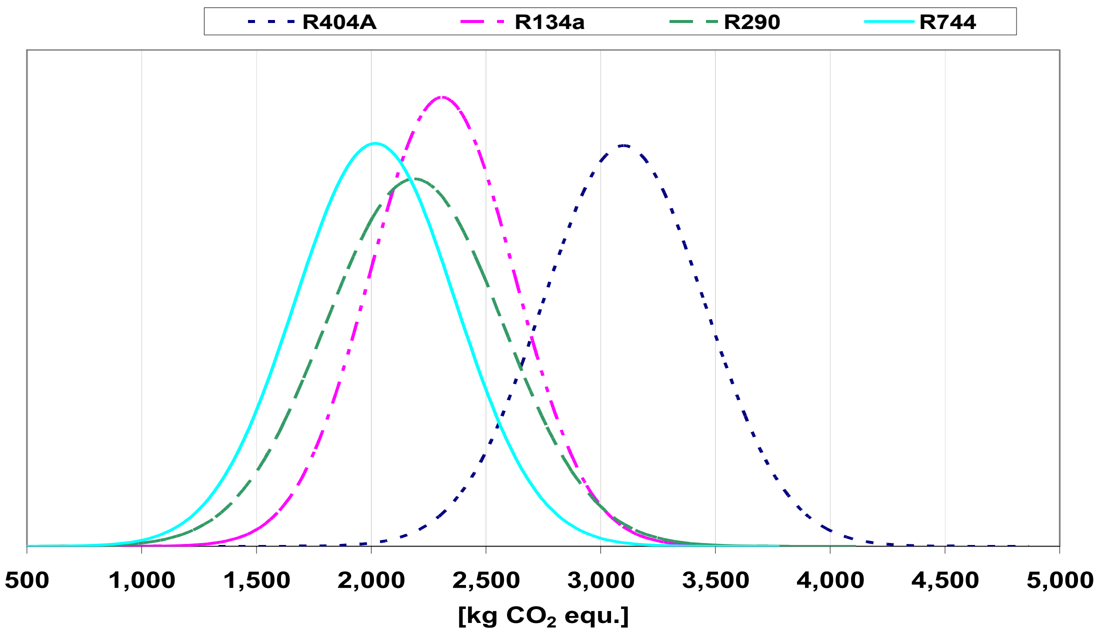

Figure 6: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for the discounter in connection with different layout options (leakage rate 11.65 % = policy scenario 1) (schematic)

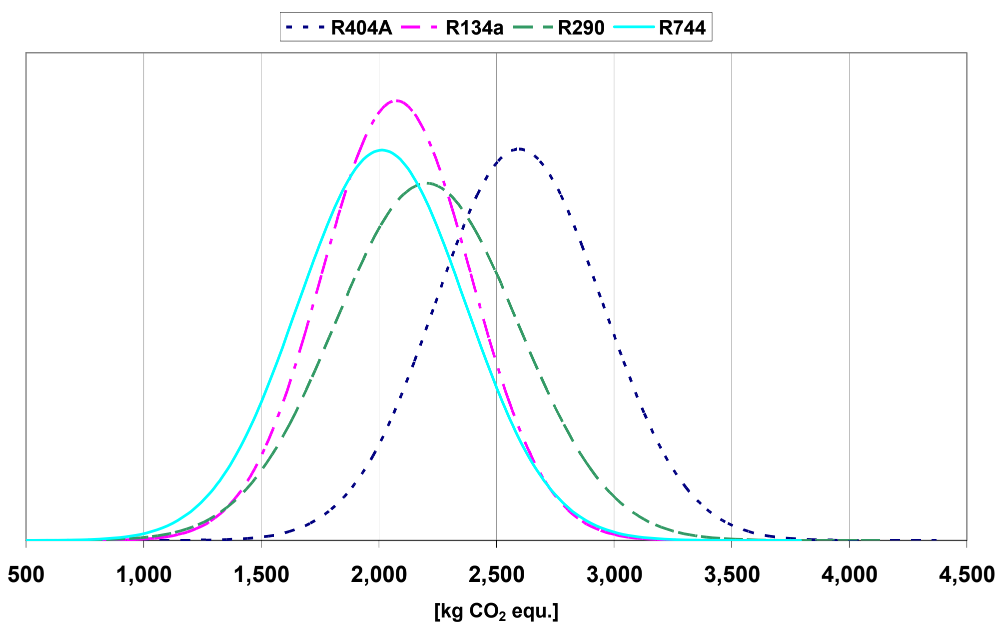

Figure 7: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for the discounter in connection with different layout options (leakage rate 6.15 % = policy scenario 2) (schematic)

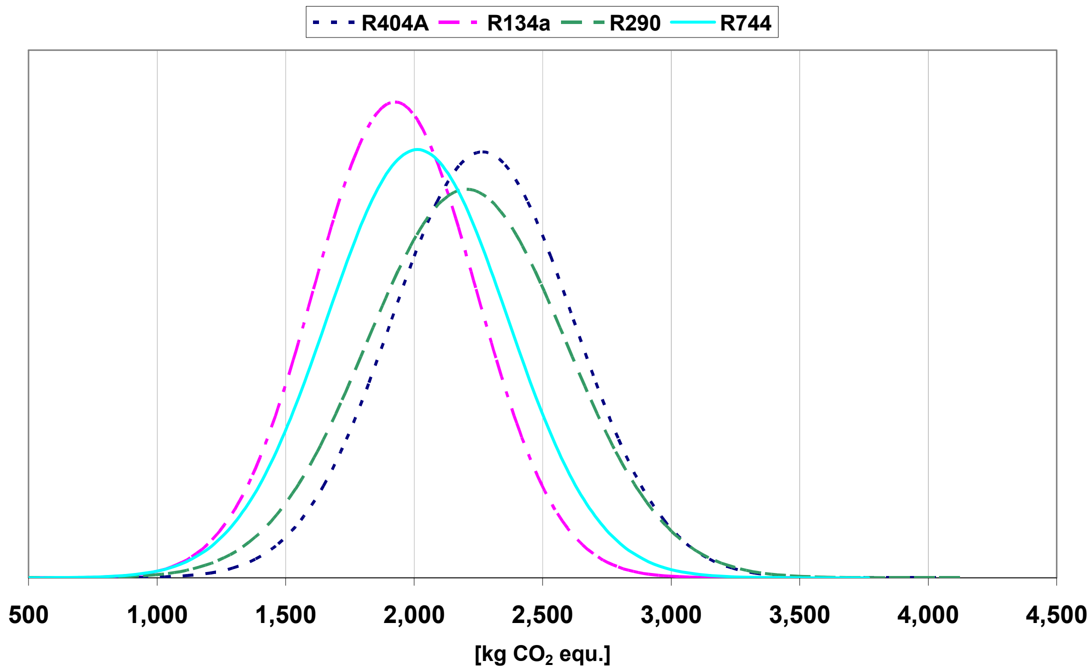

Figure 8: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for the discounter in connection with different layout options (leakage rate 2.65 % = policy scenario 3) (schematic)

The figures 9-11 show the GHG emissions of the different layout options within the policy scenarios 1-3 each allocated to its emissions of energy or refrigerant. With increasing strictness of legal provision the refrigerant emissions of any layout option will reduce with rising policy scenario number. As the share of refrigerant emission within the entire emissions is higher for layout options I and II, the effect is clearly more obvious for these variants. Thus the differences between the layout options become smaller from which follows that layout option II showing the second highest degree of emissions in scenario I has the lowest emission degree within policy scenario III.

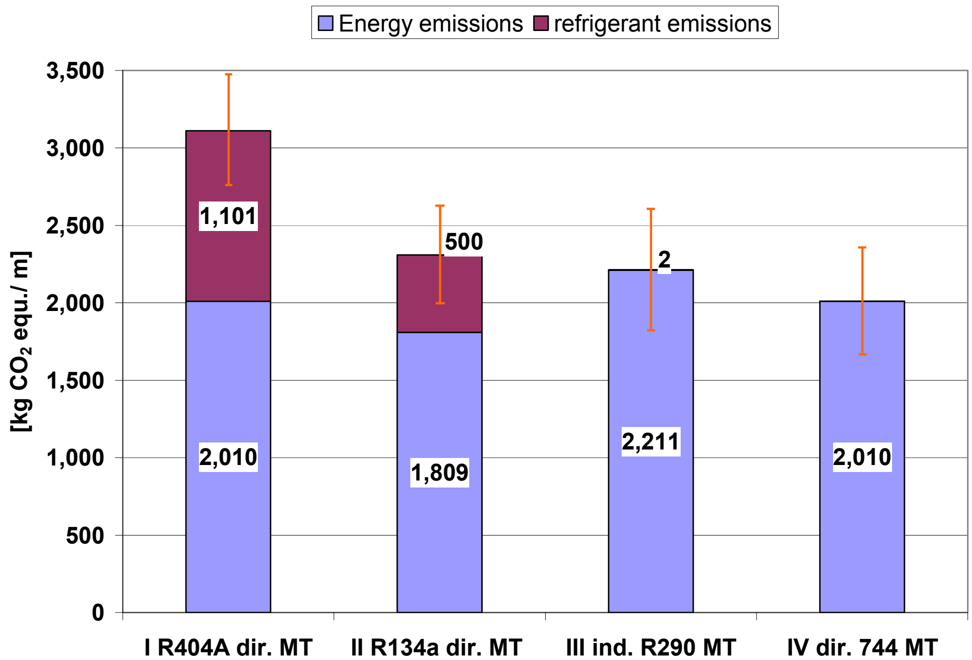

Figure 9: Annual GHG emissions per linear meter of refrigeration unit for the discounter in connection with different layout options (leakage rate 11.65 %)

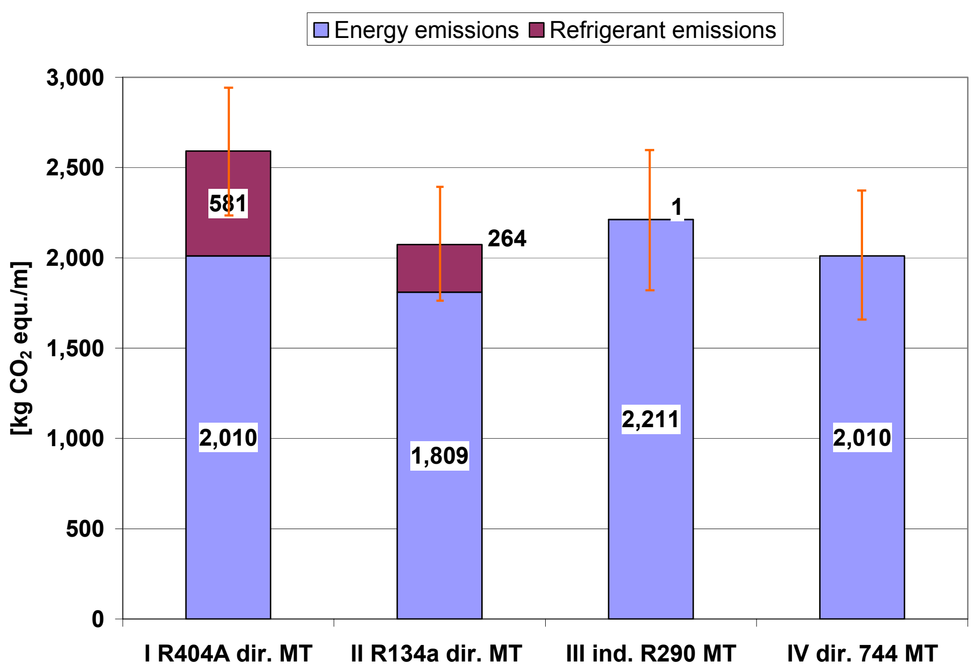

Figure 10: Annual GHG emissions per linear meter of refrigeration unit for the discounter in connection with different layout options (leakage rate 6.15 %)

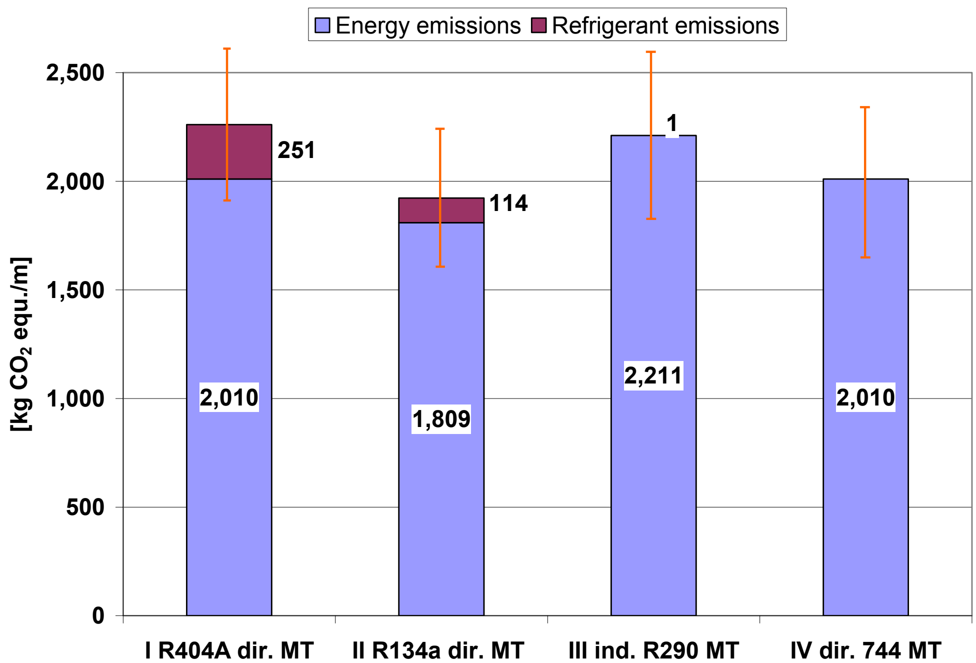

Figure 11: Annual GHG emissions per linear meter of refrigeration unit for the discounter in connection with different layout options (leakage rate 2.65 %)

Following the TEWI analyses, the emissions from refrigeration equipment for the generation of MT as per discounter in Germany are represented in table 19 in accordance with their policy scenario.

Table 19: Annual emissions as per discounter in Germany (only MT)

	I R404A dir.	II R134a dir.	III ind. R290	IV dir. 744
	[t CO_2 equ./a]	[t CO_2 equ./a]	[t CO_2 equ./a]	[t CO_2 equ./a]
Scenario 1	70.0	52.0	49.8	45,2
Scenario 2	58.3	46.6	49.8	45,2
Scenario 3	50.9	43.3	49.8	45,2

For LT normally plug-in chest freezers are used. Depending from refrigerant, plug-in freezers have an annual energy consumption between 2,400 and 3,000 kWh per linear meter of refrigeration unit (see chapter 3.1). Due to the low refrigerant charges and high tightness of freezers, emissions from refrigerants are negligible. Figure 12 shows the annual emissions from energy consumption of freezers as per discounter. A market with new R290 chest freezers exceeds the emissions illustrated in table 19 by almost additional 60 t CO_2 equ. per year.

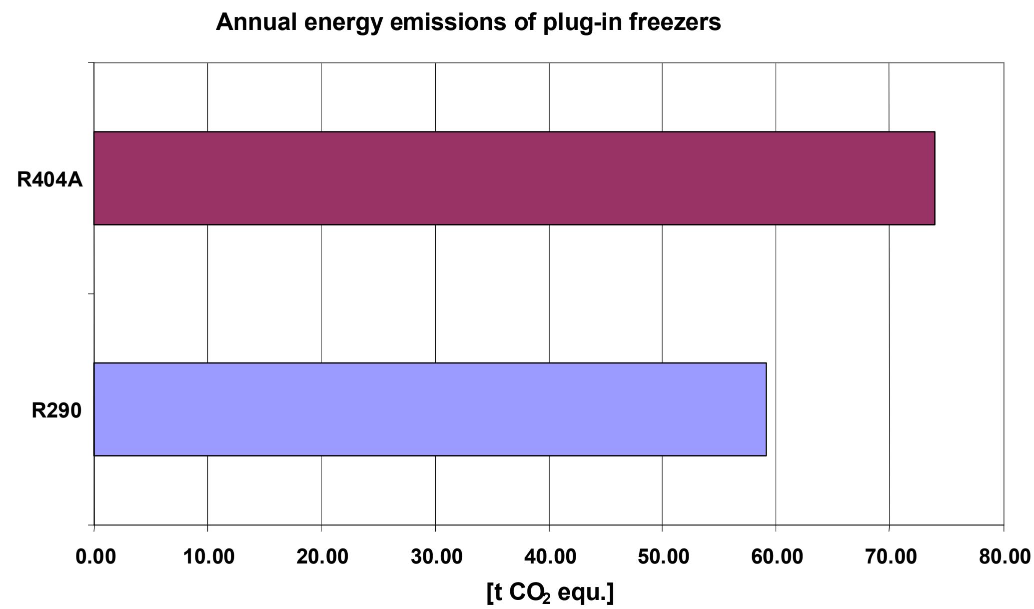

Figure 12: Annual GHG emissions caused by freezers at the discounter

5.1.2 Supermarket

The Monte-Carlo emissions illustrated in figures 13-15 provide similar results for supermarkets as previously for discounters. The GHG emissions of the layout options will be decreased by the emission-intensive variants due to stronger stipulations from policy scenario 1 to 3. Thus the layout options will become similar in their aggregate emissions, while the sequence between the variants will remain mainly constant. By reason of clearness the graphs of the Monte-Carlo simulations for the supermarket are represented by two coordinate systems one below the other.

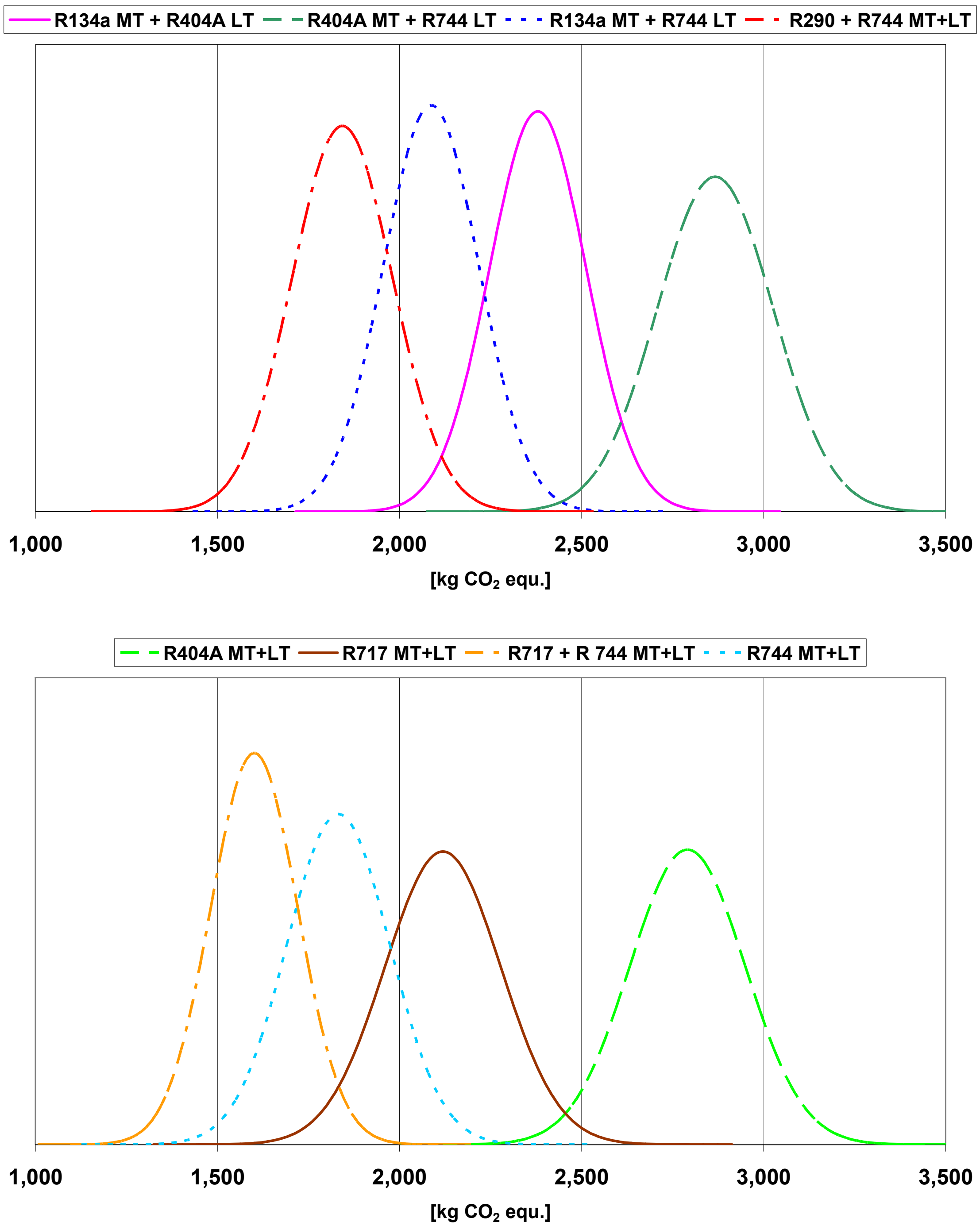

Figure 13: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for supermarkets in connection with different layout options (leakage rate 11.65 %) (schematic)

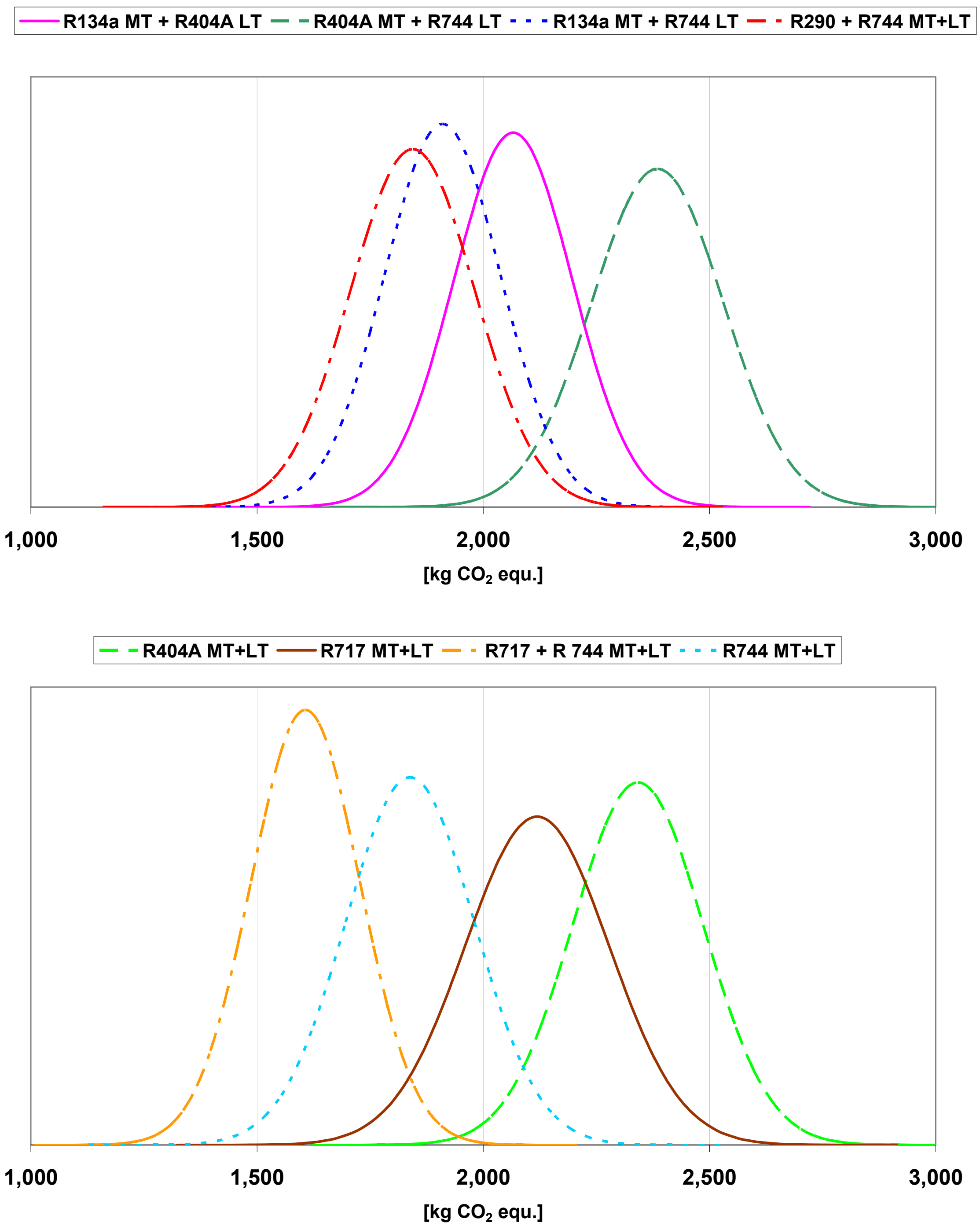

Figure 14: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for supermarkets in connection with different layout options (leakage rate 6.15 %) (schematic)

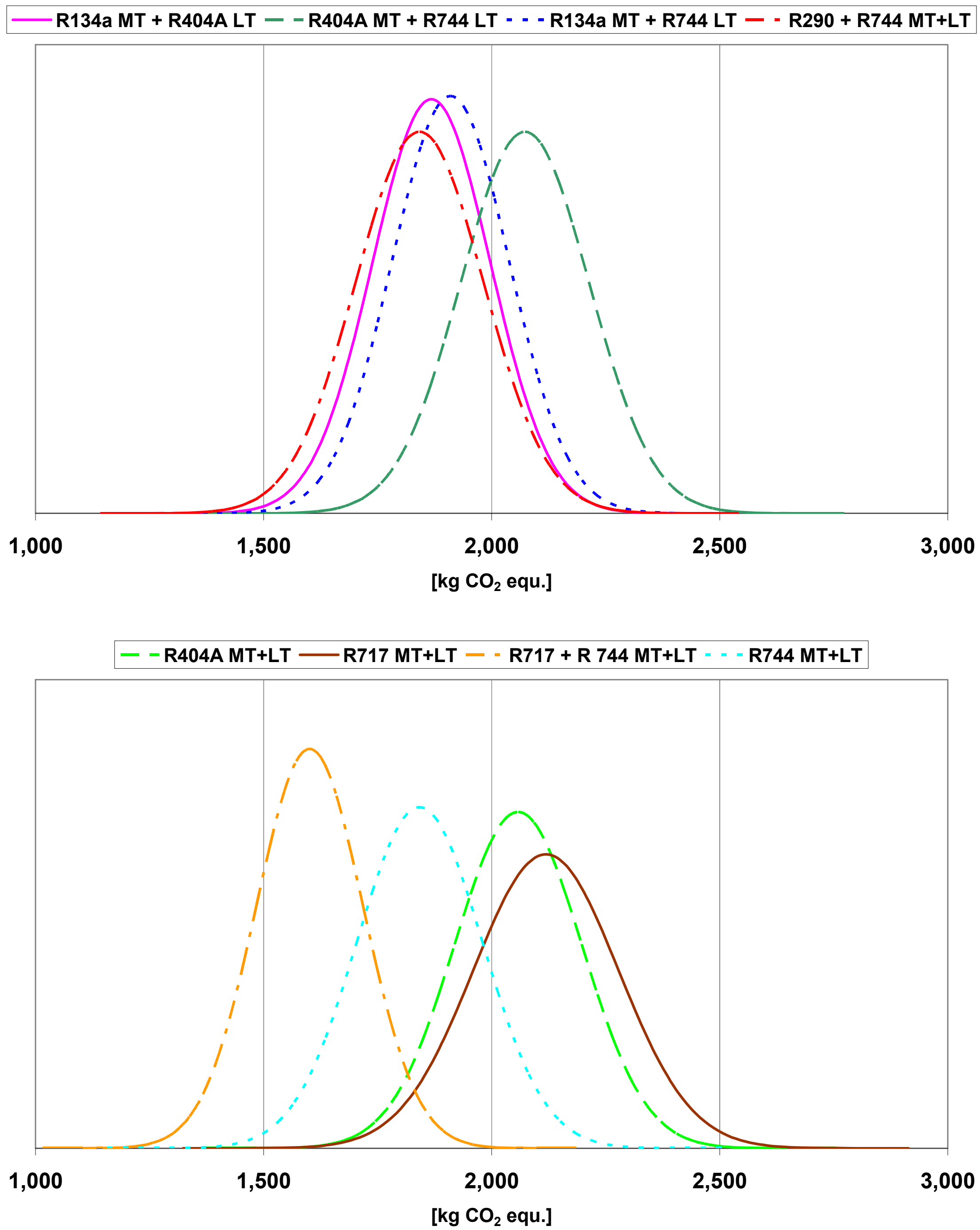

Figure 15: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for supermarkets in connection with different layout options (leakage rate 2.65 %) (schematic)

Figures 16 to 18 show the emissions of the layout options within policy scenario 1 up to 3 according to their energy versus refrigerant emissions. While the layout options Ia to IIb with high refrigerant emissions are still the most emissive variants on the whole, they occupy the medium range in policy scenario 3. Hereby the difference between best and worst variant reduces from 1,265 to 417 kg CO_2 equ./m.

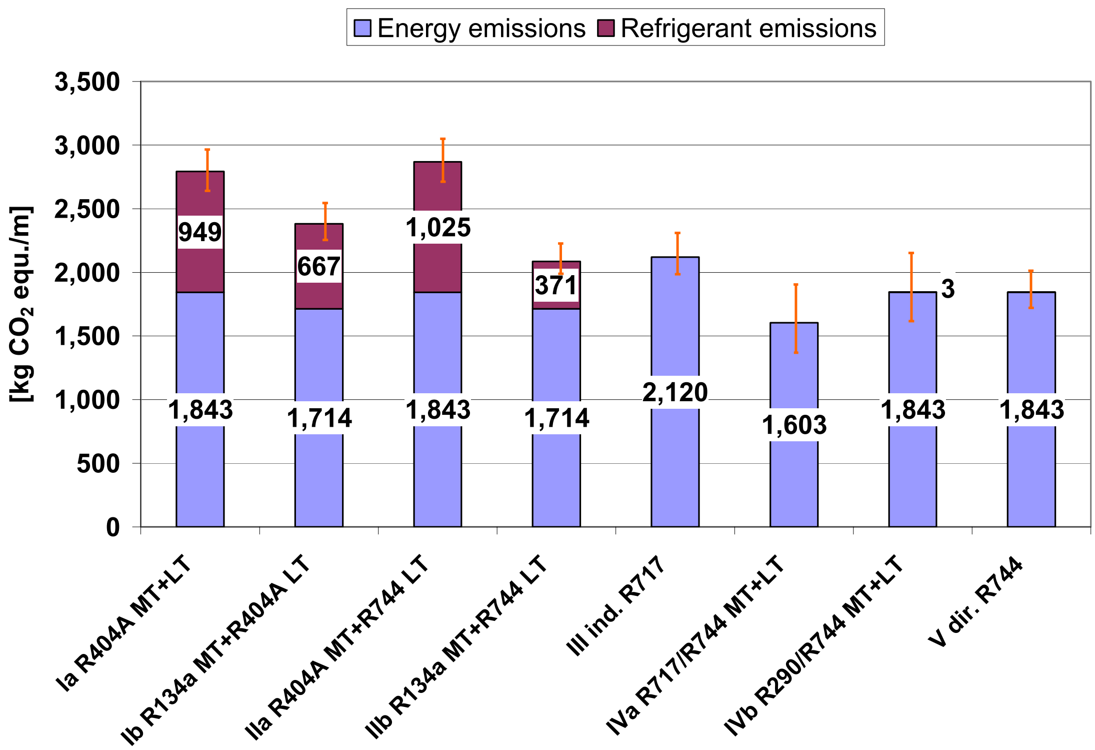

Figure 16: Annual GHG emissions per linear meter of refrigeration unit for the supermarket in connection with different layout options (leakage rate 11.65 %)

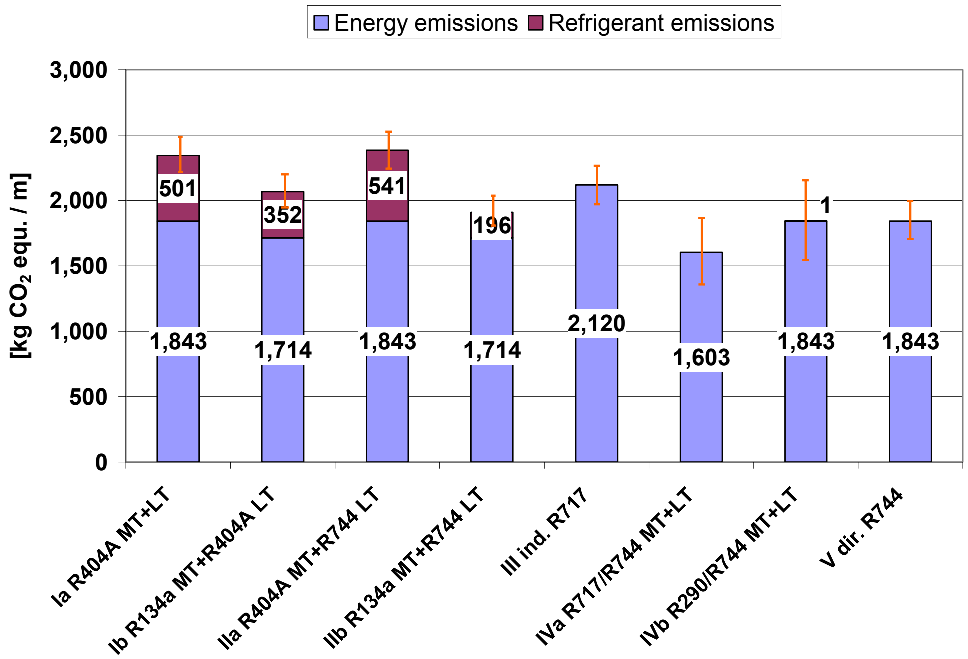

Figure 17: Annual GHG emissions per linear meter of refrigeration unit for the supermarket in connection with different layout options (leakage rate 6.15 %)

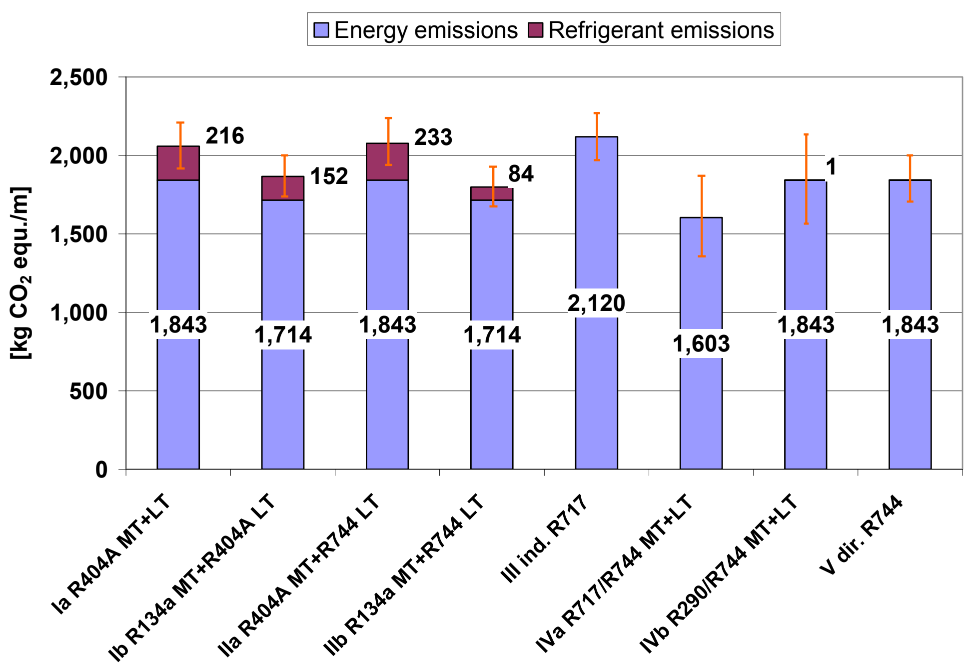

Figure 18: Annual GHG emissions per linear meter of refrigeration unit for the supermarket in connection with different layout options (leakage rate 2.65 %)

Following the TEWI analyses, the average emissions of a supermarket in Germany are represented in table 20 in accordance with their policy scenario. It becomes obvious that emissions from equipment using natural refrigerants remain on the same level within the three scenarios because the amended policy framework has only an impact on systems with HFC due to the natural refrigerant's low GWP.

Table 20: Annual emissions per supermarket in Germany

	Ia R404A MT+LT	**Ib R134a MT+R404A LT**	**IIa R404A MT+R744 LT**	**IIb R134a MT+R744 LT**
	[t CO_2 equ./a]	[t CO_2 equ./a]	[t CO_2 equ./a]	[t CO_2 equ./a]
Scenario 1	265.3	226.3	272.5	198.1
Scenario 2	222.7	196.3	226.5	181.5
Scenario 3	195.6	177.3	197.3	170.9
	III ind. R717	**IVa R717/R744 MT+LT**	**IVb R290 /R744 MT+LT**	**IV dir. 744**
	[t CO_2 equ./a]	[t CO_2 equ./a]	[t CO_2 equ./a]	[t CO_2 equ./a]
Scenario 1	201.4	152.3	175.3	175.1
Scenario 2	201.4	152.3	175.2	175.1
Scenario 3	201,4	152.3	175.1	175.1

5.1.3 Hypermarket

In connection with three layout options identified for hypermarkets, only the layout option with R404A has a reduction potential of direct emissions susceptible to be exploited by means of stronger legal provisions concerning tightness. Accordingly, the probability distribution for emissions of this layout option comes clearly closer to the distribution of both other variants within policy scenario 1 up to 3 (figures 19-21).

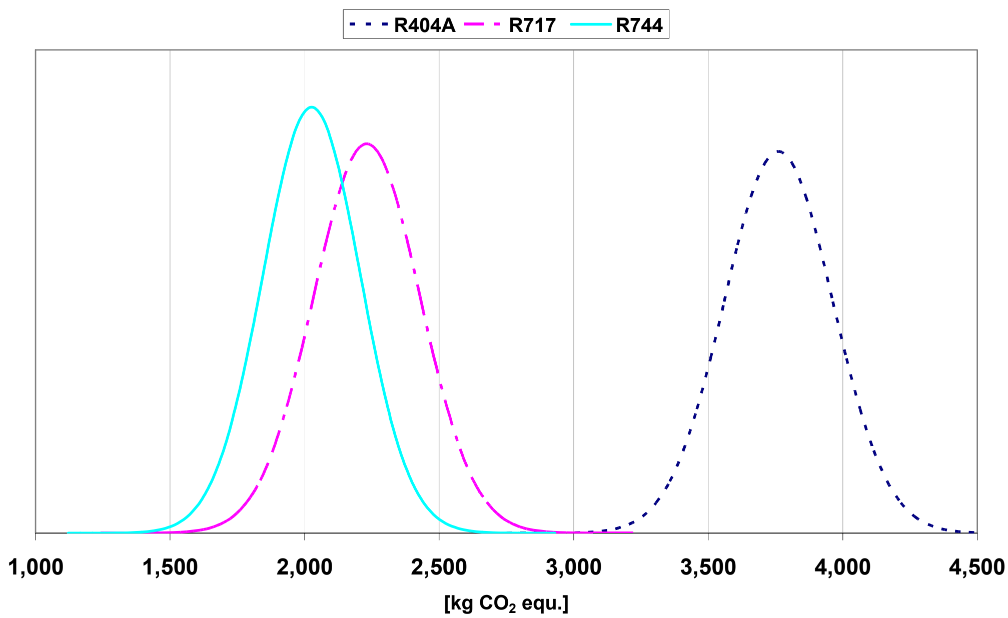

Figure 19: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for hypermarket in connection with different layout options (leakage rate 11.65 %) (schematic)

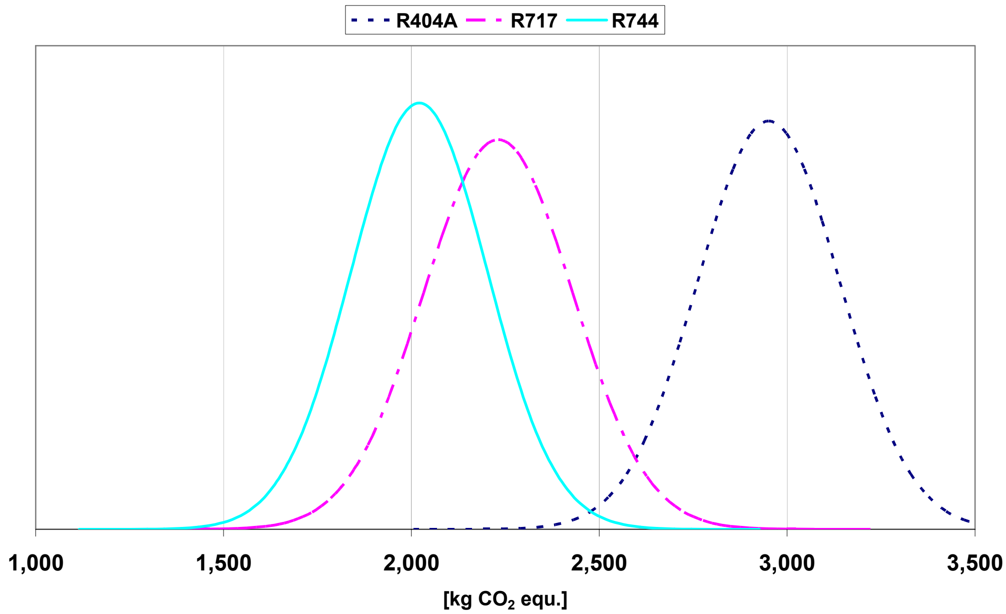

Figure 20: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for the hypermarket in connection with different layout options (leakage rate 6.15 %) (schematic)

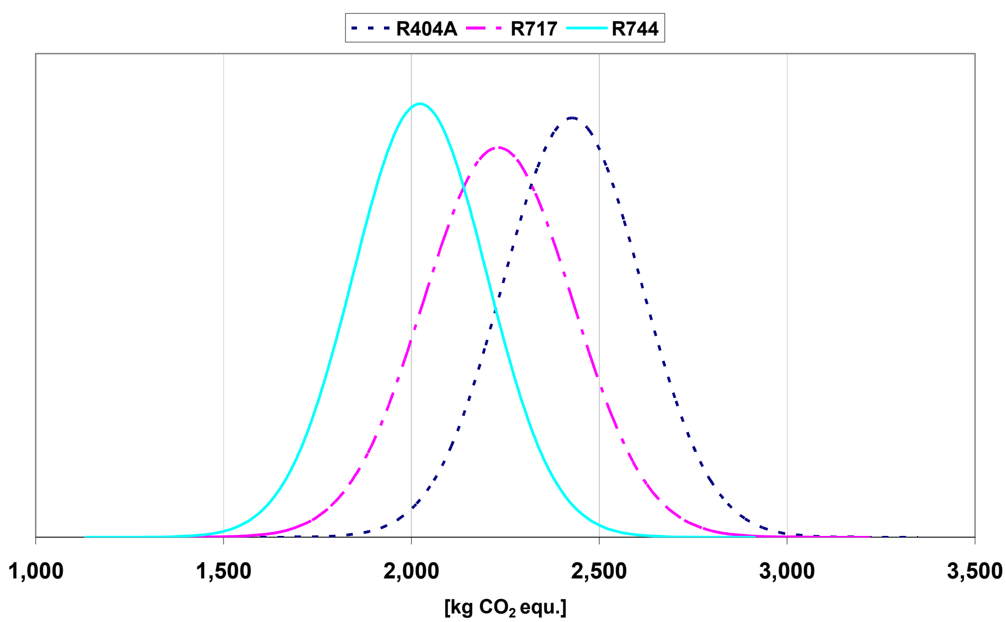

Figure 21: Probability distribution of annual GHG emissions per linear meter of refrigeration unit for the hypermarket in connection with different layout options (leakage rate 2.65 %) (schematic)

When differentiating between energy and refrigerant emissions, a reduction potential concerning the refrigerant emissions will also only result for layout option Ia. Thereby the aggregate emissions in policy scenario 3 of the different options become closer to each other, while the sequence among the systems is remaining constant.

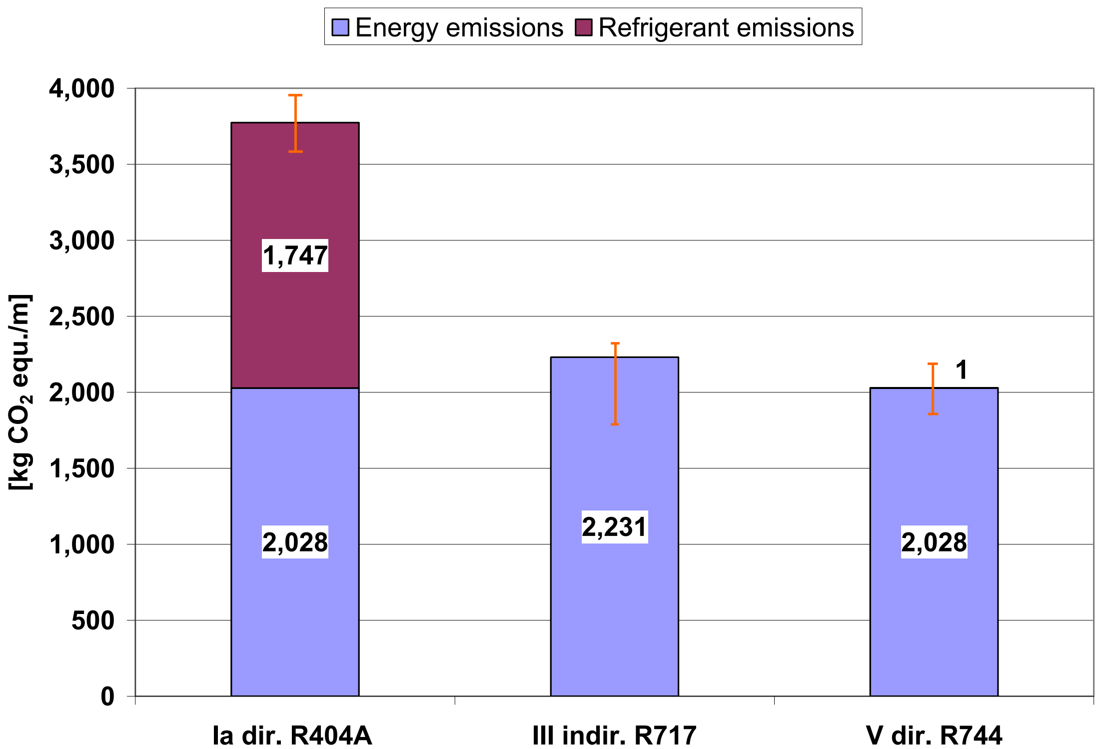

Figure 22: Annual GHG emissions per linear meter of refrigeration unit for the hypermarket in connection with different layout options (leakage rate 11.65 %)

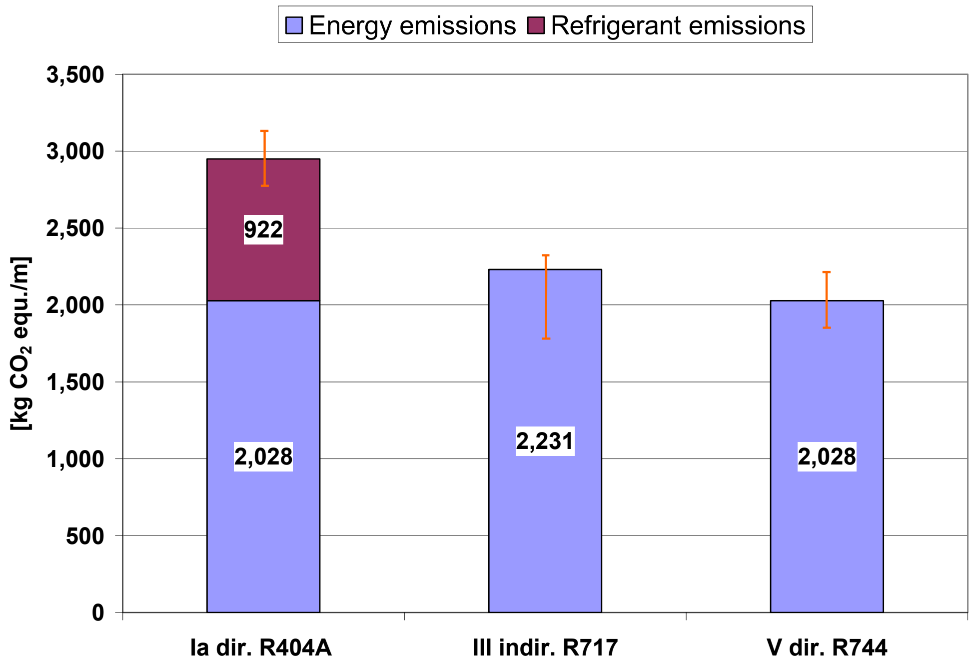

Figure 23: Annual GHG emissions per linear meter of refrigeration unit for the hypermarket in connection with different layout options (leakage rate 6.15 %)

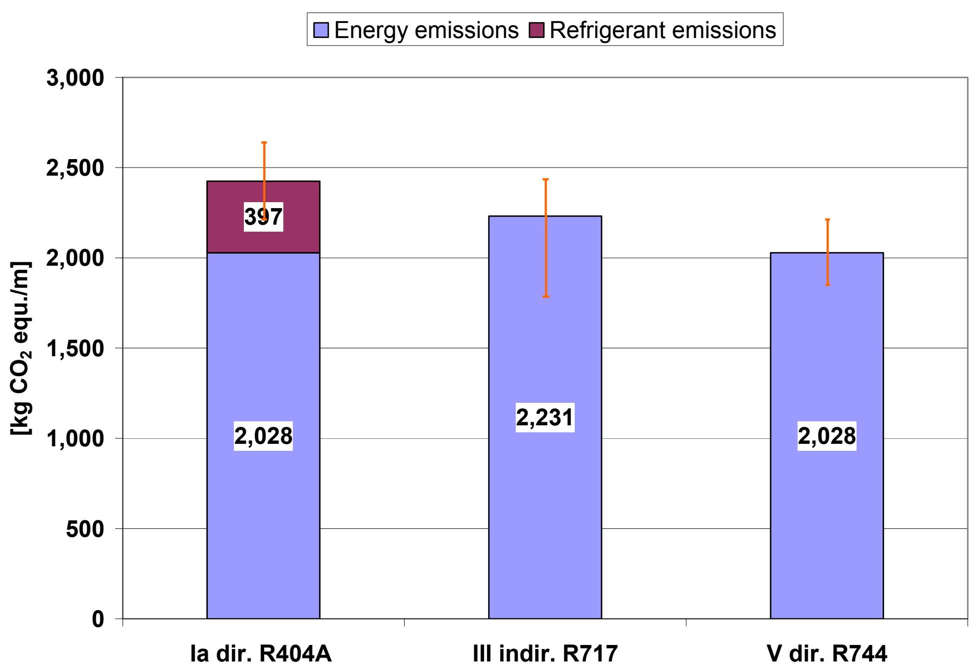

Figure 24: Annual GHG emissions per linear meter of refrigeration unit for the hypermarket in connection with different layout options (leakage rate 2.65 %)

The annual emissions of refrigeration technology systems from a German hypermarket will correspondingly match table 21. Due to the system extensions, one can recognize the largest reduction potentials as per market here.

Table 21: Annual emission as per hypermarket in Germany

	I R404A dir.	III indir. R717	IV dir. 744
	[t CO_2 equ./a]	[t CO_2 equ./a]	[t CO_2 equ./a]
Scenario 1	924.9	546.5	497.0
Scenario 2	722.8	546.5	496.9
Scenario 3	594.2	546.5	496.9

5.1.4 Discussion

The results of the TEWI analyses show a considerable reduction potential in relation to the application of refrigeration systems in the retail sector, in particular for the reference technology. Nevertheless, with increasing system tightness the emission differences of reference technology and alternative technology with natural refrigerants become closer. It is obvious that the most common German retail system technology based on R404A shows essentially higher emissions against any of the alternative technologies in any of the three store categories. In order to reduce the disadvantages of the reference technology with HFC-containing refrigerants, considerable efforts will have to be made concerning the systems’ tightness. Within the EU-F-Gas regulation are multiple measures legally required which should implement the system’s tightness on a higher degree. The results for policy scenario 2 which is reflecting the situation by consequent application of the EU-F-gas regulation however show that alternative system conceptions with natural refrigerants are better from the ecological point of view.

Only when refrigeration systems are nearly fully tight, as represented by policy scenario 3, systems with natural refrigerants are only slightly less emissive. Reduction potentials of indirect emissions via energy efficiency measures are hereby not taken into consideration.

5.1.5 Impact of specific energy consumption

As already described, the measured energy consumptions show essential variations. The impact of variation is already illustrated by means of the Monte-Carlo simulation carried out. As the system's energy efficiency, beside the choice of refrigerant, is the predominant factor within the current political discussion about climate friendly refrigeration technology, sensitivity analyses for the TEWI calculations are carried out as a second step which only vary according to the energy consumption of the model technology. Via varying the energy consumption by +/- 25 %, it will become clear that an essential surplus in energy savings can be achieved by means of especially energy-efficient refrigeration systems.

Discounter

The figures 25-27 show the results from sensitivity analyses according to the discounter's model technology and policy scenario, respectively. On the whole, TEWI values will of course be lower in connection with smaller energy consumptions and stronger legal imposition. Due to the higher relative share of energy emissions of layout options III and IV, the emission reductions via reduced energy consumption are more obvious with these variants against variant I and II, in particular within scenario I. Regarding policy scenario 3, though, which is related to the highest system tightness, the energy consumption has determining impact on the climate relevance of the technology.

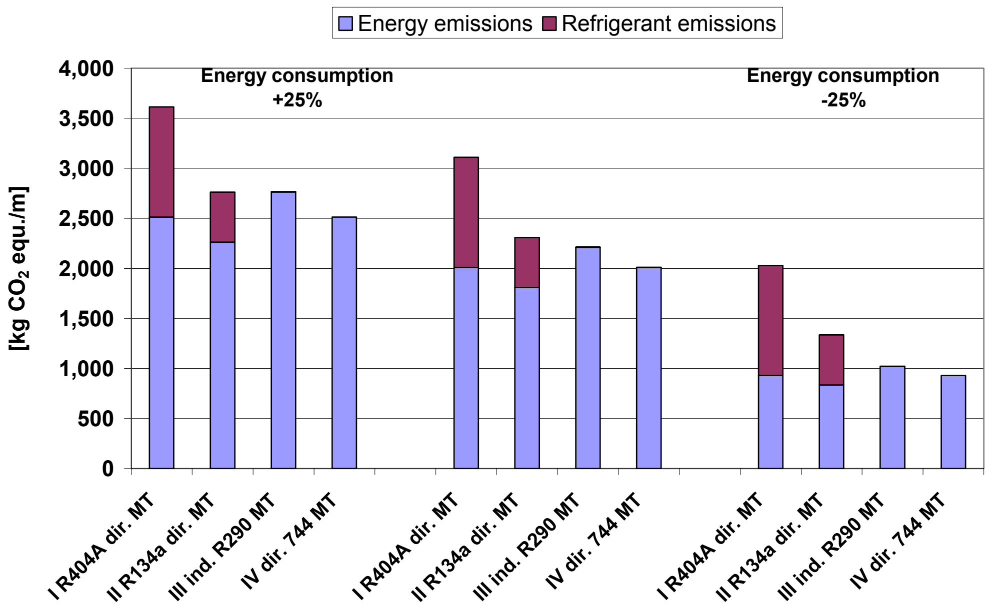

Figure 25: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the discounter (leakage rate 11.65%)

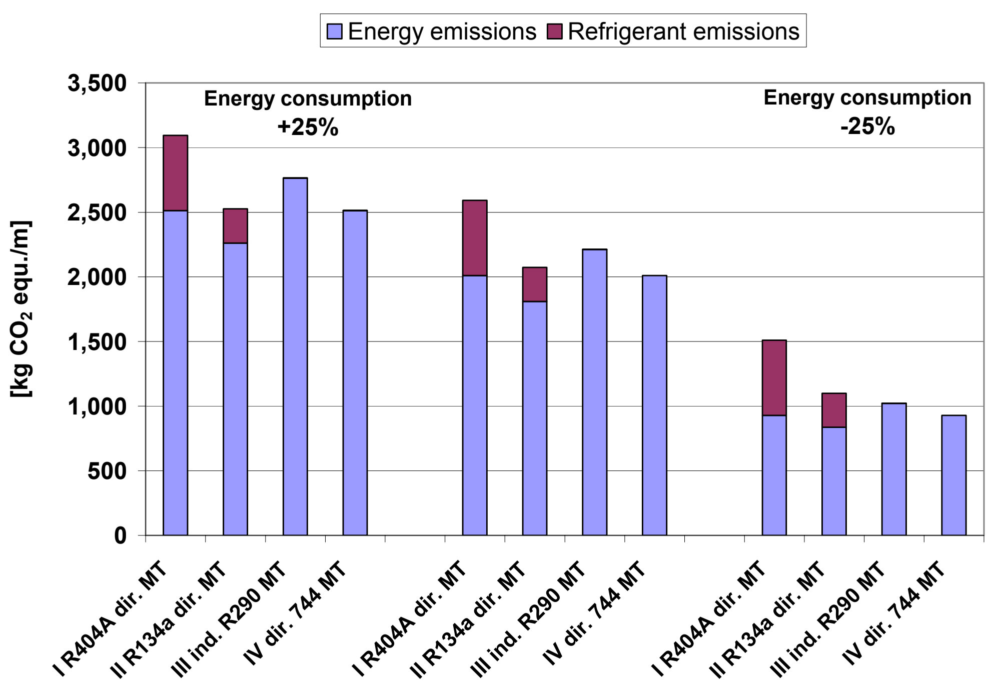

Figure 26: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the discounter (leakage rate 6.15%)

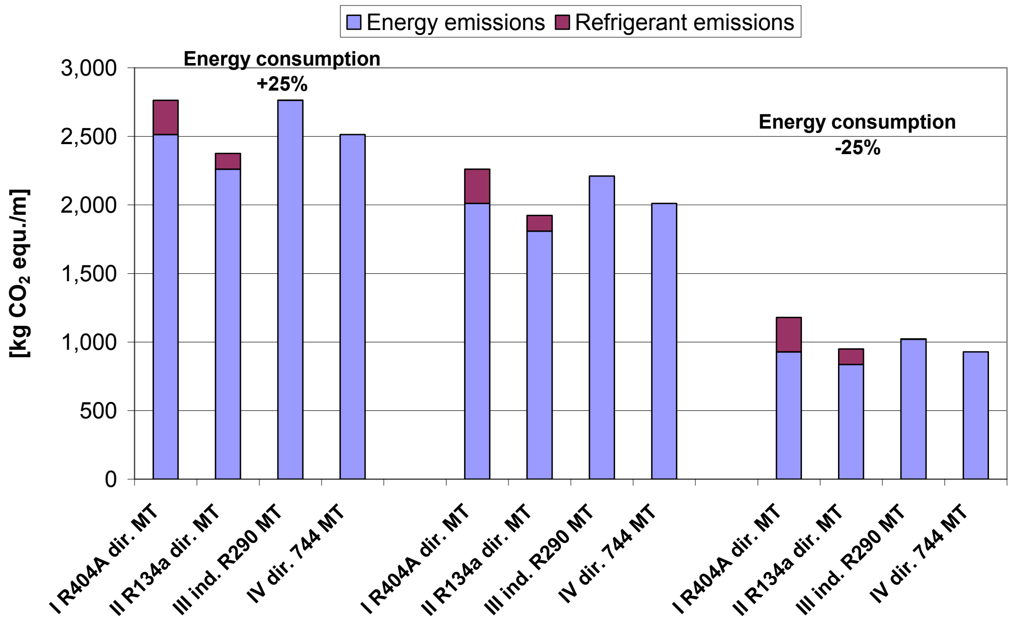

Figure 27: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the discounter (leakage rate 2.65%)

Supermarket

The results from the sensitivity analyses for systems in supermarkets are represented by figures 28-30. Also in this case it will follow from the variation of the energy consumption that the TEWI values of the layout options without relevant refrigerant emissions become closer to the TEWI values for the variants with relevant refrigerant emissions (+25 % energy consumption) or lie below them (-25 % energy consumption). This is particularly valid for scenario 1, while the relative differences between the variants remain mainly constant in scenario 3.

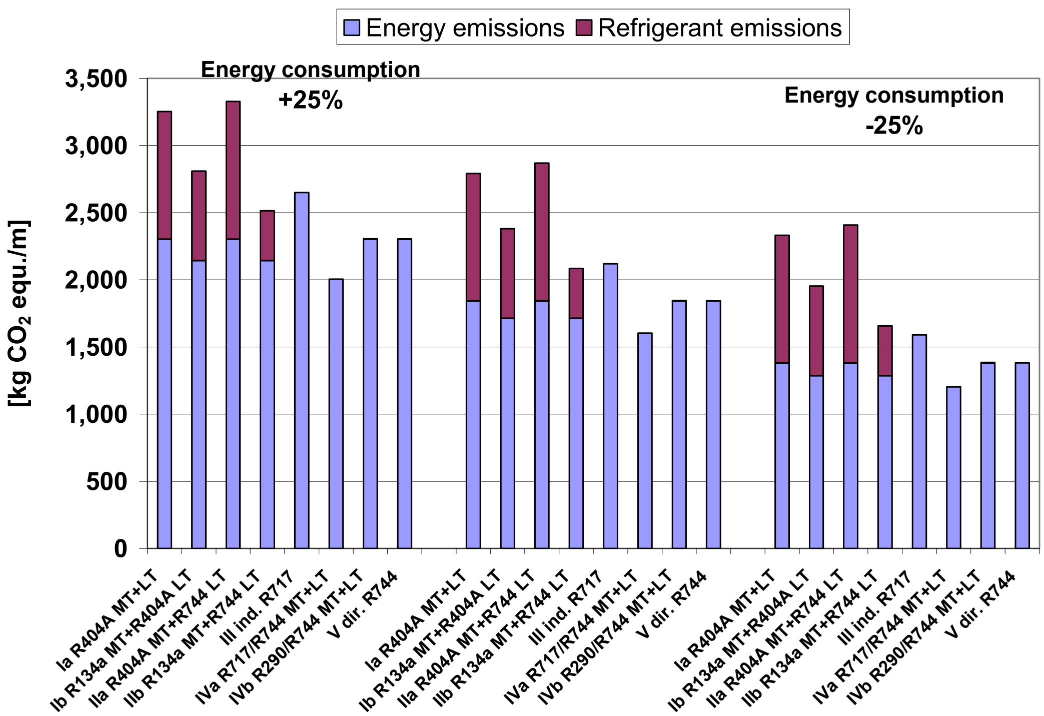

Figure 28: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the supermarket (leakage rate 11.65%)

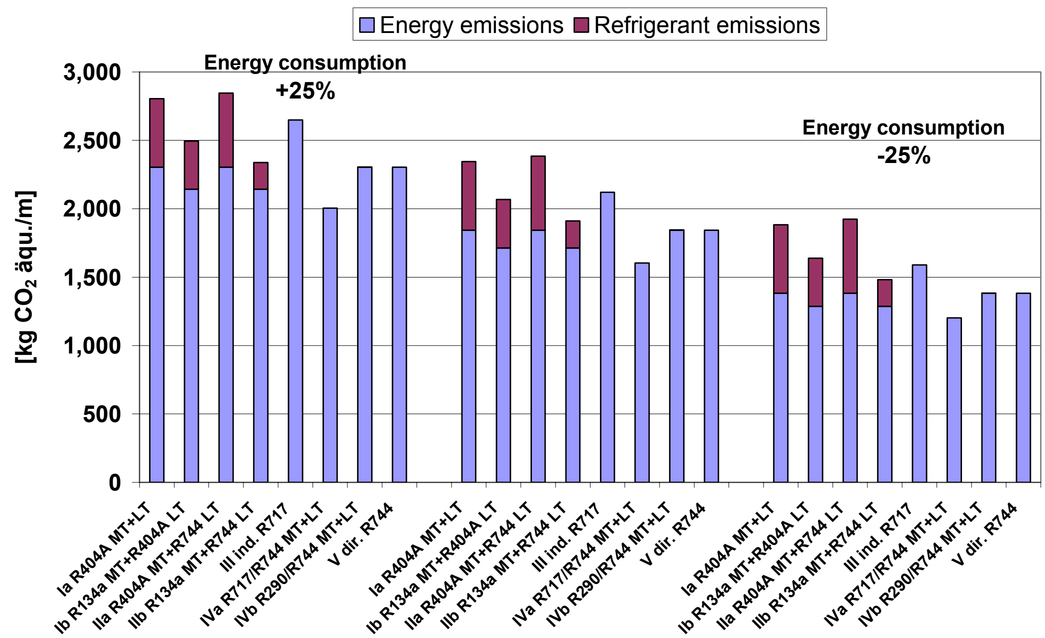

Figure 29: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the supermarket (leakage rate 6.15%)

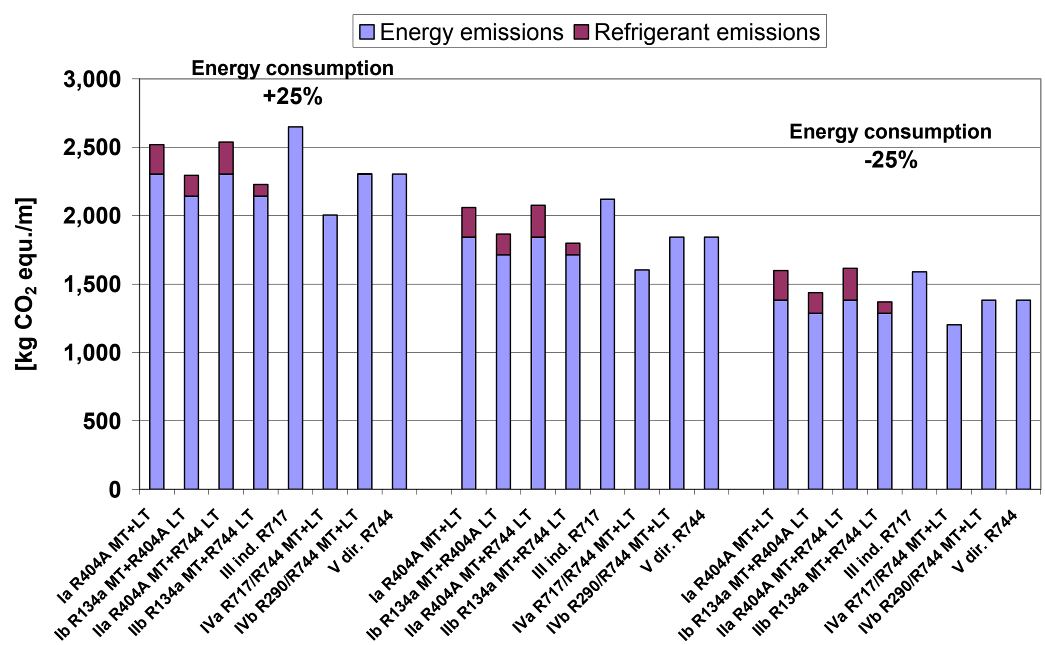

Figure 30: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the supermarket (leakage rate 2.65%)

Hypermarket

In figures 31-33 is shown how energy variations will have an impact on the TEWI values for any of the three hypermarket variants among which reference variant Ia proves a clearly higher level of (refrigerant) emissions compared to variant III and IV being refrigerant emission-free.

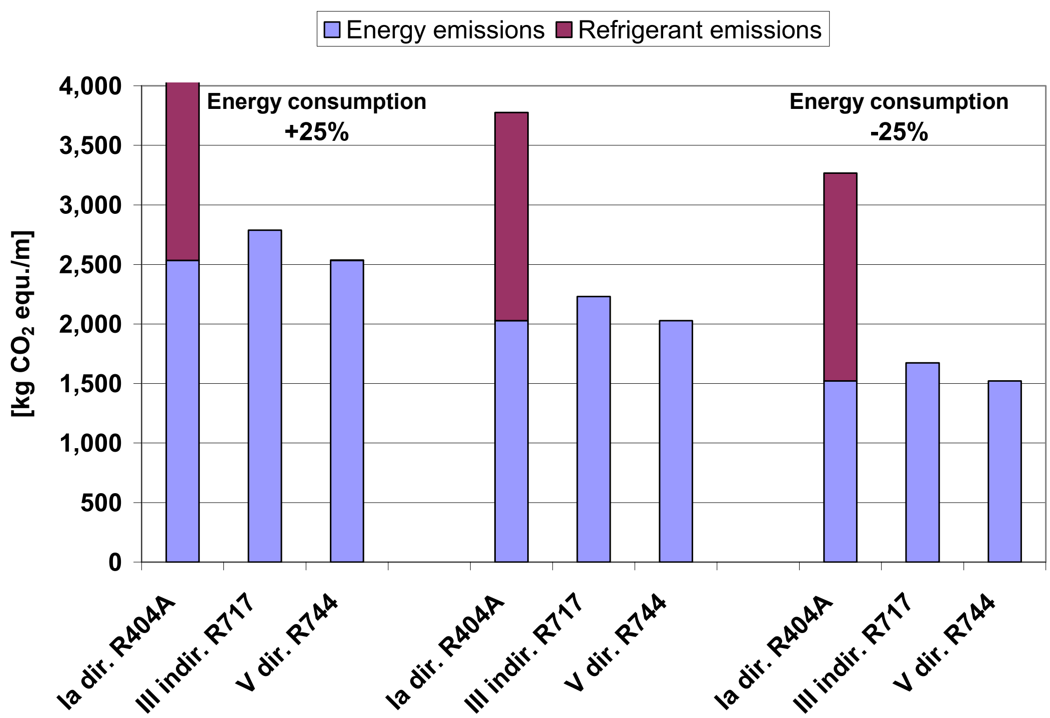

Figure 31: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the hypermarket (leakage rate 11.65%)

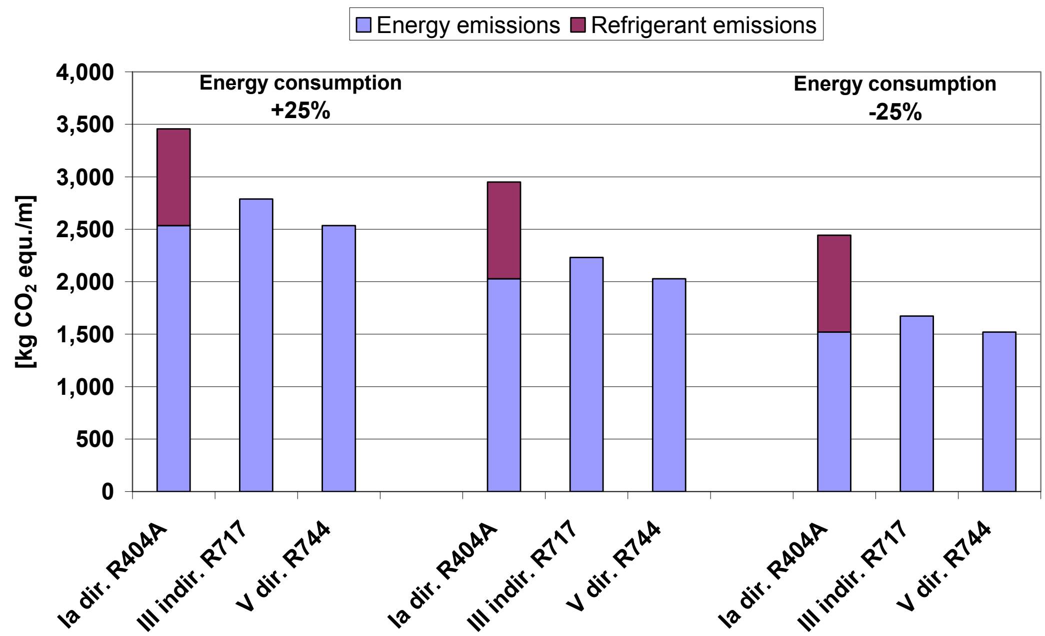

Figure 32: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the hypermarket (leakage rate 6.15%)

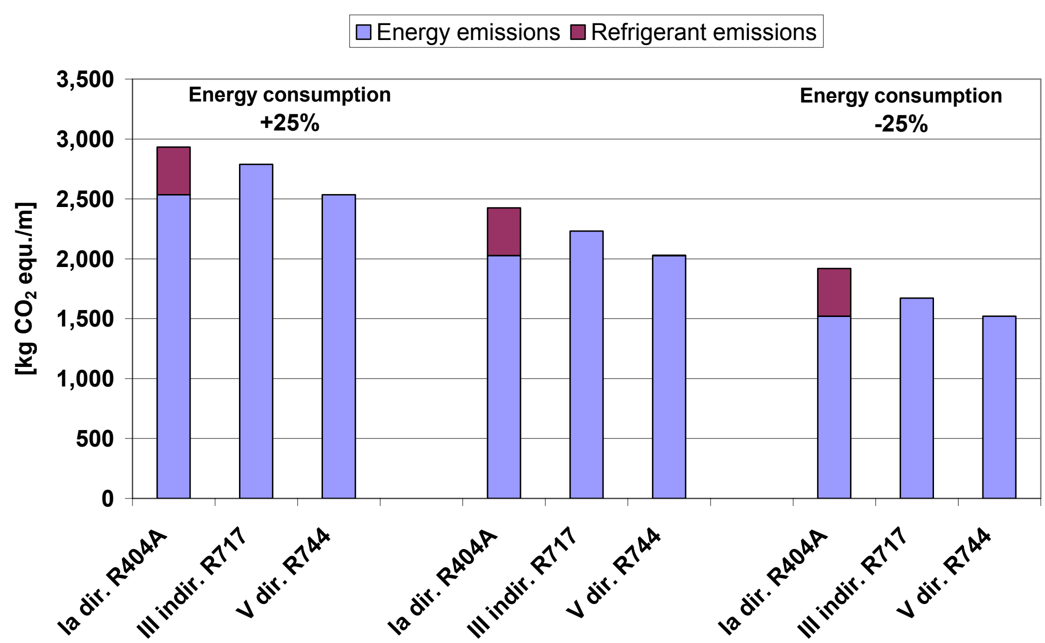

Figure 33: Impact of specific energy consumption upon annual greenhouse gas emissions of the model technologies used by the hypermarket (leakage rate 2.65%)

5.1.6 Impact of annual refrigerant losses

From the results of the TEWI analyses shown above, the impact which the system tightness has upon the aggregate emissions of a refrigeration system with HFC already becomes obvious. The three policy scenarios assume continued improvements of the system tightness already on a high level by means of stronger political stipulations and improved system technology. Despite of any measure in practice the total loss of a refrigerant will happen consistently by reason of system breakdowns. Though the number of breakdown cases will decrease due to the increasing awareness of operating companies, manufacturers, and maintenance personnel, one will never be able to completely prevent the total loss of refrigerant. From the current point of view one can therefore assume that on average the annual leakage rate will clearly lie above the rates used in this study in many cases. For illustration the TEWI analyses are calculated again with leakage rates of 15 %, 20 %, and 25 % for any of the 3 store categories. The results are shown in figures 34-36.

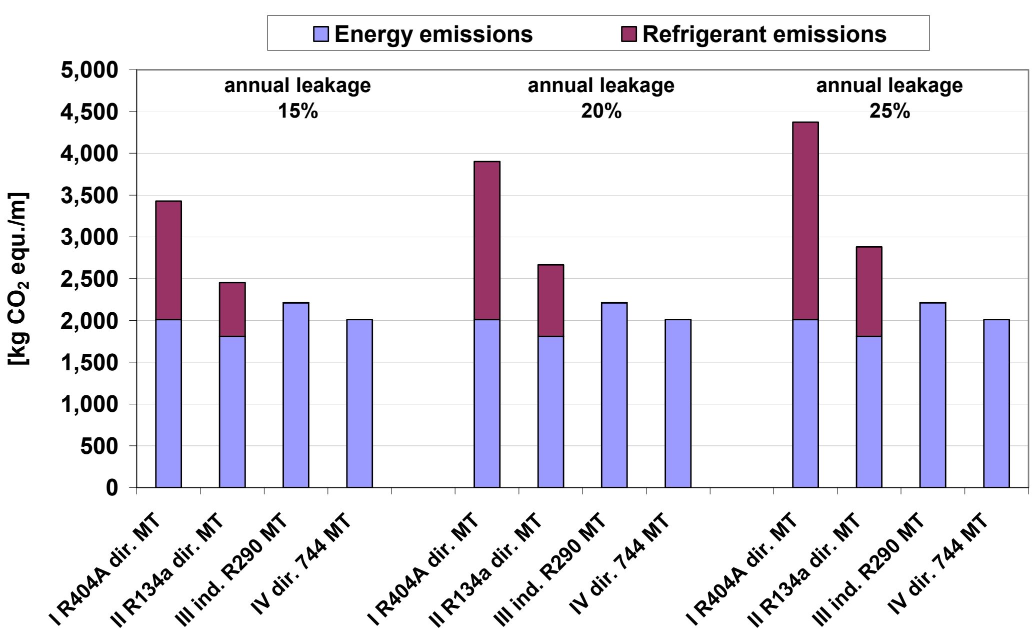

Figure 34: Impact of the refrigerant leakage rate upon annual emissions of the model technologies at the discounter

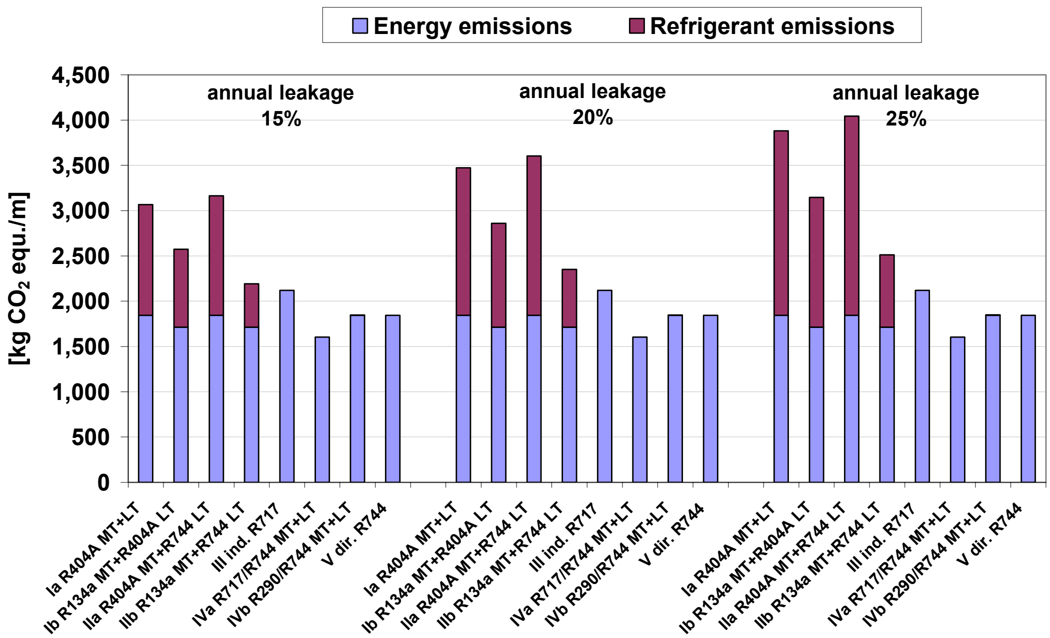

Figure 35: Impact of the refrigerant leakage rate upon annual emissions of the model technologies at the supermarket

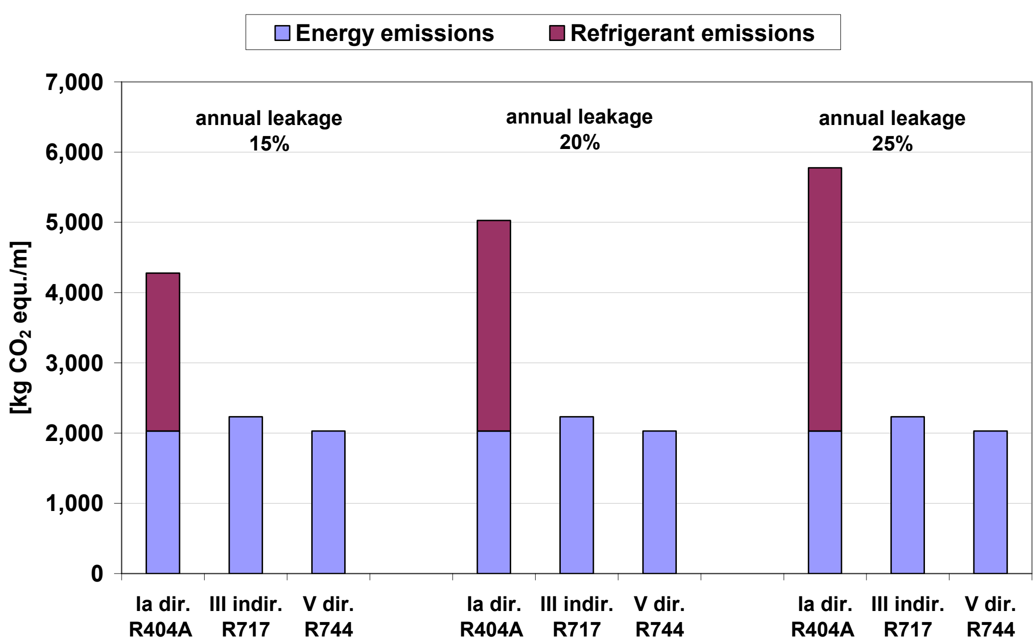

Figure 36: Impact of the refrigerant leakage rate upon annual emissions of the model technologies at the hypermarket

Figures 34-36 illustrate the significant emission surplus of conventional systems with HFC in connection with annual leakage rates on a high level.
Indeed, the annual amount of the annual refrigeration leakage can only be estimated at the moment. Hopefully one will gain a better insight in the near future following the EU regulation No. 842/2006 requiring operator logbooks for refrigeration and air conditioning equipment with refrigerant charge > 3 kg as of 4th July 2007. There, the operating companies are required to keep records on refilling of refrigerant charges and recovered refrigerant amounts during maintenance, upkeeping, and final disposal.
The here assumed higher refrigerant leakages would also have a mitigating effect upon the abatement costs referred to in chapter 5.3. A corresponding comparison of abatement costs in connection with refrigerant emissions higher than within the three policy scenarios is carried out in chapter 5.3.

5.2 Climate relevance of German retail industry

On the background of the TEWI analyses it is possible to estimate the aggregate emissions of refrigeration technology equipment used by the German food retail industry. For this purpose the calculated emissions per market (see table 19-21) were extrapolated for the German retail sector and policy scenario 1 based on the current sales area of German retail stores in 2006 (see table 22).

Table 22: Sales area of the examined store categories in Germany 2006

Operational base	Aggregate sales area [1000 m²]	Average sales area as per market [m²]
Small food stores	6,080	186
Discounter	10,050	682
Supermarket	6,650	789
Hypermarket	6,050	2,020

Source: [EHI 2007]

The aggregate sales area of any store category examined within this study amounts to 22,750,000 m^2 in 2006 distributed upon 26,325 groceries/food stores [EHI 2007].
When the emissions of the R404A reference technology are standardized by CO_2 equivalent per m^2 sales area (see table 23) and extrapolated upon the aggregate sales area according to store category, then in connection with the three examined store categories an aggregate annual emission of 6.9 Million t CO_2 equ./m^2 will result for the three examined store categories of the German retail industry.

Further emissions will have to be added from 32,740 small food stores with an aggregate sales area of 6,080,000 m^2 [EHI 2007]. These type of store as the corner shop, the gas station shop and kiosks normally do not use multi-complex refrigeration systems but single-unit plug-in refrigerated shelves and freezers. By reason of their heterogeneity they are not implied within this study.

In order to get an impression of the climate relevance of this not inconsiderable type of business, the emissions of small markets were estimated on the basis of survey data of Öko-Recherche GmbH from 2005 [Schwarz2005]. The indirect emissions of energy consumption were analysed in accordance with the number and key performance indicators of refrigeration units used by small groceries. The key performance indicators were taken from [Kruse2002].

In table 23 the area-normalized emission values of the 4 store categories are shown for their direct and indirect emissions, respectively.

Table 23: Annual specific refrigerant emissions per m^2 sales area in German food retailing

Shop category	Refrigerant emission	Energy emission
	[t CO_2 eq./m²]	[t CO_2 eq./m²]
Small groceries	0.023	0.092
Discounter	0.036	0.153
Supermarket	0.114	0.222
Hypermarket	0.212	0.246

Figure 37 shows the annual aggregate emissions in relation with refrigeration technology in German retail industry in 2006, allocated to the shop category and direct as well as indirect emissions. As a simplification, the assumption is a complete and finished conversion from HCFCs to HFCs which can be expected until the year 2015[24].

[24] Regulation (EC) No. 2037/2000 prohibits the application of ozone-depleting fluoro-chloro-hydrocarbons as of 1st January 2015.

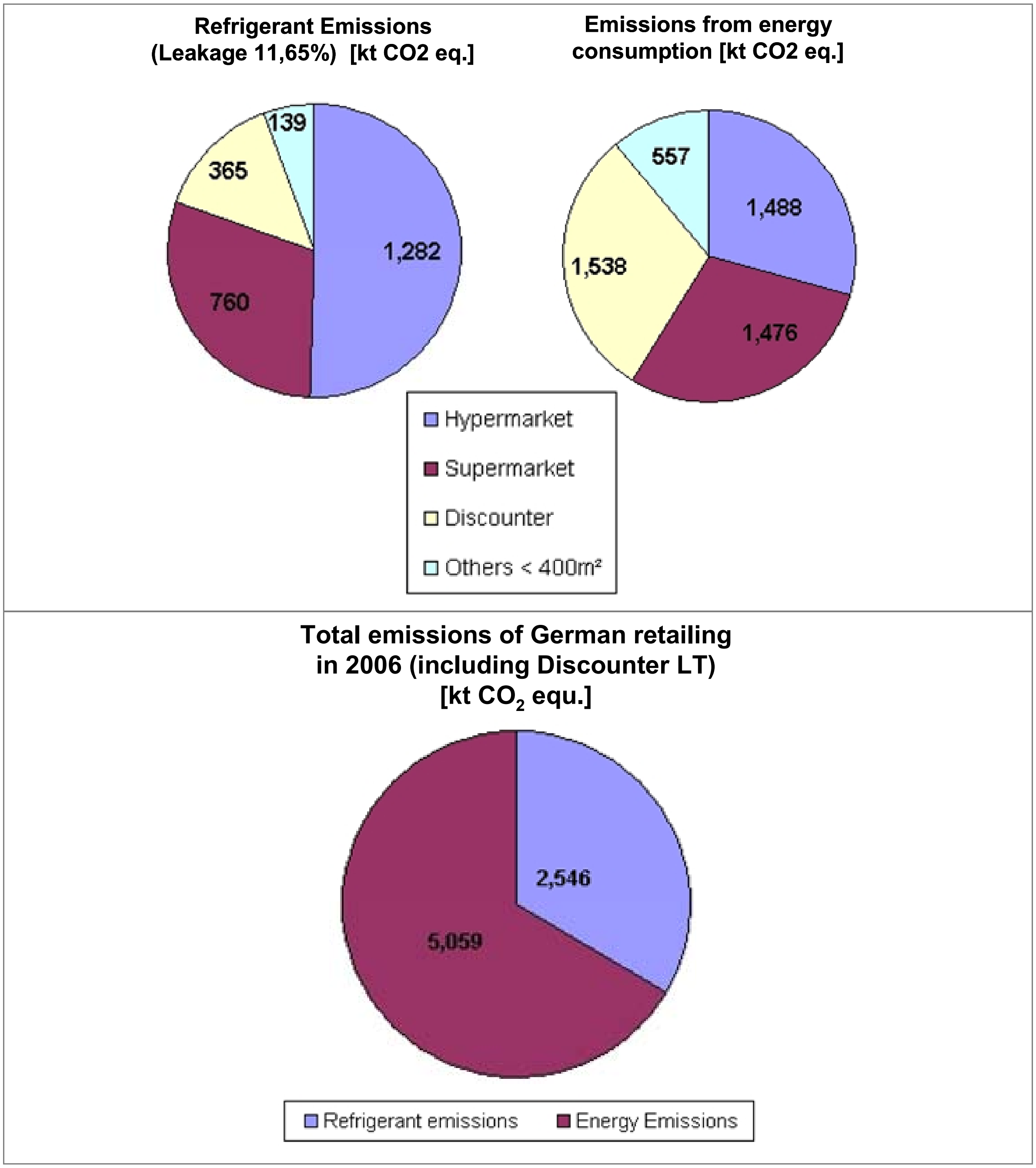

Figure 37: Annual emissions from refrigeration equipment of German food retailing in 2006

In sum, the emissions from refrigeration equipment in German food retail reach about 7.6 Mio. t CO_2 equ. per year. Approximately one third thereof are direct emissions from the application of HFC-containing refrigerants.
Thus the mere production of cooling in the food retail industry is responsible for about 1 % of the German greenhouse gas emissions, not taken into account any emissions from heating equipment and district heating. Hence promoting opportunities for the reduction of refrigerant emission as well as options for better energy efficiency should lead to relevant contributions to German efforts of reducing global warming.

5.3 Abatement costs

Specific abatement costs are indicated in € per ton of abated CO_2 equivalent, related to the R404A reference technology. Hereby only additional costs in respect of the reference technology are considered, apart from absolute costs which would arise in connection with replacement of the reference technology.
Table 24, 26, and 28 show the abatement potentials within the corresponding policy scenario, whereas table 25, 27, and 29 illustrate the correlated abatement costs. For this purpose the increases in costs shown in table 18 are underlying in accordance with their policy framework related to systems with HFC containing refrigerants.
The investment costs are indicated on an annual basis for a system's life time of 10 years. The annual costs comprise the energy costs and the full maintenance costs (see table 12-17).

Table 24: Emission abatement potential in relation to model technologies (scenario 1 – leakage rate 11.65%)

No.	Model technology	Emissions [t CO_2 equ./a]	Abated emissions [t CO_2 equ./a]
Discounter			
I	**Reference system**	**70.0**	**-**
II	R134a dir. MT	52.0	18.0
III	ind. R290 MT	49.8	20.2
IV	dir. 744 MT	45.2	24.8
Supermarket			
Ia	**Reference system**	**265.3**	**-**
Ib	R134a MT+R404A LT	226.3	39.0
IIa	R404A MT+R744 LT	272.5	-
IIb	R134a MT+R744 LT	198.1	67.2
III	ind. R717	201.4	63.9
IVa	R717/R744 MT+LT	152.3	112.0
IVb	R290/R744 MT+LT	175.3	90.0
V	dir. R744	175.1	90.2
Hypermarket			
I	**Reference system**	**924.9**	**-**
III	ind. R717	546.5	378.4
V	dir. R744	497.0	427.9

Table 25: Specific abatement costs for different abatement measures in relation to a R404A direct evaporation system (scenario 1 – leakage rate 11.65%)

No.	Model technology	Additional investment costs [€]	Annual additional costs [€]	Abatement costs [€/t CO_2 equ.]
Discounter				
I	**Reference system**	**-**	**-**	**-**
II	R134a dir. MT	1,110	-960	**8**
III	ind. R290 MT	1,726	1,450	**157**
IV	dir. 744 MT	1,726	500	**90**
Supermarket				
Ia	**Reference system**	**-**	**45,500**	**-**
Ib	R134a NK+R404A LT	5,671	-3,000	**68**
IIa	R404A NK+R744 LT	0	1,000	**-**
IIb	R134a NK+R744 LT	5,671	-2,000	**55**
III	ind. R717	12,576	7,500	**314**
IVa	R717/R744 MT + LT	12,822	-3,500	**83**
IVb	R290/R744 MT+LT	6,904	0	**77**
V	dir. R744	9,124	1,300	**116**
Hypermarket				
I	**Reference system**	**-**	**-**	**-**
III	ind. R717	27,617	14,000	**110**
V	dir. R744	19,727	4,000	**55**

Table 26: Emission abatement potential in relation to model technologies (scenario 2 – leakage rate 6.15%)

No.	Model technology	Emissions [t CO_2 equ./a]	Abated emissions [t CO_2 equ./a]
Discounter			
I	**Reference system**	**58.3**	**-**
II	R134a dir. MT	46.6	11.7
III	ind. R290 MT	49.8	8.6
IV	dir. 744 MT	45.2	13.1
Supermarket			
Ia	**Reference system**	**222.7**	**-**
Ib	R134a NK+R404A LT	196.3	26.4
IIa	R404A NK+R744 LT	226.5	-
IIb	R134a NK+R744 LT	181.5	41.2
III	ind. R717	201.4	21.3
IVa	R717/R744 MT+LT	152.3	70.4
IVb	R290/R744 MT+LT	175.2	47.5
V	dir. R744	175.1	47.6
Hypermarket			
I	**Reference system**	**722.8**	**-**
III	ind. R717	546.5	176.3
V	dir. R744	496.9	225.9

Table 27: Specific abatement costs from different abatement measures in relation to the R404A direct evaporation system (scenario 2 – leakage rate 6.15%)

No.	Model technology	Additional investment costs [€]	Annual additional costs [€]	Abatement costs [€/t CO_2 equ.]
Discounter				
I	**Reference system**	**-**	**-**	**-**
II	R134a dir. MT	1,110	-960	**13**
III	ind. R290 MT	1,726	850	**302**
IV	dir. 744 MT	1,726	-100	**124**
Supermarket				
Ia	**Reference system**	**-**	**-**	**-**
Ib	R134a MT+R404A LT	5,671	-3,000	**101**
IIa	R404A MT+R744 LT	0	1,300	**-**
IIb	R134a MT+R744 LT	5,671	-1,700	**96**
III	ind. R717	12,576	5,550	**849**
IVa	R717/R744 MT+LT	12,822	-5,450	**105**
IVb	R290/R744 MT+LT	6,904	-1,950	**104**
V	dir. R744	9,124	-650	**178**
Hypermarket				
I	**Reference system**	**-**	**-**	**-**
III	ind. R717	27,617	9,200	**209**
V	dir. R744	19,727	-800	**84**

Table 28: Emission abatement potential in relation to model technologies (scenario 3 – leakage rate 2.65%)

No.	Model technology	Emissions [t CO_2 equ./a]	Abated emissions [t CO_2 equ./a]
Discounter			
I	**Reference system**	**50.9**	**-**
II	R134a dir. MT	43.3	7.6
III	ind. R290 MT	49.8	1.1
IV	dir. 744 MT	45.2	5.6
Supermarket			
Ia	**Reference system**	**195.6**	**-**
Ib	R134a MT+R404A LT	177.3	18.3
IIa	R404A MT+R744 LT	197.3	-
IIb	R134a MT+R744 LT	170.9	24.7
III	ind. R717	201.4	-
IVa	R717/R744 MT+LT	152.3	43.3
IVb	R290/R744 MT+LT	175.2	20.5
V	dir. R744	175.1	20.5
Hypermarket			
I	**Reference system**	**594.2**	**-**
III	ind. R717	546.5	47.7
V	dir. R744	496.9	97.3

Table 29: Specific abatement costs from different abatement measures in relation to the R404A direct evaporation system (scenario 3 – leakage rate 2.65%)

No.	Model technology	Additional investment costs [€]	Annual additional costs [€]	Abatement costs [€/t CO_2 equ.]
Discounter				
I	**Reference system**	-	-	-
II	R134a dir. MT	1,276	-960	**42**
III	ind. R290 MT	432	-450	**-17**
IV	dir. 744 MT	432	-1,400	**-172**
Supermarket				
Ia	**Reference system**	-	-	-
Ib	R134a MT+R404A LT	6,522	-3,000	**192**
IIa	R404A MT+R744 LT	-2,281	1,500	**-**
IIb	R134a MT+R744 LT	3,958	-1,500	**99**
III	ind. R717	5,733	4,250	**-**
IVa	R717/R744 MT+LT	5,980	-6,750	**-18**
IVb	R290/R744 MT+LT	62	-3,250	**-156**
V	dir. R744	2,281	-1,950	**16**
Hypermarket				
I	**Reference system**	-	-	-
III	ind. R717	12,822	6,000	**395**
V	dir. R744	4,932	-4,000	**10**

Following the first overview of the results from the abatement costs, it is most obvious that the abatement costs strongly vary according to the individual scenario. The reason for this is the reference technology which does not enter into the calculation as a static factor instead of showing different emission and costs data in relation to the political framework. Thus, per example, the abatement costs for systems with natural refrigerants become more expensive in connection with scenario 2, even if, related to investment costs on the same level, the maintenance costs for the reference technology and new HFC-free technology approximate each other. This, in turn, follows from the fact that at the same time as additional costs decrease lower emission abatements will result because the HFC systems become tighter so that the costs per ton of abated CO_2 will lie above those of scenario 1.

As a complement to the three policy scenarios a forth scenario was calculated, in following named the transition scenario. In this fourth scenario the abatement costs are determined for the event that within the first four years of its life time the R404A reference system is operated below the framework of scenario 2 and further six years within scenario 3. Due to higher requirements for tightness during passing from scenario 2 to 3, these systems need retrofitting. In consequence of retrofitting in accordance with table 18, additional costs of further 15% of aggregate investment costs for HFC systems will arise.

Table 30 shows the average annual emissions of the corresponding technology during its life time and the abatements costs in relation to the reference technology.

Table 30: Specific abatement costs from different abatement measures in relation to the R404A direct evaporation system (transition scenario)

No.	Model technology	Emissions [t CO_2 equ./a]	Abated emissions [t CO_2 equ./a]	Abatement costs [€/t CO_2 equ.]
Discounter				
I	**Reference system**	**630**	**-**	**-**
II	R134a dir. MT	488	142	**5**
III	ind. R290 MT	498	132	**32**
IV	dir. 744 MT	452	178	**-30**
Supermarket				
I	**Reference market**	**2,064**	**-**	**-**
Ib	R134a MT+R404A LT	1,849	215	**106**
IIa	R404A MT+R744 LT	2,090	-	
IIb	R134a MT+R744 LT	1,751	313	**52**
III	ind. R717	2,014	51	**1,854**
IVa	R717/R744 MT+LT	1,523	541	**-26**
IVb	R290/R744 MT+LT	1,752	313	**-86**
V	dir. R744	1,751	314	**13**
Hypermarket				
I	**Reference system**	**6,456**	**-**	**-**
III	ind. R717	5,465	991	**178**
V	dir. R744	4,969	1,488	**9**

Comparing the abatement costs of the different scenarios, one may observe that the rather high abatement costs of scenarios 1 and 2 become more and more cost-effective in connection with increasing requirements on tightness in scenario 3 and 4, especially for CO_2 technology.

As a scale for cost-effective abatement measures is often nominated the price for one t CO_2 within the European emission trading system. Currently, it is at about € 25 for emissions allowances for the current trading period from 2008 to 2012.

As already mentioned in chapter 5.1.6, the level of refrigerant losses also have a considerable impact on the abatement costs. In the event that the refrigerant leakages are above those of the three policy scenarios assumed, the abatement costs will clearly decrease. This is correlated with the abatement potential of alternative technologies without HFC being then significantly larger. If, i.e., the reference technology's emissions do not lie at 11.65 % as in policy scenario 1 but at 15 %, the abatement costs for R744 direct evaporation systems will decrease by about 20 %. An overview of the abatement development in connection with higher refrigerant leakages is shown in table 31.

Table 31: Abatement costs in relation to higher annual refrigerant losses

No.	Model technology	Abatement costs for different leakage rates			
		11.65 % p.a.	**15 % p.a.**	**20 % p.a.**	**25 % p.a.**
		Discounter			
II	R134a dir. MT	**8**	7	5	-10
III	ind. R290 MT	**157**	116	68	0
IV	dir. 744 MT	**90**	70	38	-18
		Supermarket			
Ib	R134a MT+R404A LT	**68**	57	46	35
IIa	R404A MT+R744 LT	**-**	-	-	-
IIb	R134a MT+R744 LT	**55**	44	37	19
III	ind. R717	**314**	223	141	60
IVa	R717/R744 MT+LT	**83**	67	42	-4
IVb	R290/R744 MT+LT	**77**	60	32	-16
V	dir. R744	**116**	90	55	2
		Hypermarket			
III	ind. R717	**110**	83	54	22
V	dir. R744	**55**	43	26	1

5.4 Applicability of the results on EU-27

The scope of this study is restricted to the situation of the German food retail industry. Nevertheless, at least a qualitative assessment of the situation for the other European member states should be provided at this place.

In recent years the demand for chilled goods has increased all over Europe. After the prohibition of ozone depleting HCFCs, HFC based refrigerants have become the principal refrigerants for cooling equipment because they are able to replace HCFCs without the need of extended technical retrofitting.

However due to their high GWP (see table 4) fluorinated greenhouse gases fall under gases set out in the Kyoto protocol. By that reason and due to their large energy consumption, commercial refrigeration systems increasingly became the focus of European regulations and legislations in the last years. Commercial refrigeration is mainly affected by the EU-F-Gas-regulation (Regulation (EC) No. 842/2006). But also in the field of energy efficiency, refrigeration systems will be subject to stricter legislation in the future. Within the “Energy Efficiency Action Plan“ of the European Commission a study including eco-design criteria for commercial refrigeration systems was issued in December 2007 lending priority, above all, to energy efficiency [Bio2007].

Beside stationary and mobile air conditioning systems in cars, equipment providing commercial refrigeration is the largest area of refrigeration and climate technology subject to the EU-F-Gas regulation. Excluded from the regulation are natural refrigerants which within the political discussion about climate change attract again increasing attraction. In the segment of commercial refrigeration the focus of system manufacturers is concentrated mostly upon CO_2 as refrigerant. In the leading position of the application of CO_2 as refrigerant are currently the Netherlands, Italy and Germany, beside the Scandinavian countries. In these countries numerous refrigeration systems have already been installed in the retail sector. Due to the low critical point of CO_2 (31ºC), its use is often seen critical in South Europe with its warmer climate. According to an investigation of the company Linde (see figure 38), CO_2 corresponds in North and Central Europe to a lower energy consumption of about 5-10 % on average compared to R404A. Figure 38 makes clear that systems by means of coldwater spray devices for better cooling of evaporators show also equal performance in comparison to R404A systems, even at hot ambient temperatures above the critical point of CO_2.

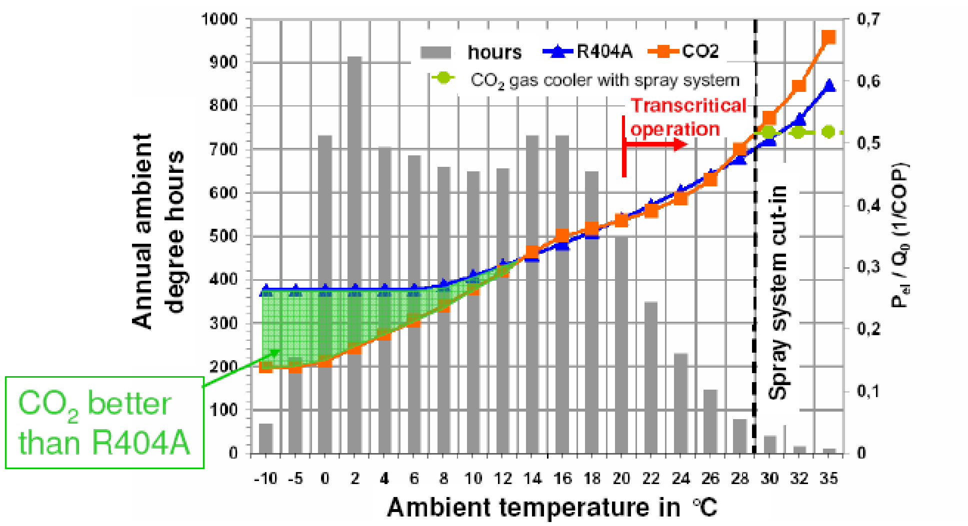

Figure 38: Comparison of energy consumption of direct evaporation R404A / R774 MT systems *Source: [Haaf 2005]*

The use of natural refrigerants should also be possible in large parts of East Europe without greater technical problems. Currently, in East Europe a great change of the market structure takes place, which moves from the small suburban or corner shop to the discounter and large super- or hypermarket, respectively. For the greater part, the large European retail companies are rushing on the East European market from which follows that numerous new retail stores obtain refrigeration technology on the cutting edge. Therefore, this market also offers a special opportunity for application of new technologies with natural refrigerants.

6. Summary

In first instance it was examined which cooling technologies in relation to three retail store categories and policy scenarios show stable advantages in their climate balances against the reference technology based on R404A, taking into account any uncertainty following from the input parameters. Hereby it became apparent that the climate balance of the CO_2 technology was significantly superior to the R404A reference technology in relation to any uncertainty under consideration for super markets and hypermarkets[25]. For discounters the significance in connection with a high level of tightness (annual refrigerant leakage of 2.65%) no more exists.

In a second step the abatement costs for the relevant emissions were calculated in order to define the cost efficiency for the individual policy scenarios incurred by technology change. Table 32 summarizes the quantitative results in a manner easily to overlook. Here it becomes clear that currently the use of natural refrigerants can only be realized at rather high abatement costs, while the specific abatement costs will see a significant decrease in the near future, due to more and more strict provisions on leak tightness for conventional systems with HFC.

As shown, also the actual level of refrigerant losses has an important impact on the abatement costs. In the event of refrigerant leakages on a higher level than assumed here, HFC-free technologies offer even higher emission reduction potentials. In consequence of, the abatement costs would clearly reduce. In future, a peculiar value should therefore be placed upon the exact evaluation of the logbooks required by EU-regulation (EC) No. 842/2006 because it will provide information on the real refrigerant leakages in the retail industry.

[25] Here: the significance level corresponds to a value which is different to the expectancy value by more than twice the standard difference.

Table 32: Combined overview of TEWI results and abatement costs for different tightness scenarios and model technologies

		Tightness scenario 1 (11.65 %)	Tightness scenario 2 (6.15 %)	Tightness scenario 3 (2.65 %)
Discounter				
I	**Reference system**	B-	B-	B-
II	R134a dir. MT	A+	A+	B+
III	ind. R290 MT	A-	A-	B++
IV	dir. 744 MT	A-	A-	B++
Supermarket				
Ia	**Reference system**	B-	B-	B-
Ib	R134a MT+R404A LT	A-	A-	A-
IIa	R404A MT+R744 LT	B-	B-	B-
IIb	R134a MT+R744 LT	A-	A-	A-
III	ind. R717	A-	A-	B-
IVa	R717/R744 MT+LT	A-	A-	A++
IVb	R290/R744 MT+LT	A-	A-	A++
V	dir. R744	A-	A-	A+
Hypermarket				
I	**Reference system**	B-	B-	B-
III	ind. R717	A-	A-	B-
V	dir. R744	A-	A-	A++

Coding of the evaluation		
Climate balance:	**A** :	Significantly superior to the reference system
	B :	No significant difference to the reference system
	C :	Significantly inferior to the reference system
Cost-effectiveness:	**++** :	negative abatement costs
	+ :	abatement costs <=50 Euros per ton CO_2 equivalent
	- :	abatement costs > 50 Euros per ton CO_2 equivalent.

Correspondingly, the results from the present study are of special importance for the other EU member states. The results of TEWI analyses presented here do not differ significantly within the uncertainties related to Central and North Europe. Only in regions with warmer climate as given in South Europe one may observe certain variations (see chapter 5.4).

When investing into new refrigeration systems, the question for the choice of refrigerant will have increasing importance for German retailers aside from the costs issue. The current public discussion about climate change shows that sustainable and environment-friendly business operation is becoming more and more important and, in addition, is also getting a sales argument. By using natural refrigerants in new equipment, already today individual retail companies make a decision for environment-friendly refrigeration because in this way double investments, once for compliance with stricter tightness requirements, and later for the installation of new technology with natural refrigerants can be avoided.

A further tightening of requirements affecting the use of fluorinated greenhouse gases can be expected in Germany as well as all over Europe in the next years. This is reflected by, among other things, the climate and energy program adopted by the German government in Meseberg, as well as by the re-evaluation clauses of article 10 of the EU-F-gas regulation.

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Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment" (FKZ 206 44 300)

Barriers and Improvement Potentials

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Table of Contents

1.State of the art – overview

The market overview from part 1 contains an overview of the processes with synthetic and natural refrigerants which nowadays are used for refrigeration in the supermarket or are under development. A series of representative layout options were selected for balancing and evaluation among numerous system configurations or “model technologies” outlaid and compared in relation to their climate relevance.

In principle, one may presuppose in connection with these selected layout options and model technologies that the processes have reached a mature state as to system and component technology, have seen their market launch, and have been proven in practice with different extent in certain European member states. Except from this are systems and appertaining components operated with CO_2 which partially are under development or testing and market introduction, respectively. This particularly obtains for CO_2 systems with transcritical operation.

The following section therefore concentrates upon the re-evaluation of the development state of these systems and their most important components, in addition eventual technical or non-technical obstacles preventing an extended market launch for commercial refrigeration. In contrast, there does not exist any *principal* need for development and testing for the other processes.

Apart from that, advanced development and optimization of the system’s configuration and control are possible and also necessary, seen from the perspective of climate protection, for all the processes aiming at more energy efficiency. For this purpose, the market overview contains a schedule of conceivable measures which, on larger part independent from the refrigerant, may be taken for the upgrading of the energy efficiency and hence for the compatibility with the climate.

According to order, the focus of the present study is the evaluation of the climate relevance of refrigeration systems and units. Its subject is not the entire complex of refrigeration, heating, and air conditioning of supermarkets. However, it will be shown that at least the pooling of these energetically intensive segments within a composite cooling-heating-system contains important energy and thus CO_2-saving potentials that must exceed any consideration restricted to partial systems and units.[26]

1.1 Development trends for refrigeration systems and refrigerants – a short retrospection

The Montreal Protocol from 1987 and the Kyoto Protocol from 1997 have triggered the critical steps for the substitution of refrigerants and reduction of greenhouse gas emissions in the retail segment. Within a development process of more than 15 years, different refrigerants and system configurations were tested. The development work within commercial refrigeration was related (summarizing [Kruse2006a and b]) to:

- Intermediate solutions with HCFC and HFC, i.e. synthetic refrigerants, for direct and indirect one- and (less often) two-phase systems and cascade systems for both temperature regions;

- The testing of flammable and non-flammable natural refrigerants (hydrocarbons, ammonia, CO_2) up to CO_2 systems with direct expansion both for MT and LT.

In the Federal Republic of Germany, these works were partially funded by the BMFT (see DKV project for the abatement of CFC emissions 1991 - 1993). Further BMFT-funded examinations were concerned with direct and indirect greenhouse efficiency of HFC refrigerants used by direct expansion systems (R404A and R407C) as well as indirect systems based on ammonia [Haaf1998].

Already a long time before the Kyoto Protocol was issued, the global warming potential of refrigerants was discussed within the Montreal Protocol (since the follow-up conference in London 1990 and the presentation of the TEWI concept within the follow-up conference in Copenhagen 1992). Soon the TEWI calculations for different systems of commercial cooling made clear that, due to their high direct TEWI contribution, conventional supermarket refrigeration systems with direct expansion, long-distance

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[26] E.g., such a concept is underlying a composite cooling-heating-system with geothermal use. A sample provides the Edeka Aktiv-Markt Schömberg. See Der Facility-Manager 6/2006, p. 24-26; TGA-Fachplaner 5/2006, p. 33-36; DIE KÄLTE & Klimatechnik 6/2007, p. 34/35.

piping systems and large HFC charges „cannot present the solution for the future, when the leakages are not driven back drastically ([Kruse2006b] in relation to [DOE/AFEAS1997]).”[27]

During the development testing it also became clear that the reduction of GWP relevant refrigerant emissions by means of smaller, decentralized refrigeration systems or indirect cooling systems with conventional cooling mediums is purchased by a higher expenditure of energy. Due to security reasons (toxicity or, as the case may be, flammability), natural refrigerants such as ammonia and hydrocarbons tested in indirect systems for supermarkets are and were normally not considered (see [Haaf/Heinbokel2002] and [Haaf/Heinbokel2003]). Hence already in the 90s CO_2 became the focus within the search for new concepts of system configuration, both as secondary fluid (energetically favorable cooling medium with essentially improved heat exchanger coefficient and less viscosity in the low temperature area compared to conventional cooling mediums) and as refrigerant for direct expansion (cascade systems) [Heinbokel2001]. During the same time, several CO_2 pilot systems with different configuration were developed in Europe for the supermarket.

The first systems with CO_2 as cooling medium for the LT range is dating back to the years 1993-1996, prevailing in Scandinavia. For the first time in 2000, systems with CO_2 as refrigerant were installed in Denmark for the LT range (direct evaporation, subcritical) as well as with propane for the MT range [Kauffeld/Christensen2001]. The same year saw the first installation of a system type with CO_2 for LT range (subcritical) and HFC for MT range (in Luxembourg, [Heinbokel2001]). In the following years, pure CO_2 systems were conceived (transcritical for MT- and LT range, [Gebhardt et al.2003]) or introduced into practice for the first time, including subcritical CO_2 operation for LT- and transcritical operation for MT range (initial installation 2004 in Switzerland;

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[27] By means of an overview article from 2000, Kruse summarized the development alternatives in the following way: “In conclusion, supermarket refrigeration systems with direct expansion and a large refrigerant charge and long refrigerant lines, which have a potential to cause reasonable amounts of leakage, can not be a future solution, although leakages can be decreased to a certain amount. Therefore, the choice for future refrigeration systems in supermarkets is either indirect systems with secondary refrigerants or direct decentralized water-cooled HFC systems. Another possibility would be the application of refrigerants with very low GWP in direct systems. Ammonia and hydrocarbons show dangerous local behaviour because of their flammability or toxicity and are not suited for direct expansion systems inside public areas of supermarkets. Therefore, for these refrigerants, indirect systems have to be used. For direct systems, only CO_2 can be used, which presents other problems that are discussed later.“ [Kruse2000], p. 18.

[Haaf et al.2005]). One of the necessary requirements was the provision of adequate system components for increased pressure levels, in particular of compressors for transcritical CO_2 operation, which were available since about 1998.

The current development level in relation to CO_2 technologies is stated by a conclusion of the Deutsche Kälte-Klima-Tagung 2007 (Hanover) in the following way: „CO_2 as refrigerant has proven its applicability at low temperature levels of cascade systems and is favorably used in full extent. As universal refrigerant, also within transcritical use for MT, it is underway to conquer the market. There is good reason to expect that the already numerous prototype systems of supermarket stores with equipment that exclusively is based on CO_2 will soon become the standard solution for both temperature levels [KK1/2008].“

1.2 CO_2 Technology

In the realm of the *new development* of multi-compressor refrigeration systems with natural refrigerants of low climate impact, the refrigeration system manufacturers and their suppliers of components in Germany today give their vote throughout for CO_2 (R744). The system manufacturers see it as being the critical alternative for the supermarket segment (see [Brouwers2007]; [Epta2007]; [Kröger2007]; [Linde2007a]; [Tillner-Roth2008]). However, in this context problems arise that are due to the peculiar properties of CO_2 as refrigerant.

CO_2 is a refrigerant for the very high-pressure level. The evaporation pressure curve for CO_2 is at about one decimal power above the other customary refrigerants. Therefore, R744 possesses within the temperature range relevant for supermarket refrigeration systems a significantly higher pressure than any other refrigerant. Following these high pressure levels, the conception of the components of CO_2 systems must reckon with both in the LT- and MT range, against any system operated with HFC. While in the subcritical range one has to account for pressure levels up to 40 bar, essentially higher pressure levels occur within transcritical operation on the high pressure side with up to 120 bar.

Because of its low critical temperature of 31 °C, CO_2 can only be used within the classical cold evaporation process, at temperatures up to 20 - 25 °C of the condenser's heat sink. Yet, this temperature is often exceeded in summer time by supermarket systems using air-cooled condensers. Then, a CO_2 condensing is no more possible. Therefore, CO_2 refrigeration systems for MT operate at high ambient temperatures in the transcritical range. After condensing the gas is not liquefied, but chilled in a gas cooler.

R744 systems used for the lower grade of a cascade refrigeration system in supermarket freezing (about -18 °C) have since a long time successfully passed the pilot phase, so that they may be considered as the standard system. Since that time numerous corresponding systems have already been installed in supermarkets in Europe. The first LT refrigeration systems for supermarkets were put into operation in 2000 [Haaf/Heinbokel2002, 2003]. According to the system manufacturers, today the necessary equipment and control components providing any desired specification at acceptable prices are available for subcritical CO_2 operation with pressure levels up to 40 bar.

On the contrary, multi compressor systems with CO_2 as refrigerant being also used for MT (about 0 - 8 °C) with transcritical operation and high pressure are still in the testing phase. Important high pressure components of such systems manufactured in series are still not available, so that the costs are comparatively high. The corresponding pilot systems were installed for the first time a few years ago [Haaf et al.2005], their number is still low – this is especially valid for the Federal Republic of Germany in comparison with Scandinavian countries as well as Switzerland and Luxembourg – and corresponding experience has still to be gathered. Complete CO_2 solutions with R744 for MT and LT are announced for 2008/2010 as the standard system for the supermarket segment in Central Europe ([Brouwers2007]; [Tillner-Roth2008]).

1.3 Other natural refrigerants

Apart from CO_2, NH_3 (ammonia, R717) as well as hydrocarbons (propane, R290; propene, R1270; iso-butane, R600a) with different scope of application are used as natural refrigerants (see [Bitzer2006a]; [Haaf/Heinbokel2002]; [Haaf/Heinbokel2003]; technology data sheets C8-C10, C11). Contrary to CO_2, the system technology has fully matured in these cases. NH_3, propane, and propene systems installed for refrigeration in German supermarkets are in most cases decommissioned because several disadvantages of ammonia and hydrocarbon refrigerants have proved, such as higher investment costs and energy consumption in comparison to direct evaporation systems.

The known material disadvantages of ammonia are its combustibility, toxicity, and the fact that, due to its pungent odour, it is not „panic-proof" even at small, non-toxical concentrations. Therefore, ammonia is only possible for indirect systems with cooling mediums insofar facilities with public traffic such as supermarket stores are concerned. Consequently, additional expenditures related to energy and system technology have to be accounted for concerning the cooling medium system, pumps, and motor technology which becomes more expensive due to the separation of compressor and engine (see [Haaf/Heinbokel2002], [Haaf/Heinbokel2003]; [Renz2007]). Hydrocarbons such as propane, propene, and ethane have superior cooling properties, yet also the disadvantage of flammability and, following from that condition, stricter and costly safety provisions (i.e. effects upon the compressor construction; [Renz2003]; [Renz2007]). This makes their use for refrigeration systems in connection with public traffic more difficult, and it includes the limitation of units with small refrigerant charges (150 g pursuant to IEC 60335-2-89 for commercial refrigeration and freezers) or indirect systems.

1.4 Synthetic "low-GWP" Refrigerants

Some companies of the chemical industry have announced the development of new synthetic refrigerants with a GWP <150 for automobile (mobile) air conditioning in consequence of the prohibition of the use of R134a for air conditioning of vehicles as of 2011. Composition, technical qualities, toxicity, and environmental effects of these fluorinated "low GWP" refrigerants were not available in the middle of 2007 ("Blend H" of Honeywell and "DP-1" of DuPont; [Reichelt2007]). The refrigerant HFO-1234yf jointly presented by DuPont and Honeywell in November 2007 has a low GWP value of 4; more detailed material data and evaluation results are to be published in 2008 [Honeywell/DuPont2007]. One may conceive that in this case a refrigerant family will be inaugurated which eventually might also be operable as an alternative in the supermarket store. 2007 however, this was not on the agenda, because at this time the need for action was most urgent in the area of mobile air conditioning following the interest situation of the refrigerant industry. System and component manufacture, though, were rather sceptical in this context.

1.5 CO_2 refrigeration systems for supermarkets: Inventory at the end of 2007 in Europe and Germany

At the end of 2007, the inventory of multi compressor CO_2 systems for the supermarket LT range in Europe reached several hundreds (see technology data sheet C5-C7); in most cases R404A was used for the MT range in the supermarket. Locations were in Norway, Sweden, Denmark, Germany, Luxembourg, Switzerland, and Italy. According to information of the manufacturers, about 60 CO_2 systems for the MT and LT range were installed in Europe (see technology data sheet C13), i.e. Norway (4), Sweden (20), Denmark (11), Great Britain (1), Germany (6), Belgium (1), Luxembourg (3), Switzerland (6), as well as Italy (5), mostly in large-area stores.

2. Obstacles preventing the expansion of the use of R744 multi compressor systems for supermarkets (state: middle of 2007)

As currently CO_2 systems for *transcritical* operation in the MT range are in the testing and pilot system phase, the state of the art and possible technical, economical, and other obstacles claimed by the side of the user company and preventing a wide application of this technology will be considered in the following.

2.1 Technical aspects

The point of departure of the analysis can be summarized in the following way (see [Bitzer2006a]; [Bitzer2007]; [Bock2007]; [Danfoss2007a]; [Danfoss2007b]; [Epta2007]; [Linde2007a]):

1. Today the CO_2 technology in the freezing (LT) range with subcritical pressure levels at 40 bar is state of the art. According to the system manufacturers, the necessary components are available with the specifications desired and at affordable prices.

2. In contrast, several technical obstacles exist when the CO_2 technology for medium temperature (MT) is to extend beyond the previous inventory of pilot systems. For the MT range (transcritical operation in summer) the components must be designed partially for pressure levels of maximally 120-130 bar.

3. The maximum operational pressure of MT *low pressure* multi-compressor systems is at 40 bar. This concerns installations in the sales area of supermarkets. The corresponding system components are in principle available, only thermostatic expansion valves produced in series were lacking in 2007. Their series production would make a contribution for the system’s cost efficiency.

4. Several problems, however, occur in the *high pressure* range (max. operative pressure level 115 - 120 bar). This range includes: pressure part of the compressor, the liquefier or gas cooler as well as eventual heat recovery systems, pre-running and return piping to the gas cooler, locking and service components, high pressure valves. The high pressure modules are located in system components outside the proper supermarket (sales area). Such components are standard for industrial applications (industrial hydraulics equipment), but not as application for refrigeration systems installed in the supermarket. Several of the required components were not available in 2007 neither necessary specifications (product range), nor at affordable prices. For any of the pilot systems operating to date such components were manufactured as a special design.

5. An additional need for development has been analysed (in different degree) in connection with the following components:

   -Compressors
   -High pressure control valves
   -Shut off valves
   -Heat exchanger
   -other fittings.

   Development issues are also related to lubrication/refrigerator machine oils as well as to sealing materials.

6. Gas coolers on high pressure side for the MT range are not anymore problematic and are supplied by two manufacturers in Germany (according to system manufacturers, the price is still too high). Piping from steel is available; however welding assembly not customary in the retail industry should be avoided. Regarding the soldering technology (steel), development efforts are still necessary.

7. A special problem concerns the decreasing energy efficiency of operation with CO_2 in the transcritical range compared to R404A systems in connection with ambient temperatures > ca. 28 °C [Haaf et al.2005]. Principally, this energetic disadvantage resulting from high ambient temperatures can be compensated in different manner. One alternative is the combination of the CO_2 gas cooler with an additional cooling water spray system, which, at least for southern countries with water shortcomings, might be problematic and includes further problems (corrosion, chalk deposit, and the like). Yet in future also other technical solutions will get a chance. Tested are expansion machines as well as an optimized use of reciprocating compressors. Here development efforts still have to be accomplished.

2.1.1 Compressors

The development of compressors has key importance. In this context, CO_2 systems with transcritical operation, meet new challenges related to engineering. Factors defining time and work flow are:

- The duration for the development and testing of prototypes,
- The passage to serial production of a larger number of different models (different cooling capacity and piston displacement), and
- Passage to production numbers enabling cost degression.

How rapidly the development will take place will not only depend on the technical progress, but also essentially from the demand side.

Development trend: In Europe, compressors for *subcritical* CO_2 operation are currently supplied from 5 - 6 important compressor manufacturers (with very different quantities). The development was able to rely upon the experiences made with compressors for R404A and R410A, which since the 90s implied a large model range and increasing operational experience. The cooling capacity related to volumetric flow and hence the cooling capacity of the compressor is significantly higher with CO_2 compared to R404A. This enables to use a smaller discharge volume (smaller pistons) even at the compressor's comparable capacity and coefficient of efficiency. Hereby, the pressure levels regarding subcritical CO_2 operation are higher than with R404A, but they are in similar ranges as those of R410A.[28] On the whole, the development of compressors for R410A (in air conditioning technology) and CO_2 (in low temperature cascade systems for the supermarket application) are designated as „an adjustment to standard semi-hermetic reciprocating compressors in order to comply with the physical and thermodynamical properties of the refrigerants. These are in particular the pressure levels, the mass flow, the vapor density, the highly specific cooling capacity and power consumption, as well as the oil and pressure gas temperature" [Große-Kracht2005].

On the contrary, the development of semi-hermetic compressors for stationary *transcritical* CO_2 operation is to a large extent new construction. A manufacturer speaks of "a completely new system technology and control" (see [Bitzer2007], [Renz2007]; [Bock2007]; [Bock/Knudsen2007]). With deferrals of time the development began by the second half of the 90s in connection with different manufacturers of compressors. The current state, too, is characterized as still in the development/testing phase.

Regarding the high pressure side, the compressors are to design for maximum operational pressures of about 130 bar, requiring a by far higher pressure level in comparison with R410A and subcritical CO_2. The consequences of this are differences in design. Among other things, this relates to the compressor housing (application of engineering material with higher strength: ductile material, spheroidal graphite/sphero-cast instead of gray-cast iron), as well as the valve plate, working valves, and bearings which are equally subject to much higher loads than subcritical CO_2 applications.

A further problem results form the decreasing energy efficiency within transcritical CO_2 operation at ambient temperatures above about 28 °C. According to a manufacturer, this must be compensated by means of design measures (cylinder heads with separate high and low pressure chambers, parallel compressing), while an increase of approximately 15 % is indicated for the COP [Renz2007]. In comparison of the energetic behavior of CO_2 with R404A systems (relation of power consumption to

[28] When applying subcritical CO_2 in cascade systems, the maximum high pressure at about 40 bar is „approximately identical with the application limit of R410A at high pressure. For both refrigerants the high pressure levels lie above the previously customary values of R22 or R404A at 25-28 bar." [Große-Kracht2005]

cooling capacity, considered in connection with cumulative frequency of ambient air temperatures) this would include a significantly better energy performance of CO_2.

Market launch intervals: 10 years after the initial market launch (1998), the largest manufacturer of CO_2 compressors for *subcritical* operation offered a scope of 16 models corresponding to a cooling capacity range from 4,4 to 80 kW (until 2006 only 5 models). Each year the sales figures had nearly doubled from 2004 until 2007. During this stage the series production was achieved (app. 1.000 pieces/a). The application of the components does no longer happen exclusively upon the cooperation with selected system manufacturers, as in pilot phases, but also with wholesale and frigorists. The same manufacturer had developed two smaller basic models for *transcritical* operation (12 and 9 m^3/h piston displacement) until the second half of 2007 which provided operative experience in the supermarket segment (hypermarkets, discounter) since 2004 and 2006, respectively. A third larger model (about 17 m^3/h piston displacement, cooling capacity app. 35 - 40 kW) was in the testing phase at that time. During this development phase the application of compressors was restricted to selected system manufacturers. The unit sales demonstrated a dynamic comparable to the compressor types for subcritical operation, however with a time deferral of about 4 - 5 years past. The anticipation insofar seems reasonable that, given a similar development speed and demand, the introduction of series production with extended scope of products will be achieved in a couple of years.

Availability: In the middle of 2007, the system manufacture looking for CO_2 equipment in the MT range, was supplied by different producers with small high pressure compressors with piston displacement of about 12 m^3/h and cooling capacity of 20 - 25 kW according to design (Bitzer, Dorin, Bock). The cooling capacity of 40 - 50 kW necessary for the discounter segment is provided by parallel connection of two small compressors. For higher cooling capacities a correspondingly larger number of these compressors is used (i.e. at COOP-Wettingen 12 Bitzer 4HC4-20K for a cooling capacity of 2 x 161 kW). Due to safety, these redundancies are reasonable and absolutely necessary regarding the system’s partial load capacity. They are common practice at any larger supermarket store. With a larger compressor expected for the end of 2007 with about 17 m^3/h piston displacement and in multi compressor arrangement (6 compressors), one should be able to achieve cooling capacities of 230

- 240 kW. Previous scope of cooling capacity required by system manufacturers ranged from 250 up to 320 kW. Still there is the need for even higher capacities (requirement up to max. 800 kW).

Regarding compressors for transcritical operation, a range of different types of performance similar to the LT range is required which currently are not available. The existing component sizes would have to be complemented by continuous component sizes. Generally, availability here does not mean availability at affordable prices required by the extension of CO_2 technology (see chapter 2.2).

2.1.2 Valves, control devices and other components

The LT range (*subcritical operation*) today is completely covered by components produced in series ([Callesen2007a] and [Callesen2007b]. The need for development does no longer exist here, to the extent that customary optimization and redevelopment of components is not concerned. Regarding control technology, different producers also in this case offer standard versions for electronic refrigeration unit controls, overheating controls and integrated controls.

In connection with the MT range (*transcritical operation*) and like the development of compressors one must differentiate between low pressure and high pressure side.

For the <u>low pressure range</u> any component at the level of series production is available [Callesen2007a]. Among other things, this follows from the fact that since a long time such components designed for pressure level between 35 and 46 bar are available in standard versions for R134a or R410A systems, respectively (including heat pumps) and that they may also be used for CO_2 equipment.

This is applicable to magnetic valves, ball shut off valves, return valves, electronic expansion valves, filter dryers, moisture gauges, pressure controls, pressure transmitter, and safety valves.

In contrast, the <u>high pressure side</u> has to be characterized. The necessary supermarket system components designed for up to 120 bar were still not available as standard versions at the second half of 2007, but only as prototypes or standard versions used in industrial process technology.

Explanations to several components:

Magnetic valves:	Electronically activated shut off valves which are mainly used for the piping of liquids in order to interrupt the refrigerant flow to the expansion valve, if necessary.
Ball shut off valves:	Serve for locking of system parts, i.e. during repair and maintenance work.
Return valves:	Need for preventing the backflow of refrigerant in pipings.
Expansion valves:	Throttle device between low and high pressure side of the refrigerant system. Expansion valves control the overheating of the cooling medium vapor at the evaporator’s outlet and provide the evaporator with just as much refrigerant as it is able to evaporate. According to control, one distinguishes between thermostatic and electronic expansion valves.
Safety valves:	Prevent that the admissible operational pressure of the system is exceeded (blowing off).
Filter dryer:	Extract from the refrigerant cycle water, acid, and other contaminations in order to prevent corrosion, dissolution of the refrigerant, deterioration of the lubrification oils, and other things.
Moisture gauges:	Serve for indication of the moisture content (water content) in the refrigerant cycle.
Pressure controls:	Pressure switches which control or limit a special default pressure in order to protect the compressor against too high or too low pressure.
Pressure transmitter:	Serve for pressure measuring and pressure monitoring with corresponding electronical devices.

High pressure shut off valves (used after the compressor) on stainless steel basis were supplied by one producer as standard in industrial hydraulic version (ball valves) in the middle of 2007. To the extent, they were not specifically adjusted to the supermarket segment and were not available in any necessary nominal diameter. In the middle of 2007 the nominal diameters DN15 and DN20 were covered. Valves with nominal diameter DN25 and DN32 were still to develop. The system manufacturers desire valves for soldering (brass or steel with copper plating) because welding is not used in the supermarket segment. Serial production is strongly dependent on quantities in connection with comparably low differences in price between stainless steel and brass valves.

Pressure switches, transmitter, and controls were also still not available in standard versions for this market segment.

High pressure expansion valves: At the middle of 2007 system manufacturers were able to procure for transcritical CO_2 systems high pressure throttle valves which had been developed for industrial applications which required much service, were expensive and were estimated often as “overengineered“ in respect of the retail segment (FRI). Prototypes specifically designed for the retail industry were developed from several producers. Production numbers in the three-digit range of these prototypes specifically produced from steel for capacity ranges up to 240 kW might eventually be delivered to the system manufacturers until the second half of 2007. Prototypes exist in at least three different sizes (different nozzles according to necessary cooling capacity, smallest variant: 20 kW). While the individual parts such as nozzle set, magnetic clutch, drive, etc. are normally standard parts, the housing has to be adjusted to the high pressure level. For this purpose the prospective series production will use cast housings. According to the planning of the producer requested, the next step consisted in the development of the 0-series (cast standard) until the end of 2007 providing the possibility to gather further experience. Among other things, it was to check as to whether and to what extent the range of valve sizes was to extend. Provided the demand of system manufacturers is stable, in about one year a commercial valve series could be developed from the 0-series, for which numbers are calculated in the four-digit range and also a reduction of average price is expected.

Mechanical (thermostatic) high pressure valves have still not been developed. In comparison, electronic expansion valves offer by far more control alternatives and optimization options [Bachmann2004]. This is especially valid for high pressure fluctuations occurring within transcritical CO_2 operation. But they are significantly more expensive (about factor 4 - 5). The large difference in costs results, among other things, from the expenditure for controls and additional sensors.

Electronic controls for MT CO_2 range (individual control, control systems with monitoring; control systems with monitoring and optimization function) to date are only available as prototypes which are to develop for serial production for any size of retail supermarket from the discounter up to the hypermarket.

Heat exchanger for heat recovery: currently pipe bundle and coaxial heat exchangers can be used which comparatively are very expensive and have been developed for industrial application (versions in steel or copper pipe, designed for pressure levels from 100 to 200 bar). Desired is the development of cost-effective plate heat exchangers, if applicable also air-cooled pipe-lamella heat exchangers in micro-channel version and the adjustment to the smaller application range of supermarket refrigeration systems.

Regarding pressure controls, their design for higher pressure levels with transcritical operation is still necessary.

2.2 Aspects of costs / economical barriers

2.2.1 Required cost reductions

According to system manufacturers, the expansion of CO_2 technology in MT range presupposes a significant reduction in cost for the components aforementioned which currently are not available in serial production but have to be produced as individual items. The requirement of reduction in cost amounts to 50 % for compressors and valves, to 75 % for heat exchangers. The expectation is that such reduction in cost will make possible to enter serial production and this also from different suppliers.

Currently, additional costs for CO_2 systems (transcritical operation) in comparison with customary HFC systems are numbered with 30 - 40 %. This obtains for larger systems above ca. 150 kW; in the range around 50 kW additional costs can amount up to 80 %. In connection with larger systems advantages from reduction in cost follow from then accountable savings for piping as, due to smaller diameters, material can be saved for CO_2 technology in comparison with HFC systems.

As a condition of the material, the maintenance expenditure regarding time and costs is (dependent from the substance) greater for CO_2 systems as for HFC systems (among other things, low blow-off pressure, problem of fast valve replacement due to low triple point).

2.2.2 Threshold assessment for serial production

Concerning CO_2 systems used for LT range (with a lower pressure level), the threshold for serial production of the components has now been achieved, with an annual retail demand of 100 - 150 systems in Europe and a growth rate of 20 - 30 percent/a. In Switzerland, i.e., such systems are standard. In Denmark they are standard since 1st Jan. 07 (HFC prohibition above 10 kg refrigerant charge). In the other Scandinavian countries they begin to become standard.

In order to reach the threshold for series production of compressors used for transcritical CO_2 operation with higher pressure levels, an annual demand of at least

1,000 compressors p/a is deemed as necessary by the system manufacturers which would include new systems for about 250 - 300 discounters (according to 4 compressors/system). Regarding larger stores with 100 - 120 kW for MT range and about 8 compressors, this would correspond to about 125 stores p.a. as a minimum. In this context, system manufacturers do not want to become dependent from solely one supplier of components.

The higher demand for transcritical MT-systems compared to LT-systems is following from the fact that the components for CO_2 LT-systems and R404A systems are almost identical so that here the demand for components has a broader basis, while in the transcritical MT range it would result solely from the operation of CO_2 systems used in FRI.

On the other side, the component producers themselves anticipate a reduction in cost after the threshold for series production has been reached. Concerning the current costs for the central high pressure components used for CO_2 operation such as compressors or expansion valves, they are, as already described, pure prototype costs and hence one cannot compare them with those incurred by HFC systems. The component producers believe that, due to higher material expenditure following from the pressure level and more comprehensive electronic control, the costs will also be high in future.

2.2.3 Market assessment / necessary penetration rate

Roughly estimated, the sectors hypermarkets, consumer markets, discounters, supermarkets, and other medium size and large stores account for 60 % of the German food retail sector. 2006 these were about 30,000 stores in Germany [LZ-Report2007/2008]. If the average (high) life time of 15 years per refrigeration system is calculated for any store category in this sector, then an annual refurbishment rate of 7 % will result corresponding to about 2,100 systems/year. This magnitude is confirmed by surveyed retail agents whose quota for new systems in any store category reaches from 6 to 10 percent of the retail system inventory. This corresponds to about 800 - 1,300 systems for discounters, 600 - 900 for supermarkets, 100 - 160 for consumer markets, and 40 - 65 for hypermarkets, in total 1,540 up to 2,400 systems/year or on average almost 2,000 systems/year for these store categories. Beside replacement of old equipment due to wear and tear, the demand for new systems results also from disproportionate growth of individual retail chains, especially of consumer markets and in the discount sector (market extension, market launch), leading to the wreckage of old equipment before due date in the other retail sectors because on the whole the number of stores is regressing.[29]

The annual domestic demand for new and replacement systems thus amount to the magnitude of at least 2,000 items. Estimated 10 - 12 % of this annual new installation or refurbishment need would have to be equipped with transcritical CO_2 systems in order to reach the aforementioned threshold for serial production of components solely by means of demand from the German market.

An additional approach concerning the distribution of refrigeration systems with natural refrigerants including CO_2 systems is provided by the retrofit requirement of R22 systems until start of 2010 (and beyond) which can complied with through different HFC refrigerants or natural alternatives.[30] An estimation of the R22 system inventory is difficult. As a consequence from communication with retail agents one may conclude the following magnitudes as the lower estimation value: 2,000 systems in discount markets, 1,500 systems at supermarkets, 400 at consumer markets and 200 at hypermarkets (together 4,100 systems). Significantly higher numbers are indicated by DuPont ([Gerstel2007]: 7,300 FRI affiliates with R22 systems) and Epta Deutschland ([Tillner-Roth2008]: 26 percent of all markets with R22 systems) which in relation to the aforementioned 30,000 stores would amount to about 7,800 systems). A portion of these systems is attired and is falling under the refurbishment need already mentioned. For a portion of the systems with longer duration the anticipated replacement through new systems seems favorable which becomes necessary in connection with the change to natural refrigerants, as CO_2 cannot be used in now existing systems. Also accounting for this prospective system demand, the threshold for serial production of components and equipment should be reached with a market penetration of 10 percent of the new system and replacement system market.

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[29] REWE is planning to open 1.000 new REWE and Penny stores until 2012, EDEKA including NETTO Marken Discount in each case 300 new stores „in the coming years.“ Compare FAZ from 17th Nov. 07, 5th Dec. 07, 20th Feb. 08.

[30] The need for retrofitting results from the prohibition of servicing and maintenance of R22 freshware all over Europe as of 1st Jan. 2010 pursuant to (EC) No. 2037/2000 as well as full prohibition of R22 servicing as of 2015.

2.2.4 System and operational costs

According to the opinion of food retailing companies, system and component manufacture, the HFC substitution through CO_2 multi-compressor refrigeration systems for MT and LT will only then obtain a dynamical momentum within retail sector when the reduction in cost of system manufacture and component production can be pushed through and CO_2 systems are energetically better or on equal level with existing HFC systems. On one hand, the retail companies as „end customers“ know that current high system (investment) costs for MT CO_2 operation are due to their development and prototype character. On the other hand, they demand a decrease in cost on or at least near to the level of that for HFC systems. In contrast, system and component manufacturers claim that significant cost reductions of systems and components require their serial production through suppliers. This, in turn, would need a correspondingly increasing demand for equipment from food retailers.

Two further arguments should be mentioned. In particular system manufacturers and their supplier industry emphasize that contrary to the previous practice, when the demanding FRI sector makes a decision upon the purchase of systems, it will be necessary to account not only for the investment costs but also for the operational costs, and this even more than to date including the energy costs of the entire equipment. Partially higher investment costs for CO_2 systems could be compensated by favorable operational costs in connection with a corresponding system optimization by means of multiple energy saving measures and system control including external system monitoring and control (a fact that of course also obtains for HFC systems). Furthermore, several retail store chains see energy and GWP saving or “climate friendliness” as an “image factor“ and competition element of increasing importance.

As factors which could stimulate the demand for energetically optimized and climate-friendly refrigeration systems in FRI are considered i.e.:

- The strict implementation of the F-gas regulation to be expected (monitoring and tightness checks) which will make the HFC operation as a trend more expensive.

- It is conceivable that within the public discussion on climate policy further framework conditions for the operation of refrigeration systems such as increasing cost and/or the limitation of HFC consumption are imposed.
- Measures relevant for image and publicity such as labelling of refrigeration units, systems or markets under the perspective of energy efficiency and climate friendliness.

It is pointed to the fact that such framework conditions exist in different versions outside of Germany in Switzerland, Luxembourg, Denmark, Norway, and Sweden, thus those countries in which the bulk of alternative multi-compressor refrigeration systems for MT and LT (CO_2, cooling medium, etc) were installed in recent years. In addition, there is an increasing number of retail companies which try to use climate friendliness as a competition argument. The fact that an increasing sensibility of the retail customers for climate arguments is registered by retail companies is demonstrated by the growing willingness to put measures for energy saving under testing which previously were deemed as being rather client- and sales-hostile. This, i.e., concerns doors for MT shelves, which previously were rejected with the argument they would prevent “impulse purchases” and sale on the whole. Earlier, this argument was objected against covering of chest freezers with slide lids.

3. Further possibilities for improvement of energy efficiency / climate footprint in the supermarket: Special examination of the energy saving potential through covered refrigeration units

In the past energy efficiency of refrigeration systems has played no special role in connection with investment decisions of retailers, according to system manufacturers. Normally only the investment costs were relevant. Today, however, energy efficiency is gaining importance as a decision factor.

An overview of opportunities for the improvement of energy efficiency and CO_2 balance in supermarket refrigeration systems is contained in chapter 6 of the market overview.

Continuous covering (day and overnight) of refrigeration units with slide lids (chest freezers) or doors (shelves) is seen as an important option for energy saving. Generally, the saving potential is numbered at up to 40 % of the energy consumption of the open, also at night not covered refrigeration unit (see market overview, chapter 6.1). Equipping and retrofitting of refrigeration units, first of chest freezers, by means of continuous covers began about ten years ago. Beside energy saving, a crucial motive for covering refrigeration units is the improved temperature maintenance for the chilled goods.

In order to better assess the importance of this potential a present survey about the state of refrigeration unit covers in German supermarkets was performed in connection with relevant retailers (in the middle of 2007). In addition, we would like to point to the current debate in the Netherlands where covering of refrigeration units has become the subject of public discussion for energy savings in the supermarket area for the first time.

3.1 Inventory and covering of refrigeration units in Germany in the middle of 2007

Because data relating to the current state of refrigeration covering in Germany were not present and the information from refrigeration equipment manufacturers, retrofit companies and operating companies show a wide margin, a survey with the most important retail chains upon the covering of refrigeration units was carried out in the middle of 2007.

The survey comprised companies with all together about 28,600 stores[31], divided between about 14,440 discounters and 14,140 other stores (hypermarkets, consumer markets, supermarkets as well as a certain number of small traditional food retail markets; sampling year 2006/2007). The aggregate number of stores in these categories matches approximately with the information from the EHI-Retail Institute, Cologne, which for 2006/2007 assumes 26,170 hypermarkets, consumer markets, discounters, and supermarkets in Germany [EHI2007]. The number of markets analyzed here is somewhat greater because also a number of smaller, traditional food retail markets entered into the survey by reason of the aggregate assessment for EDEKA. The companies were requested to provide their aggregate number of chest freezers and freezer cabinets/shelves according to LT and MT range in linear meters (lm), as well as to the share estimated of refrigeration units with day/night covers. Counters, sets (chest freezers with cabinet up-build) and similar other refrigeration units were not analysed.

For 2006 the LZ-Report 2007/2008 assumes 806.4 km chest freezers and freezer cabinets related to 51,000 stores – including also small stores with only small refrigerator equipment. This corresponds to the magnitude given in table 1 (816.0 km), even if it should have been estimated a little bit too low due to the higher number of stores.

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[31] Entered: Rewe-Group, Tengelmann-Group, Schwarz-Group (Lidl, Kaufland), Aldi-Nord and -Süd, Edeka (incl. Marktkauf and Netto Marken-Discount), Netto-Nord, Norma, Coop/Kiel, Tegut. No response: Metro-Group.

Table 1: Inventory of refrigeration units in Germany in the middle of 2007, structural data

	span/store (lm)	∅ per store (lm)	aggregate inventory (lm)
LT chest freezers	8.5 - 72	27.5	785,050
LT cabinets	0 - 15	1.1	30,970
MT chests	0 - 45	2.3	66,575
MT shelves	8.3 - 100	21.0	599,495
Sum			1,482,090

Basis: information about 28,528 affiliates; lm: linear meter. Own survey Öko-Recherche.

According to linear meters, 55.1 % from almost 1,500 km refrigeration units fall under the LT range and 44.9 % under the MT range. Dominating were LT chest freezers (53 % according to lm) and MT shelves (especially for dairy products, approximately 40 % according to lm). The differences of the equipment of the individual retail chains and store categories in accordance with the refrigeration unit categories are large which is expressed by partially large „spans“ of the individual refrigeration units (table 1). The average refrigeration unit equipment of the discounter amounts to 31.5 lm per store, whereas it is less for the remaining retail sector with 23.4 lm.

Table 2 provides information about the degree of covering installed upon refrigeration units. Again calculated in linear meters, in the middle of 2007 half of the refrigeration units were equipped with slide lids or doors and thus also closed by day when chilled goods are not taken (49.9 %). While LT chest freezers are closed for more than four fifths (85.9 %) and LT cabinets are completely closed, this is only valid for one half of MT chests (49.6 %) and almost not for MT shelves (0,2 %). To the extent, in particular MT shelves for dairy (DaiPro), sausage/meat or similar products, which previously were permanently open, carry weight accounting for about 40 % of the entire length of refrigeration equipment analysed by this survey.

Table: 2 Number of covered refrigeration units in the middle of 2007

	Total refrigeration units			inventory discounter		inventory other retailers	
	in sum (lm)	of these "covered"		in sum (lm)	of these "covered" (%)	in sum (lm)	of these "covered" (%)
		in lm	in %				
LT chest freezers	785,050	674,687	85.9	454,700	95.5	330,350	72.8
LT cabinets	30,970	30,970	100.0	-	-	30,970	100.0
MT chests	66,575	33,000	49.6	33,000	100.0	33,575	0.0
MT shelves	599,495	1,300	0.22	307,345	0.0	292,150	0.44
Sum	1,482,090	739,957	49.9	795,045	58.8	687,045	39.7

Basis: Information about 28,528 affiliates; lm: linear meter. Own survey Öko-Recherche.

Significant differences between discounters and other supermarkets analysed by this survey not only become apparent in respect of the refrigeration equipment, but also in respect of refrigeration unit covering.

With discounters, the share of closed LT chest freezers amounts to above 95 %, with other stores it is lower at approximately 73 %. Open LT chest freezers (mostly "special offer" devices) do not play any role with discounters, while with other supermarkets they make up 9 % of the entire refrigerator inventory. Freezer cabinets (closed) are also not relevant for the discounter, while they are more often used by other stores. Almost permanently open LT DaiPro shelves account for 38.7 % of the entire equipment in linear meters with discounters, contrasting with 42.5 % of the supermarket segment.

In the middle of 2007, again measured by the face length per refrigeration unit, the aggregate share of closed units against the entire equipment analysed amounts to 58.8 % with the discounter, while for the other supermarkets it is 39.7 %. The strong expansion of the discounter segment in the last years obviously has led, on average, to a modernized inventory of refrigeration units in comparison with the supermarket sector.

According to information of the surveyed food retailers, in the middle of 2007 about 87 % of the normally *open* refrigeration units had at least an overnight cover (table 3). This is valid for nearly one half of the open LT chest freezers, for more than one quarter of MT chests and for 98 % of open DaiPro shelves. However it is questionable whether these overnight covers are regularly used. In particular, this is valid for chest freezers which require that the lids are put on and off by hand, if necessary. In connection with larger stores, this should often not be the case due to the expenses for personnel and time.

Table 3: Open refrigeration units with overnight cover in the middle of 2007

	aggregate inventory (lm)	of these with overnight cover	
		in lm	in %
LT chest freezers	110,363	52,890	47.9
MT chests	33,575	9,000	26.8
MT shelves	599,495	587,245	98.0
In sum	743,433	649,134	87.3

Trend: Since the second half of 2007 the share of open chests has further reduced due to the retrofit of open chests with slide lids, on one hand, and the replacement of old refrigerators through new ones, on the other hand.

In 2007, the first retailers reported upon ongoing testing with glass doors for MT shelves. The investigation comprised energy consumption, temperature maintenance and the issue of a possible obstacle concerning sale. Apart from logistic aspects (need for space), the last one is expressed as the main argument against the use of glass doors for DaiPro shelves (and occasionally against the covering of freezers). Quantitative results from such testings, however, were still not available.

In summary, table 2 and 3 make clear that today a rather high degree of covering is achieved for LT units, while in connection with MT chests and in particular MT shelves energy saving does not play any or only a small role.

3.2 Figures based on experience about energy saving potential through covering of refrigeration units

The energy saving potential through covering of freezers and display refrigerators/shelves is generally determined by means of pre-/after-comparison in relation to the retrofit of freezers with slide lids or cabinets/shelves with doors.

In the middle of 2007, the installation of refrigeration units with slide lids or doors was mainly a retrofit business. The manufacturers of refrigeration units themselves do not produce slide lids or doors, but procure them in large numbers from big glass firms for standard refrigeration units. On the other side, the retrofit market is the domain of small retrofit companies.

Finally, it should be noted that several issues are solved differently by individual producers such as the prevention of the production of condense water through slide lids or the fogging of shelve doors. Where a frame heating or glass heating is used, the energy saving effect through covering is a little bit reduced. There are also laminations that prevent fogging without consuming energy.

3.2.1 Freezers

A special concern related to retrofit of chest freezers is the adjustment of their control technology. This concerns the reduction of the amount of circulating air in the unit and of defrosting phases, LT and MT chests being largely different. The first measure can be reached by corresponding rotation control of the fans/ventilators (rotation reduction to 30 - 40 % of default value for LT chest freezers, significantly lower for MT chests) or assembly of different ventilation blades. According to information from trade and operating companies, a reduction to two defrosting phases per week against the recommended two defrosting phases per day is possible in connection with covered LT chest freezers. When covering MT chests, normally no change of the defrosting period takes place.

Trade and retrofit industry in Germany indicate[32] energy saving achieved by this measure is at nearly 40 % with LT chest freezers and at nearly 10 - 15 % with MT chests (comparison of open refrigerators without overnight cover with closed freezers, [Remis2007]; [Pan-Dur2007]). The Dutch ECN (Energieonderzoek Centrum Nederland, [ECN2006]) indicates 40 - 52 % as saving potential for horizontal LT refrigeration units through covering, while the lower value is related to units with night cover. Similar magnitudes of 40 - 55 % are reported in two studies of the Dutch engineering company Van Beek Ingenieurs (Arnhem/NL, [Van Beek2003, 2004]).

In individual cases the operating companies of German supermarkets declared that the energy saving values through covering of LT chest freezers reported by trade and retrofit firms are too high and that only savings at approximately 10 % (against units with overnight cover) are achievable.

3.2.2 Refrigerated shelves

The energy saving through the retrofit of MT shelves for meat, dairy products, and vegetables with glass doors is reported in a test report of the company Remis (comparison shelve with doors against shelve with overnight cover) at about 49 % [Remis2007], where the saving effect resulting from mere overnight roller blinds (against shelves without overnight cover) makes up 20 - 25 %. The Dutch ECN (2006) reports an average value of 55 % energy saving from measurement in practice, where, i.e., an uncommon high saving value of 86 % is not entered into this average value (refrigerated wall shelves as part of an ammonia/cooling medium system [AGM2004], a fact that might depend on an unfavorable condition of the open refrigeration unit (low effective air film, [Remis2007]). The saving through widespread night roller blinds has to be deducted from this saving effect which in this study is accounted for 18 - 20 %.

[32] The company Remis communicated test reports for 6 LT islands from three markets where the energy saving through covering against open refrigerators was at 40.5 % and 58.6 %. The energy consumption was calculated from the connection performance after measurement of the running times of compressors, ventilators, and thaw heaters of the individual units [Remis2007].

3.2.3 Decision 2007: obligation to cover refrigeration units in Amsterdam

The reasons for two judgements of the Dutch Raad van State (state council, supreme administration court) from 12th September 2007 referred also to the cited surveys [Van Beek2003] and [ECN2006] about energy saving potentials by means of covering refrigeration units and freezers. In these judgments the claims of several Dutch supermarket operating companies against orders of the Amsterdam authority for environment and construction supervision and the environmental authority Ijsselmond was rejected, to retrofit any LT and vertical refrigeration units by means of 90 % overnight and day covers as of 31st December 2009 [Raad van State2007]. Such orders rely upon an imposition of the Dutch environmental law from 1998 due to which supermarkets with an energy consumption of more than 50,000 kWh/a may be subject to obligatory measures for energy saving. Until 31st October 2008, an energy saving rate of 32 % is to achieve, compared to the reference year 1995. This concerns measures which imply that the amortization period for buildings and equipment is below five years. The judgements are based upon the amortization periods for day covers defined by [ECN2006] which are on average 2.9 years (+/- 0.9 years) for vertical refrigeration units and 2.4 years for horizontal freezers (overnight covers: 1.8 - 4.1 years). The cut-off date 31st December 2009 refers to (EC) No. 2037/2000 (use ban of HCFCs such as R22 after 31st Dec. 2009 as new product). Apart from aspects related to administration law, the claiming supermarket companies objected against the day cover of vertical refrigeration units, this was generally not accepted as representing the state of the art, incurring additional costs for maintenance and cleaning, reducing the effective sales room and impairing ‘impulse purchases ’. Furthermore, the amortization period for covering of refrigeration units and freezers were longer than five years.

4. Possible and necessary measures for the promotion of the use of natural refrigerants in FRI

Public promotion measures: In the past, the development of refrigeration systems with natural refrigerants including CO_2 was promoted in Germany and the EU in several ways. [33] Concerning the advanced state of system technology, one should not anticipate that system manufacturers as well as component producers will orient towards a research-based development promotion today.

The situation is otherwise with technology and market launch. While on the level of the Länder[34] only in individual cases promotion funds for the financing of such projects are available, on federal level the "key points for an integrated energy and climate program" of the government ("Meseberg" paper) adopted in August 2007 provide under point 23, the "reduction of the emission of fluorinated greenhouse gases", the „promotion of the development and market launch of energetically high efficient and climate friendly refrigeration systems with natural refrigerants within the climate protection-efficiency fund" ("Klimaschutz-Effizienz-Fonds"), where the "promotion … according to TEWI contribution shall be graded and realized temporally in degressive order." The realisation of a share of 50 % of natural refrigerants until 2020 is seen as an essential requirement in order to enforce the expected effect of key point 23 (reduction of F-gas emissions by about 8 mill. t/CO_2 equ.), apart from the legal definition of the leakage rate of 2 % for stationary refrigeration systems [Umweltbundesamt2007].

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[33] See section 1. State of the art; most recently within EU-"Life"-Project "Development and demonstration of a prototype transcritical CO_2 refrigeration system" (200 5- 2007); [European Commission2005], [Madsen2007].

[34] The Department of the Environment of Baden-Württemberg has created a subprogram „Energy efficiency in MSE. Operational processes and cross-section techniques," containing a promotion section "Process cooling" in May 2007. Here, measures for cooling machines and cooling systems may obtain a promotion. Upon evidence of a relevant energy saving a promotion of maximally 15 percent of the investment costs is possible. According to EU definition (max. 250 employees, annual turnover below 50 mill. EUR), only small and medium companies are able to be considered as applicants. Competent is the KEA Klimaschutz- und Energieagentur Baden-Württemberg GmbH, Karlsruhe.

4.1 Proposal for promotion of refrigeration systems with natural refrigerants pursuant to key point 23

Pursuant to the targets of key point 23, the following proposals are made to serve for the promotion of the installation of refrigeration systems with natural refrigerants used in the LT and MT range within the whole food retail industry. As a contribution that seeks to improve the greenhouse gas balance of the Federal Republic of Germany, they are projected to

- promote the distribution of pilot systems;
- facilitate the threshold to market penetration with corresponding standard systems;
- beside the installation of new equipment (need for extension), promote the use of natural refrigerants also in connection with the replacement of systems due to wear and tear, as well as the replacement of R22 systems;
- motivate the increase in energy efficiency of refrigeration systems with natural refrigerants; and
- support further qualification of the refrigeration technology trade concerning the handling of natural refrigerants.

Apart from funding which in first instance aims for the distribution of natural refrigerants, the proposal further contains a competition to raise awareness, which is to reward any system with natural refrigerants and outstanding low TEWI and which also may be carried out, if the funding cannot be met (compare chapter 4.2).

<u>Target group</u>: The target group of the funding proposal are retailers, system manufacturers, and refrigeration technology trade. The entitlement to submit their application holds for any retail company seated in Germany. The promotion request will be filed by the retailer in respect of a special store in Germany. Hereby, the equipment related to the application is either new systems in new constructed or replacement systems in existing stores, where the operating companies of R22 systems to be changed-over in the near future represent a special target group.

Funding instrument: Not redeemable subsidy payment for additional costs incurred by refrigeration systems in the retail sector, subject to exclusive use of natural refrigerants (thus promotion of natural refrigerants in LT and MT range, not of cascade systems with CO_2/HFC, however of systems with natural refrigerants + cooling mediums), graded in accordance with as to whether

- it is a new system in a new or existing market; or
- a replacement of an old R22 system.

Furthermore, the promotion will be accompanied by a training program based on reduction in cost for the refrigeration servicing and technology trade related to the planning, construction, operation, and maintenance of refrigeration systems. Within the funding also information brochures for the trade and the retail segment should be prepared, as well as accompanying articles for scientific journals.

Additional costs of systems with natural refrigerants: The funding for refrigeration systems with natural refrigerants is a consequence of the climate policy constraint aiming at the reduction of CO_2 emission, as well as the fact that CO_2 refrigeration systems compared to conventional equipment require higher investment costs because transcritical systems are currently only in the phase of being launched into the market so that they still cannot represent the standard system. Also prospectively ("in three up to five years"), system manufacturers expect that system costs will be 20 - 25 % higher, though the saving of operational costs will still be possible [Tillner-Roth2008].

Concerning the funding and the level of funding, a difference should be made between new systems at a new built or existing store, on one hand, and the replacement of old R22 systems at existing stores, on the other hand, in order to provide an incentive for immediate change towards natural refrigerants, away from R22 being harmful to the ozone layer and the climate. Therefore, a potential residual value of the old system, independent from the age of the system, is taken into account (about 35 %) when old R22 systems are replaced by new systems based on natural refrigerants. In table 4 an estimate of additional investment costs for CO_2 systems against conventional technology is shown according to store categories (higher costs in connection with R22 replacement systems due to inclusion of the potential residual value of the old systems).

Table 4: Additional investment costs for CO_2 systems (new systems and R22 replacement systems)

Store categories	Additional costs for CO_2 system per store in relation to		CO_2 reduction potential in CO_2 equ./a.
	New systems in new or existing stores	R22 replacement systems including the old system's residual value	
Discounter	10 - 40 K€	40 - 80 K€	5 - 10 t
Supermarket	40 - 180 K€	180 - 360 K€	50 - 100 t
Hypermarket	120 - 500 K€	500 - 1,000 K€	500 - 700 t

The additional costs for systems based on other natural refrigerants such as ammonia or hydrocarbons are normally of a similar magnitude and in individual cases they are below a small margin of those for CO_2 systems. Therefore, one can assume that also ammonia and hydrocarbon systems will benefit from the general funding of natural refrigerants so that the inventory of systems will include their wider range.

Funding level, basis of calculation: The subsidy payment is to cover a portion of the estimated additional costs for systems with natural refrigerants (as a rule 20 - 50 percent) and will be measured according to the sales area per square meter (food) in the year of new system's commissioning. There are also other reference values conceivable (such as cooling capacity installed; linear meters of refrigeration units). In connection with the detailed formulation of the funding terms one should observe that an incentive for energy-efficient solutions is created in relation to the corresponding impositions based on minimal size and the condition of the refrigeration systems, whereby any misuse is prevented which should follow from eventual „over-funding".

The subsidy payments proposed in table 5 are graded in intervals and degressive order according to their level (reduction to one half within promotion period). The basic contribution related to sales area for R22 systems is twice as high as for other new systems (considering the value of the old system and a special incentive for immediate change).

Table 5: Subsidy payments for systems with natural refrigerants in Euro/m^2 sales area (food) after the year of commissioning

	2008	2009	2010	2011	2012
New systems in new and existing stores	15	13	11	9	7
R22 replacement systems	30	26	22	18	14

The proposal renounces to make any defaults concerning the real energy consumption because this would temporarily defer the settlement of the program and impose bureaucracy obstacles (final settlement of the subsidy payment only after one full year, etc.). The proposal does also not recommend to make any differentiation between the store categories. Larger stores and systems slightly benefit from the calculatory basis related to area, what seems reasonable from the ecological perspective (climate friendly change of larger refrigerant volumes).

The funds, despite the resulting dynamisation, should not be paid out according to the Greyhound Principle which means that the limited funds are granted according to the submission date. Instead of, the applications should be prioritized according to the adequacy of the concept including the energy efficiency. One should attempt to address a multiplicity of retailers in order to avoid the concentration of the funds granted to a couple of especially decisive retailers or retail store chains.

Volume and use of funds: When the program's volume of funds is based on 22.7 mill. EUR within a duration of four and a half years (7/2008 - 12/2012), then it will be possible to encourage the annual construction of 265 new systems with natural refrigerants (new systems: 150 discounter and 50 supermarkets/hypermarkets; R22 replacement systems: 50 discounter, 15 supermarkets/hypermarkets) as of 2009. In accordance with the threshold estimates for series production, this would considerably facilitate the market launch of CO_2 systems. The use of funds could be allocated to the different program items as shown in table 6. The aggregate number of systems falling under the funding program is largely dependent on the dynamic in both sectors "new systems" and "R22 replacement."

Table 6: Use of subsidies for natural refrigerants (thousand EUR)

	2008	2009	2010	2011	2012
Promotion of new systems	1,200	2,500	2,500	2,500	2,500
Promotion of R22 replacement	900	1,800	1,800	1,800	1,800
Training of refrigeration technology trade	300	400	400	400	400
Program management	100	200	200	200	200
Costs of materials and subcontracting	200	100	100	100	100
Total costs	2,700	5,000	5,000	5,000	5,000

4.2 Proposal for a competition „Award for Energy-efficient Refrigeration Systems in Supermarkets"

The dimension of the proposed program is appropriate in order to create a momentum in a market whose dynamic regarding the stakeholders (component manufacturers, system manufacture, retailers) is currently restrained by reason of existing thresholds related to costs. Apart from that, further climate protection measures for supermarkets are of great importance, such as:

- Increasing awareness for the climate relevance of refrigeration systems in food retailing, both among the retailers themselves as among professionals and in the public; and
- Support of the public acceptance and "demand" for climate friendly refrigeration systems as well as encouragement of their "image".

At the same time one should consider that natural refrigerants are only able to exploit their ecological advantage on the background of existing solutions – no GWP due to refrigerant – when from the point of view of energy they are at minimum equally efficient as refrigeration systems with conventional refrigerants [Bovea et al.2007]. Hence the goal of the competition („Deutschland sucht den klimafreundlichen Supermarkt") is to discuss the reduction of energy consumption of supermarket refrigeration systems in public and to further their awareness.

Concept of the competition: Subsequently, it should be considered to link the aforementioned funding measures (if granted) with a publicity competition which will award the prize for *new refrigeration systems with natural refrigerants and a low TEWI value*. As the case may be, the competition could also be carried out without the funding programme, even if its publicity should not gain the same large effect in the public. Contrary to the promotion program which does not include energy consumption monitoring, this award will require the exact measurement and documentation of the systems' energy consumption and thus the corresponding effort of their operating companies to save and balance any energy consumed. The target group of the competition are those stakeholders (component and system manufacturers, retailers) which are willing to set prospective standards for low energy consumption of refrigeration systems with natural refrigerants and, as such, are able to take on the function of motivators. From this competition would also benefit many other measures for energy saving aiming at the optimization of system components, system operation, and refrigeration units which may contribute to the reduction of TEWI values of refrigeration equipment. The competition period should parallel the promotion of new systems with natural refrigerants.

Target group: Food retail industry according to store categories (discounter, supermarkets, hypermarkets) in Germany. Like the funding, the award is designed in first place for the operating company of the system which finally is accountable for the system's layout and energy saving measures. As refrigeration systems are to award, the award may also consider and name system and component manufacturers (type of system, technical specifications, etc.) which will have a special effect in the professional public. The subdivision according to store categories seems necessary by reason of different technical conditions and designs (following the system's size) and it will also enable to consider a large scope of retailers and system manufacturers.

Criteria: Natural refrigerants, the lowest TEWI as possible, new systems (not older than 3 years)

- The system is only operated with natural refrigerants (hydrocarbons, NH_3, CO_2) or cooling mediums, respectively. As “system” is counted any multi-compressor systems including refrigeration units connected, not the comprehensive inventory of refrigerators and units of a store (thus, i.e., multi-compressor refrigeration system including standalone units).
- The award will be given for systems with the lowest possible TEWI value per linear meter refrigeration unit and year because the reduction of energy consumption is to award, beyond the use of natural refrigerants. As upper limit for the TEWI value are valid 2,800 kg CO_2/a*m for the discounter, 2,000 kg CO_2/a*m for the supermarket and hypermarket (see part 2 of this report). Within the calculation base the factor for indirect emissions caused by energy consumption is settled with 0.616 kg CO_2/kWh in accordance with most recent calculations of the Umweltbundesamt.
- The energy consumption must be measured and documented exactly for each day over the period of one year.
- The target of the competition is to increase the share of new systems with larger energy efficiency and reduced greenhouse gas emission. Systems that participate in the competition should therefore not exceed a three year commissioning period. During the entire competition period a system can only be awarded once.

Award form: The prize awarded within the competition may be a combination of a symbolic aiming at public awareness (publicity) as the main aspect and a (limited) financial incentive. For that purpose, it is conceivable to award a prize or a quality seal, respectively, which may also be used for PR and marketing purposes, and an acknowledgement prize (EUR 5,000 - 10,000). The additional expenditure for the measurement of energy consumption and documentation can serve as basis for the acknowledgement prize. Whether the award is an “environment angel“ or a referable certificate („Award with the competition…”) should be clarified during the detailed preparation of the competition’s concept.

Competition costs: An estimated calculation according to expenditure for work, costs of materials, the jury and event costs for the stages preparation / competition / evaluation and presentation amounts to about EUR 17,000 net for the first year: In the following years, the preparation costs would be lower due to decreased expenditure (about 10,000 Euro). The costs for the awards depending from the level of the acknowledgement prize (EUR 5,000 - 10,000) and the number of systems to be awarded will amount to about EUR 45,000 - 90,000 (according to the proposal aforementioned 3x3/year). With a duration of five years the costs amount to about EUR 510,000 net, corresponding to about 2.2 % of the aggregate sum of the funding expenditure (table 6) and competition costs (table 7).

Table 7: Competition costs „Energy-efficient supermarkets with natural refrigerants“

	Award prize level 5,000 €	Award prize level 10,000 €
Award prizes for 9 systems/a over 5 years	225,000 €	450,000 €
Coordination costs	57,000 €	57,000 €
Aggregate costs competition	282,000 €	507,000 €

Competition evaluation: In order to inaugurate „standards“ the energy consumption data and TEWI values collected during the competition should be evaluated and published together with other relevant system data to make them available for the professional public and set “standards”.

Further aspects to clarify: Sponsor of the competition (partners from food retail industry) and corresponding documentation, panel jury, detailed determination of the aim in respect of participant quota, participation of the professional and general public, modes of communication (press, professional journals, internet, etc.), compliance with evaluation criteria and the like, legal matters, contractors for the settlement modalities and organisation, etc.

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