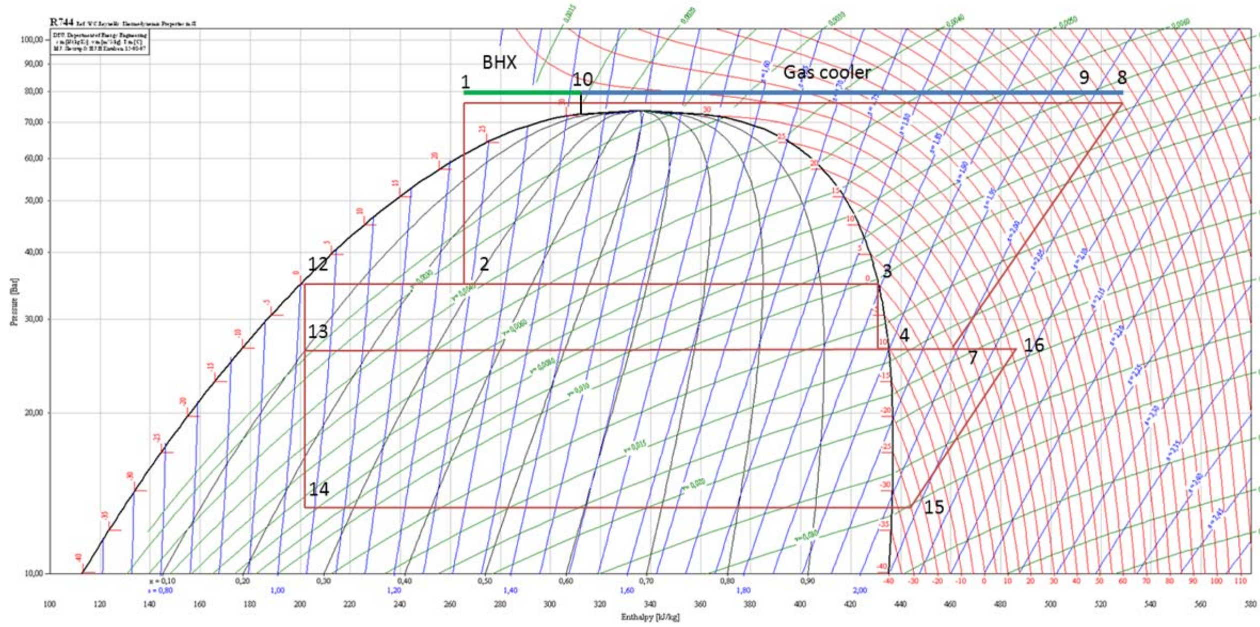

Figure 3 R744 pressure – enthalpy diagram with transcritical refrigeration cycle and gas cooler and borehole heat exchanger shares for the refrigerant desuperheating and cooling

Energy consumption objectives based on manufacturer's data were calculated with the simulation model. The yearly energy consumption of the refrigeration plant was calculated with a COP of 3,7 for the low pressure compressors and of 2,7 for the medium pressure compressors. Thus, a specific primary energy consumption of 256 kWh/m^2.a could be targeted for the refrigeration system, representing a reduction of about 7% of the refrigeration energy needs of a standard supermarket.

To validate the concept, sensors and meters were installed. The refrigerant pressure and temperatures on the high pressure side and after the evaporator groups are measured every minute and enthalpies are automatically calculated over an interface with thermodynamic properties tables based on RefProp. Power meters have been installed for each compressor group and for each major electrical component like the gas cooler or pumps. Heat and cold meters have been installed in each water circuit. Power calculation in the refrigerant circuit could not be achieved until now because of measurement issues with the installed coriolis mass flow meters. Thus, only enthalpy differences between the in- and outlet of each heat source and heat sink could be calculated.

2.4. Lighting concept

Natural light has complex physical and psychological effects on the human body; it supports well-being, affects positively the productivity and can significantly contribute to energy savings. Using day lighting also has aesthetic benefits that encourage customers to enter stores and has positive effects on sales (Edwards, 2002). The preliminary study on the energy use in over 300 subsidiaries of the food retail chain showed that lighting energy constitutes about 29 % of the total energy use of a standard supermarket with a median primary energy demand of 118 kWh/m^2.a, and is therefore an important area for energy conservation. A new daylight concept using 28 triple glazing skylights with integrated reflection gratings was developed, simulated and implemented. A restrictive constraint by using daylight is to preserve the food products quality from damaging direct sunlight. To overcome this issue and allow harvesting the maximal diffuse light quantity, the number, orientation and disposition of the skylights were optimized in a daylight study supported by a dynamic simulation with the software packages Radiance/Daysim/TRNSYS. The results of the simulation showed that a reduction of about 30 % of the energy use could be reached in this supermarket in comparison with a standard supermarket without use of daylight. The basic lighting of the sales room and the warehouse is achieved with T5 fluorescent lamps. Directional spotlights with metal-halide lamps ensure the effect lighting for cosmetics, food and promotional items. The artificial basic lighting is dimmable and controlled by mean of light meters to ensure a minimal illuminance level of 700 lux at a height of 1,30 meter in the sales area. Through this, the output of the electric lighting system can be adjusted in response to changing amounts of natural light. All the lights are turned off from supermarket closure at 8 pm to opening at 7 am and on Sundays. Outside the opening hours, the basic lighting is dimmed at 30 % of the nominal power for preparation tasks.

3. MONITORING

The aim of the monitoring phase was to continuously optimize the energy efficiency of the different systems, with a special focus on the refrigeration plant and the lightings, while collecting additional knowledge on the energy operation of the supermarket and identifying areas with further optimization potentials.

3.1. Refrigeration plant

The refrigeration plant of the new supermarket is the first transcritical R744 chiller which was build and commissioned by the manufacturer and has therefore a prototype character. Hence, after commissioning, the first goal was to produce cold and heat for the normal and safe operation of the supermarket.

The following optimizations were implemented during the first monitoring year to improve the energy efficiency of the plant:

- Just after the commissioning, the high pressure was controlled in subcritical operation at a constant value of 65 bars. The implementation of a condensing temperature dependent high-side pressure control was first achieved during summer 2011, leading to a reduction of the compressors work.
- During the winters 2010/2011 and 2011/2012, the heating cycle was supported by switching from the subcritical operation to the transcritical operation to benefit from higher temperature levels. This control strategy was changed at the beginning of 2012

by supporting the heating with the heat pump compressor exclusively in subcritical operation.

- The evaporation temperatures of the cooling points were first fixed values. In summer 2011, a control software was implemented which continuously optimizes the set values and the compressors rotation speeds.

In 2011, the specific primary energy consumption of the refrigeration plant reached 298 kWh/m^2.a and laid 14 % over the objective. These results are nevertheless encouraging considering the prototype character of the plant and the fact that optimizations were implemented step by step during the first year.

Figure **4** depicts the shares of the different components on the high pressure side in cooling the R744. Over the whole year 2011, about 25% of the R744 heat is decoupled by the heat recovery system, amounting to 47,8 MWh. In winter, this share rises to over 50 %. Without heat demand in summer, the gas cooler contributes on average 90% of the desuperheating and cooling. The remaining 10 % are ensured by the borehole heat exchanger. The mean value of the power consumption of the borehole heat exchanger pump amounted to 4% of the power consumption of the compressors power consumption, so that an energy efficiency gain of about 6% could be reached by the use of the borehole heat exchanger.

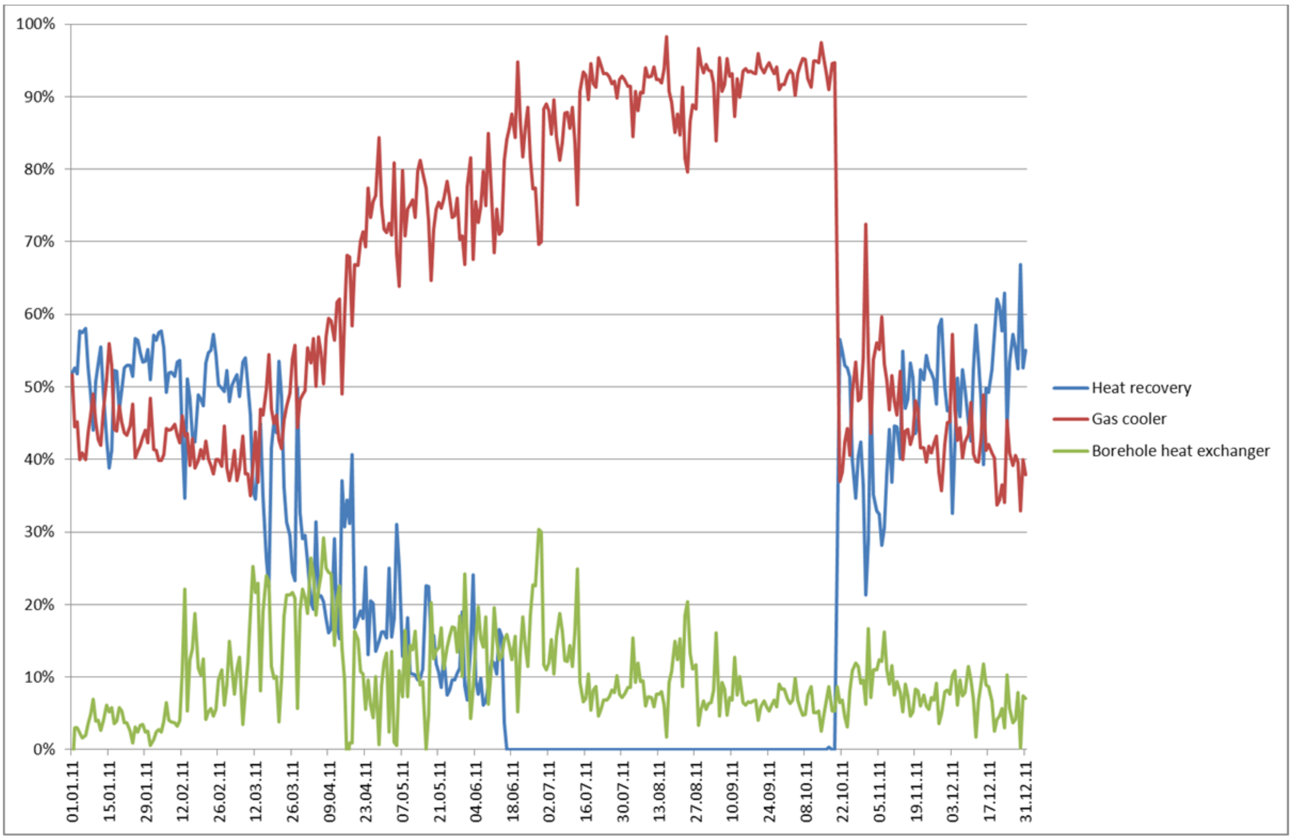

Figure 4 Shares of R744 enthalpy differences of the heat recovery system, the gas cooler and the borehole heat exchanger during year 2011

3.2. Heating / cooling

The new heating and ventilation concept has been evaluated in terms of energy efficiency and comfort.

Thermal comfort analyses in a supermarket are primarily used to assess the working conditions of the supermarket staff. The methods described in the norms EN ISO 7730 and EN 1525 were used. The boundaries and the corresponding PMV and PPD indexes of each category are compiled in Table **3**.

Table 3 Category boundaries for winter and summer period and PPD/PMV indexes

Building Type	Category	Minimum value for heating periode in °C for / Maximum value for summer period in °C	PPD* %	PMV**
Department store (ALDI), 1,6 met	I	20.0 / 24.0	< 6	-0.2 < PMV
	II	19.0 / 25.0	< 10	-0.5 < PMV
	III	18.0 / 26.0	< 15	-0.7 < PMV

The comfort categories I, II and III respectively represent a high, a moderate and a low level of comfort expectations. Figure 5 depicts the dependency between the hourly average of the indoor air temperature and the daily moving average of the outdoor air temperature in 2011. The three comfort categories are represented by the intervals between the horizontal lines for winter and summer conditions. In winter, the indoor air temperatures fall below the category I only in 16% of the time during the first year and category III was not maintained in only 1 % of the time. Category I was exceeded 17 % of the time and only 1 % of the measurements did not uphold to category III.

In summer, the room temperatures exceeded the category I threshold during only 2% of the time. Temperatures fall in category II about 40 % of the time in summer. 11 % were in category III and 2 % outside category III.

This analysis shows that a good thermal comfort could be obtained in winter as well as in summer already during the first operation year. Some enhancements of the comfort conditions are possible by low outside air temperature through additional heating by an enhanced heat pump operation. In summer, no heating occurred unlike the results of the simulation. Nevertheless, a slight heating could be foreseen to enhance the comfort during this season.

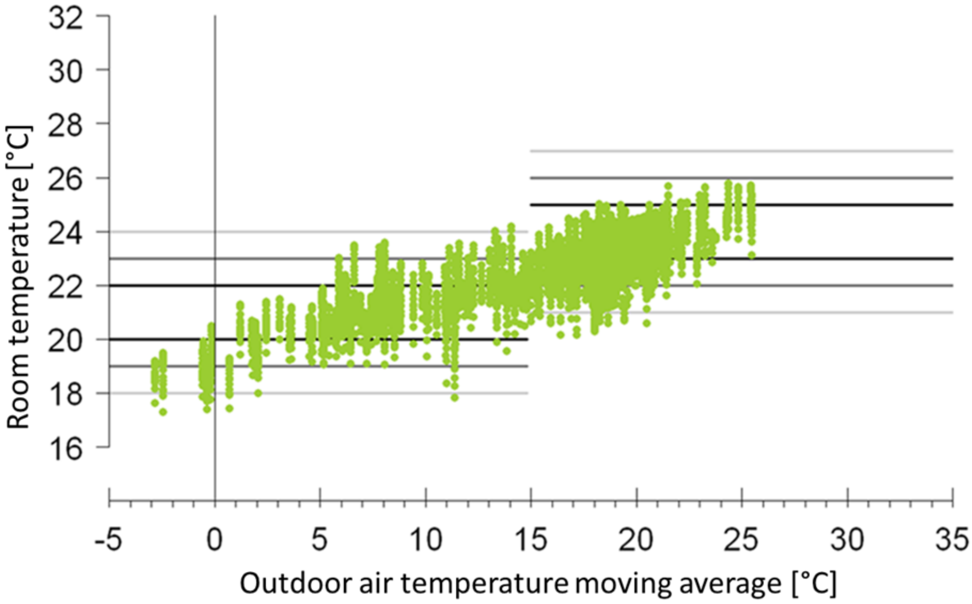

Figure 5 Relationship between hourly average of the room temperature and moving daily average of the outdoor air temperature

3.3. Ventilation

The role of the air handling unit is to control the indoor carbon dioxide level at a maximal value of 1500 ppm in order to ensure a good air quality in the supermarket. The specific primary energy consumption of air handling unit amounted to only 1 % of the energy consumption of the supermarket in the first year. With 7,0 kWh/m^2, it corresponds to a reduction of about 60 % of the energy consumption needed to ventilate a standard supermarket. The results lie also about 27 % under the objective of 9,8 kWh/m2.a. This concept could allow controlling the air quality at a very high level without significant energy efficiency losses.

3.4. Lighting

In 2011, the inner lightings consumed 67,11 MWh electrical power. It corresponds to a specific primary energy consumption of 101 kWh/m^2.a. This result lays about 21 % above the targeted value of 83 kWh/m^2.a. Several reasons listed below were identified that explain the deviation from the objective.

- The higher limit for the power input was set to 16,0 kW whereas the set value of 700 Lux for the illuminance could be reached with only 85 % of the nominal installed power. Therefore, this threshold has been reduced to 14,0 kW. The same measure was implemented for the minimal power input through a reduction of the lower threshold from 5,5 kW to 3,0 kW.
- The dimming of the basic lighting to 30 % of the maximal value in the morning before public opening was not strictly respected by the shop employees, inducing an increase up to 10 % of the daily energy consumption. The food retail chain

management raised the employee awareness on this problem resulting in a better compliance to the guidelines.
- The schedules of the effect lightings were not implemented correctly as these were switched on from 7 am instead of 8 am.
- The switching interval for the artificial light control of the warehouse was set too high, which did not allow an energy efficient dimming.

The optimization measures which were implemented during the first year of the ongoing commissioning campaign allowed a reduction of the energy consumption of the lighting over the months visible in Figure 6. Based on data of the first half of 2012, an energy consumption of 88 kWh/m^2.a can be forecast for the lightings. This calculated value is of course dependent on the future sun radiation supply but converges strongly towards the targeted value of 83 kWh/m^2.a.

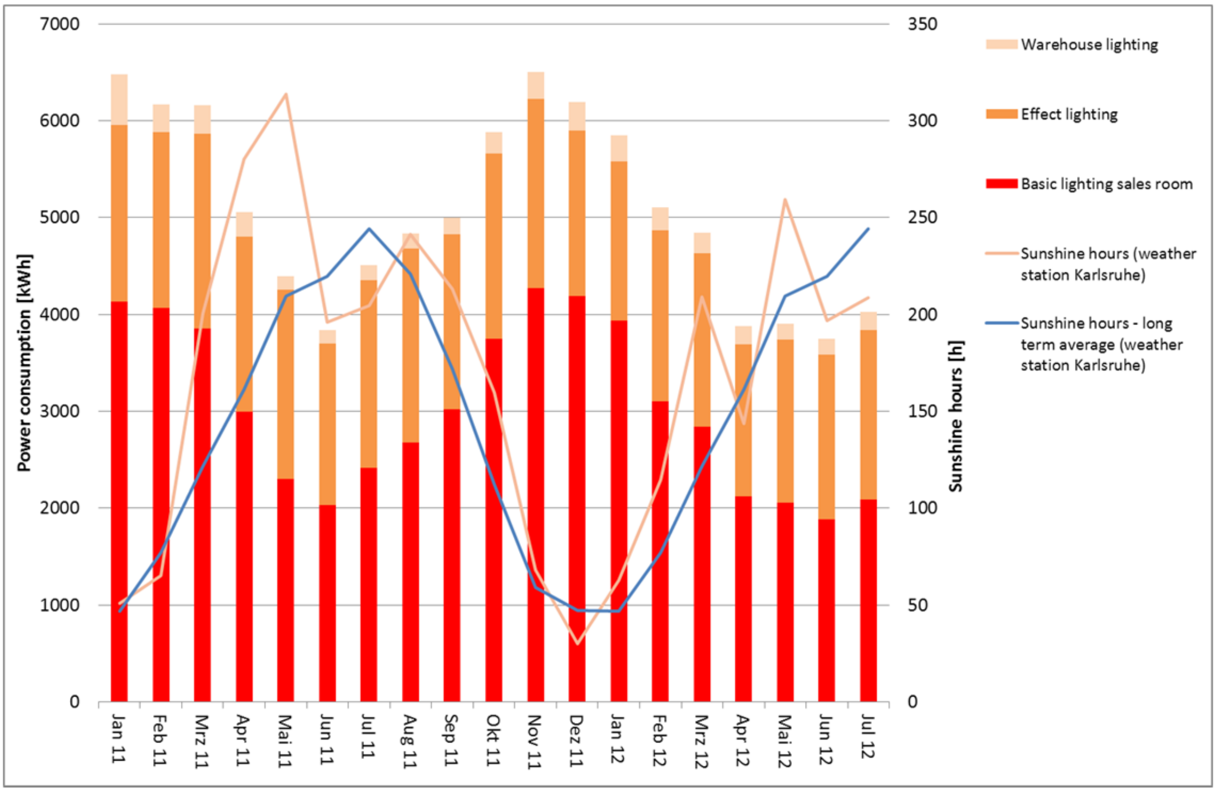

Figure 6 Electrical power consumption of lightings from Jan. 2011 to July. 2012

4. Conclusion

As depicted in Figure **7**, the specific primary energy consumption of the supermarket reached about 408 kWh/m^2.a after the first operation year. It represents a reduction of 20 % of the energy consumption of a standard supermarket of the food retail chain. Gains of about 13 % in the energy efficiency of the different components still have to be obtained in the next year to reach the goals.

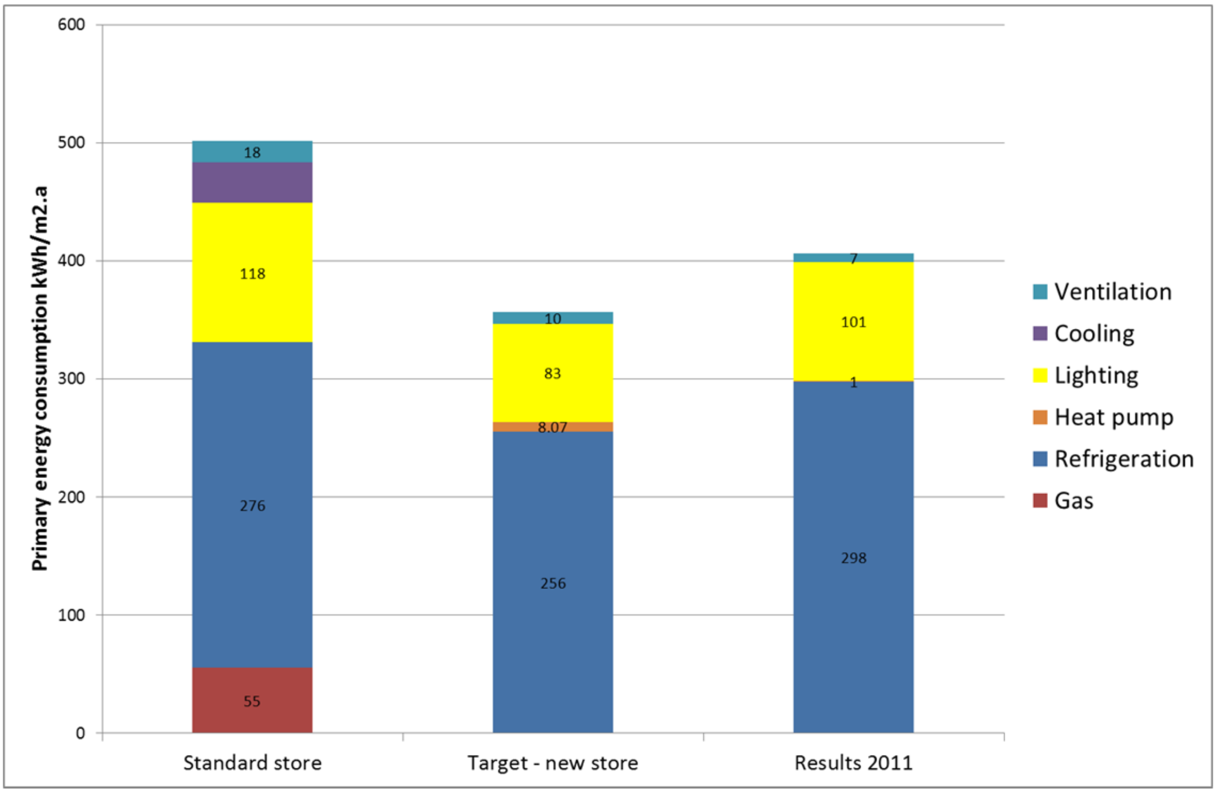

Figure 7 Comparison of the energy consumption targets with measurements after one year

The first monitoring period of the new supermarket could allow validating some basic components of the new concept in term of energy efficiency and comfort like the activated concrete slab, the air handling unit and the transcritical carbon dioxide chiller. In particularly, the new refrigeration system on R744 could perform almost as well as a standard chiller using synthetic refrigerants thanks partly to the cooling effect of the borehole heat exchanger. Nevertheless, the operation of the borehole heat exchanger still need to be optimized and analyzed to harvest the highest potential from this heat sink and show its economic viability as investment costs are high for such a technology. Lessons learned from the first monitoring year have already been implemented in the development of a new chiller generation which will be commissioned in the course of 2012 in a new subsidiary of the food retail chain. Regarding the use of daylight, the high costs of the new roof and the competition with photovoltaic could hamper a large scale replication despite the high interest of the daylight concept in terms of visual comfort and energy savings. Here, new concepts and products have to be developed to allow a smooth and economic architectural integration.

Aknowledgments

Funding for this study was provided by the German Federal Ministry of Economics and Industry.

The authors wants to acknowledge hereby their former colleague Mr. Christian Neumann, who carried out the simulation studies during the planning phase of the project. They also acknowledge the ALDI SÜD Rastatt GmbH managers Mr. Hake and Mr. Becker.

References:

Cecchinato, L., Chiarello, M. et al (2009), *Thermodynamic analysis of different two-stage trans critical carbon dioxide cycles*, International Journal of refrigeration, Volume 32, Issue 5

EnEV (2009), *Energieeinsparverordnung*, *Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden,* BMWi, BMVBS, 2009

EnOB (2006), *Förderkonzept „Energieoptimiertes Bauen"*, BMWi, 2006

Edwards, L and Torcellini, P (2002)**,** *A Literature Review of the Effects of Natural Light on Building Occupants,* NREL

EnOB (2011), http://www.enob.info/en/new-buildings/project/details/energy-efficient-supermarket-uses-daylight-and-ground-cooling/, EnOB website, 2011

Jakobs, R. (2006), *Ein Beitrag zur Marktentwicklung von Supermärkten.*
DKV-Tagung 2006, Dresden

Kauffeld, M. (2009), *Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment*, Dessau-Roßlau: German Federal Environment Agency

Kim, M., Pettersen, J., et al (2003), Fundamental *process and system design issues in CO2 vapour compression systems***,** Progress in energy and combustion science Volume 30, Issue 2, September 15 2003

Rhiemeier J-M., Harnisch J. (2009), *Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment",* Dessau-Roßlau: German Federal Environment Agency