Ongoing Commissioning of a high efficiency supermarket with a ground coupled carbon dioxide refrigeration plant

Nicolas Réhault [1] and Doreen Kalz [2]

[1] *Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany*
[2] *Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany*

Email: nicolas.rehault@ise.fraunhofer.de

Abstract:
A significant reduction in the energy consumption and greenhouse gas emissions of supermarkets can be reached by the combination of several innovative components and the continuous optimization of their operation. A German food retail chain developed a new supermarket concept combining several innovative solutions for the refrigeration, lighting and heating/ventilation with the goal to reduce the energy consumption by about 30% compared to a standard subsidiary. A highly insulated building envelope, the use of daylight and covered refrigeration units contribute jointly to reach the goals. The key component of the concept is a carbon dioxide refrigeration plant with waste heat recovery. To reduce the efficiency losses in supercritical operation, carbon dioxide is cooled through a borehole heat exchanger using the ground as a heat sink. In the paper the design concept, the results of simulation studies and of the first monitoring year are presented and discussed.

Keywords:
Supermarket, refrigeration system, carbon dioxide, heat waste recovery, daylight.

1. Introduction

About 24 GWh/a electricity are consumed each year in Germany for the production of cooling energy by the food retail industry (Jakobs, 2006). It represents about 345,000 tons of indirect carbon dioxide emissions. Furthermore, the big majority of the about 50,000 supermarkets in Germany are running on synthetic refrigerants (HCFC, HFC) with high global warming potentials values (GWP). Accordingly to (Kauffeld, 2009), the refrigerant charge losses due to leaking refrigeration plants of the food retail industry has an amplitude of 5 up to 10%. He estimates supermarket refrigeration systems to be the "strongest emission source of fluorinated hydrocarbons in Germany". In the meantime, significant efforts have to be achieved in the next years by the food retail industry to reduce its direct and indirect greenhouse gas emissions and contribute to the European "20-20-20" targets. The branch has to conform to always more restrictive energy building regulations, deal with a growing demand of frozen products, and cope with rising energy costs, making energy efficiency and emissions reduction one of their first strategic goal. Nevertheless, the potentials for emissions reduction and energy savings are high as most of the supermarkets are built with poorly insulated envelopes. Furthermore, a large majority of facilities do not utilize natural lighting, and are operating with refrigeration plants on synthetic refrigerants with high GWPs and without heat recovery systems.

In Germany, most of the biggest retail store chains have commissioned in the last years supermarket prototypes aiming to ambitiously reduce greenhouse gas emissions through innovative building and refrigeration concepts. Nevertheless, these projects have kept prototype characters and published scientific results and analysis from their operation are little available.

After having proceeded to a countrywide analysis of the energy structure and performance of more than 300 supermarkets, one of the major German retail companies decided to design a new supermarket, with the main objective to radically reduce its primary energy consumption through the implementation and evaluation of new technologies for refrigeration, building envelope, heating and ventilation and lighting. The project is funded by the EnOB program (Energie Optimiertes Bauen: energy optimized buildings) led by the German Federal Ministry of Economics and Industry, which aims to test and demonstrate energy efficient technologies in different building types. The program mandates a reduction of the primary energy needs for heating, cooling, ventilation and air conditioning (HVAC) and lighting, of at least 50 % compared to the mandatory targets fixed by the Energy Saving Regulation and calculated accordingly to the norm DIN 18599 (EnOB, 2006) (EnEV, 2009). The current project described in this article widens the typology of the EnOB program to the food retail branch and aims to show the positive effect of new technologies and to disseminate the monitoring results on a large scale. (EnOB, 2011)

The primary energy consumption of a standard supermarket of the food retail chain for refrigeration, lighting and hvac´s amounts to about 500 $kWh/m^2.a$. The share for heating with fossil fuels is about 11 %. The electrical energy consumption is dominated by refrigeration and lighting with respective shares of 54 % and 30 %. One of the main project objectives was to obtain a 29 % reduction of the primary energy needs of the new supermarket for refrigeration, lighting and hvac´s with respect to a standard supermarket. The resulting specific primary energy consumptions of the different significant energy users are listed in Table 1. A primary energy factor of 2,6 is considered for electricity and of 1,1 for natural gas.

Table 1 Primary energy consumption targets for the new supermarket

	Specific primary energy consumption [kWh/m^2.a]		
Building system	*Standard supermarket*	*New supermarket*	*energy reduction objective [%]*
Heating (gas)	*56*	*-*	*- 100%*
Refrigeration	*276*	*256*	*-7 %*
Lighting	*118*	*83*	*- 29 %*
Air conditioning	*34*		*- 100 %*
Ventilating	*18*	*10 /*	*-46 %*
Heat pump	*-*	*8*	
Total heating/cooling/ ventilating/lighting	*226*	*101 /*	*- 55 %*
Total	*501*	*357 /*	*- 29 %*

The use of a dynamic simulation model showed that these objectives could be reached by combining several innovative building envelope, refrigeration, lighting and HVAC technologies. Another objective was the use of a refrigeration plant prototype running on climate friendly CO_2 as refrigerant and coupled with a waste heat recovery system and a borehole heat exchanger. The borehole heat exchanger can be used as additional heat sink for refrigerant sub-cooling in summer operation and heat source for a heat pump compressor which supplies additional heat to the supermarket when the heat waste recovery is poor at low outdoor air temperatures. This system made the use of a gas boiler superfluous.

The store chain engaged to adopt on large scale the tested technologies which shall prove their value under the perspective of both environmental and economic criteria. The replication potential for the successful technologies is high as the store chains builds or renovates yearly over 100 stores in Germany. Hence the systematic validation of the different parts of the new concept is of major importance for the decision makers.

In this paper, we first describe the new supermarket design and deliver the results of dynamic simulation studies which supported the determination of energy reduction objectives for the significant energy users. In the second part, we show the results of the analysis and optimizations conducted during the first monitoring year on the refrigeration, HVAC, and lighting systems as well as a comfort analysis.

2. Supermarket concept description and objectives

2.1. Building envelope

The supermarket envelope was designed and built in accordance to the German passive house standard. The U-values of the different components are listed in the Table 2. The airtightness of the building measured through a blower door test reached an air change rate of 0,47 h^{-1}, below the passive house standard threshold value of 0,60 h^{-1}. The windows and skylights are fitted with triple glass window panes.

Table 2 Physical data of the envelope components

Envelope Component	*U-Value [W/m².K]*
Roof	*0,14*
Foundation concrete slab	*0,29*
External walls	*0,18*
Skylights g = 0,29	*1,26*
Windows and glazed doors g = 0,50	*0,70*

2.2. Heating and ventilation concept

In a standard subsidiary, the heating and cooling are covered by an air handling unit with an air flow rate of 12,000 m^3/h. Heat is supplied by the waste heat recovery system of the refrigeration plant and a gas boiler. A split-system supplies a direct evaporator for the air cooling. In the new supermarket, the heat is provided from the desuperheating of CO_2 at temperature levels and energy amounts which allow avoiding the use of an additional gas boiler. As depicted in Figure 1, analysis from dynamic simulation showed that heating demand occurs all year long due to the influence of the heat sinks in the supermarket (multi-desk cabinets and remote island freezers). Thus, the split-system could also be dropped out. The heating of the sales area is assured by an activated concrete slab supplied by the waste heat recovery exchanger of the refrigeration plant and designed with 26°/22°C water temperatures. This new system allows downsizing the air handling unit to the minimal hygienic rate of fresh air to 4,600 m^3/h. Thus, driving energy can be saved. A higher thermal comfort for personel and clients can also be targeted with this radiant heating system. The air handling unit is a 100% fresh air single duct plant with a rotational heat recovery system ensuring a nominal air change rate of about 0,5 h^{-1}. The air flow of the air handling unit is controlled with air quality sensors which limit the maximum carbon dioxide concentration in the supermarket at 1500 ppm. Nearby the suppression of fossil fuels, the dynamic simulation model showed that a reduction of 47% of the power consumption for the supermarket ventilation can be targeted.

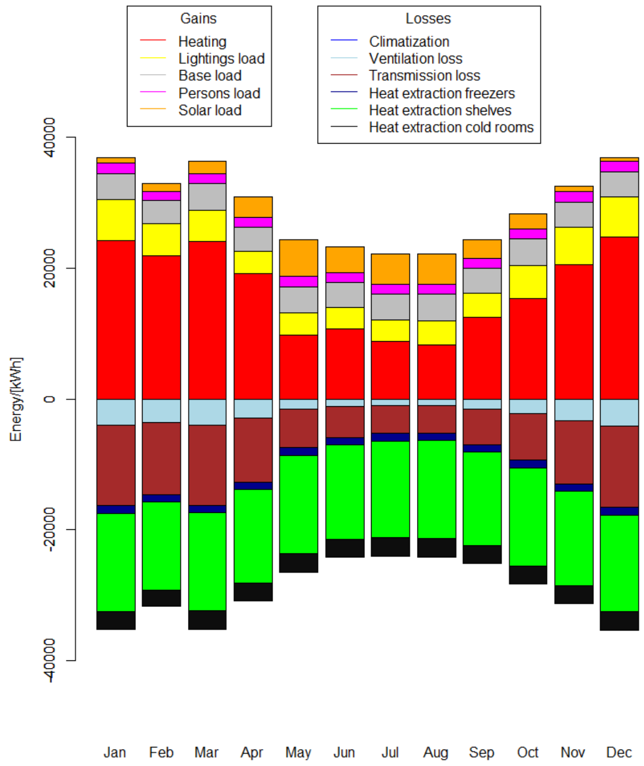

Figure 1 monthly heat and refrigeration demand and balance in the supermarket (simulation results)

2.3. Refrigeration system

To reduce the direct greenhouse gas emissions from the refrigeration plant through unavoidable leakages, the owner of the supermarket chain choose the climate friendly refrigerant carbon dioxide. Carbon dioxide - CO_2 or R744 - is one of the oldest refrigerants and was widely used in industrial and marine air conditioning from the end of 19^{th} century until the middle of the 20^{th} century. The phasing out of ozone depleting CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons) after the Montreal Protocol in 1987 and the global warming potential of widespread HFC (hydrofluorocarbons) gases like R134a and R404a led to a revival of environmental friendly gases like carbon dioxide, ammonia or hydrocarbons. The advantages of R744 towards synthetic refrigerants are its high environmental compatibility with an Ozone Depletion Potential (ODP) of zero and a GWP of 1, its high chemical stability and its excellent thermodynamic properties. The high volumetric heat capacity of R744 allows the choice of smaller components and distribution lines. Furthermore, R744 chillers can reach higher energy efficiency at low condensing temperature than plants running on synthetic refrigerant like R404A, allowing a large scale application in countries with moderate to cold climates. Compared to natural refrigerants like NH_3 or butane, R744 has the advantage of being non-toxic and non-flammable. Drawbacks of R744 are its high critical pressure (73.77 bar) and its low critical temperature (31.1 °C) which require the use of cost intensive high pressure components.

Figure 2 depicts the schematics of the refrigeration plant. The different points of the refrigeration circuit are also reported on the log p,h diagram on Figure **3**. In this article, we focus on the high pressure side of the refrigeration plant. The thermodynamic process on the low and medium pressure sides are not further detailed here. The first role of the refrigeration system is to ensure the fresh-keeping at +4°C and the freezing of food at –25°C. The plant is a two-stage system with a booster connection between the two low temperature stage compressors (LT Comp.- points 15-16) and three medium temperature stage compressors (MT Comp. – points 7-8). It serves all the cooling points in the supermarket like multi-desk cabinets, island freezers and cold rooms as well as an automatic bread machine over a distributed piping system. The installed refrigeration capacity for MT-cooling is 50,3 kW and 16,7 kW for LT-cooling. The island freezers are equipped with double glazing with low emission layer to reduce the transmission losses to the indoor environment. For the same reasons, a thermally insulated energy saving blind covers the multi-desk cabinets when the supermarket is closed. All the multi-desk cabinets and island freezers are fitted with LED lamps and high efficiency fans with internally commutated motors.

After the second compression stage, the high-pressure R744 vapor flows first through a heat recovery heat exchanger (points 8-9) where it transfers its heat to a hot water loop connected to the air handling unit and the activated concrete slab. Then, the remaining heat is rejected to the outdoor air over a gas cooler (9-10). The third heat exchanger (10-1) is connected to a borehole heat exchanger with six vertical U-tubes with a length of 100 m each. The role of this heat exchanger is to further cool down the R744 to enhance the energy efficiency of the refrigeration system in the sub- and the transcritical operation. At low outside air temperature, the heat recovered from the R744 vapor cannot compensate the heat demand of the supermarket, thus an additional compressor, working as a heat pump and extracting heat from the borehole heat exchanger has been employed. In the case of a subcritical operation, the high-side pressure is determined by the condensing temperature until an outdoor air temperature of about 20°C. When the outdoor air temperature exceeds this mark, the transcritical operation cannot be avoided due to the low critical temperature of R744. In the same time, there is only a low heat demand from the building so that most of the heat has to be rejected to the outdoor environment. When the system operates in transcritical region, there is always a maximal COP for each outdoor air temperature (Cecchinato, 2009). At increasing discharge pressure, the maximal COP is reached when the increase of the cooling capacities cannot compensate the additional compressing work. Unlike concepts aiming to reach an optimal COP by controlling the discharge pressure on the high pressure side, the high pressure is controlled here at a constant value of 75 bars which allows reaching the highest COP by using the subcooling effect of the borehole heat exchanger. Figure **3** depicts the transcritical refrigeration cycle as it occurs in summer and shows the cooling effect of the borehole heat exchanger after the gas cooler.

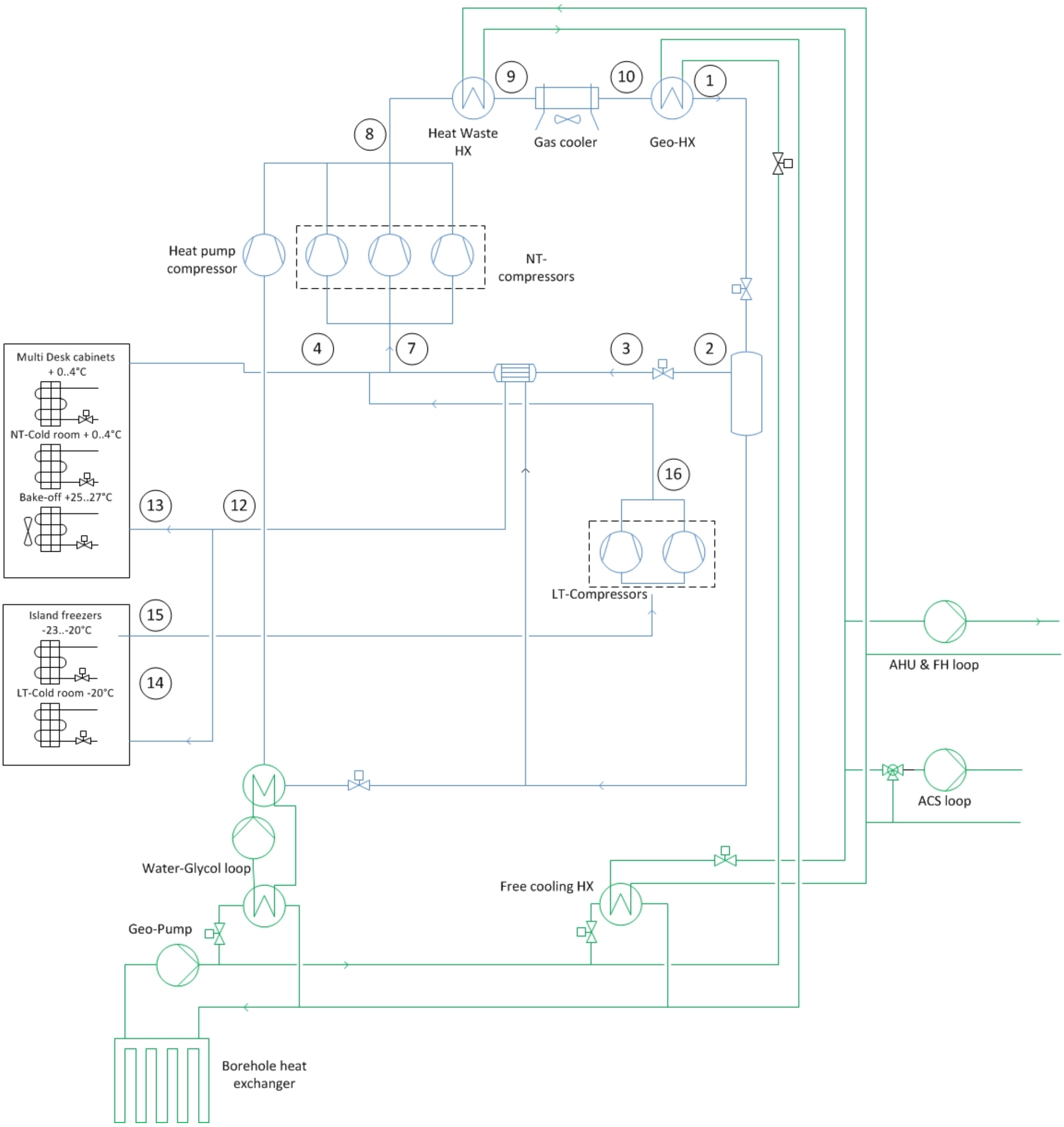

Figure 2 Schematic of the R744 refrigeration plant with borehole heat exchanger

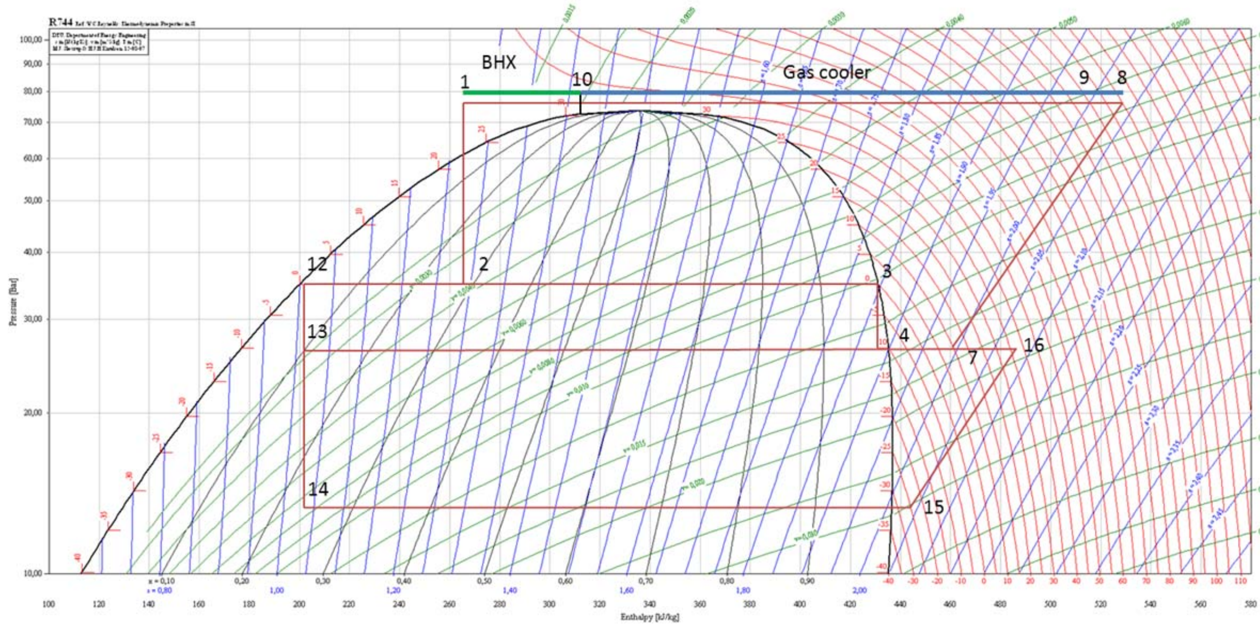

Figure 3 R744 pressure – enthalpy diagram with transcritical refrigeration cycle and gas cooler and borehole heat exchanger shares for the refrigerant desuperheating and cooling

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.

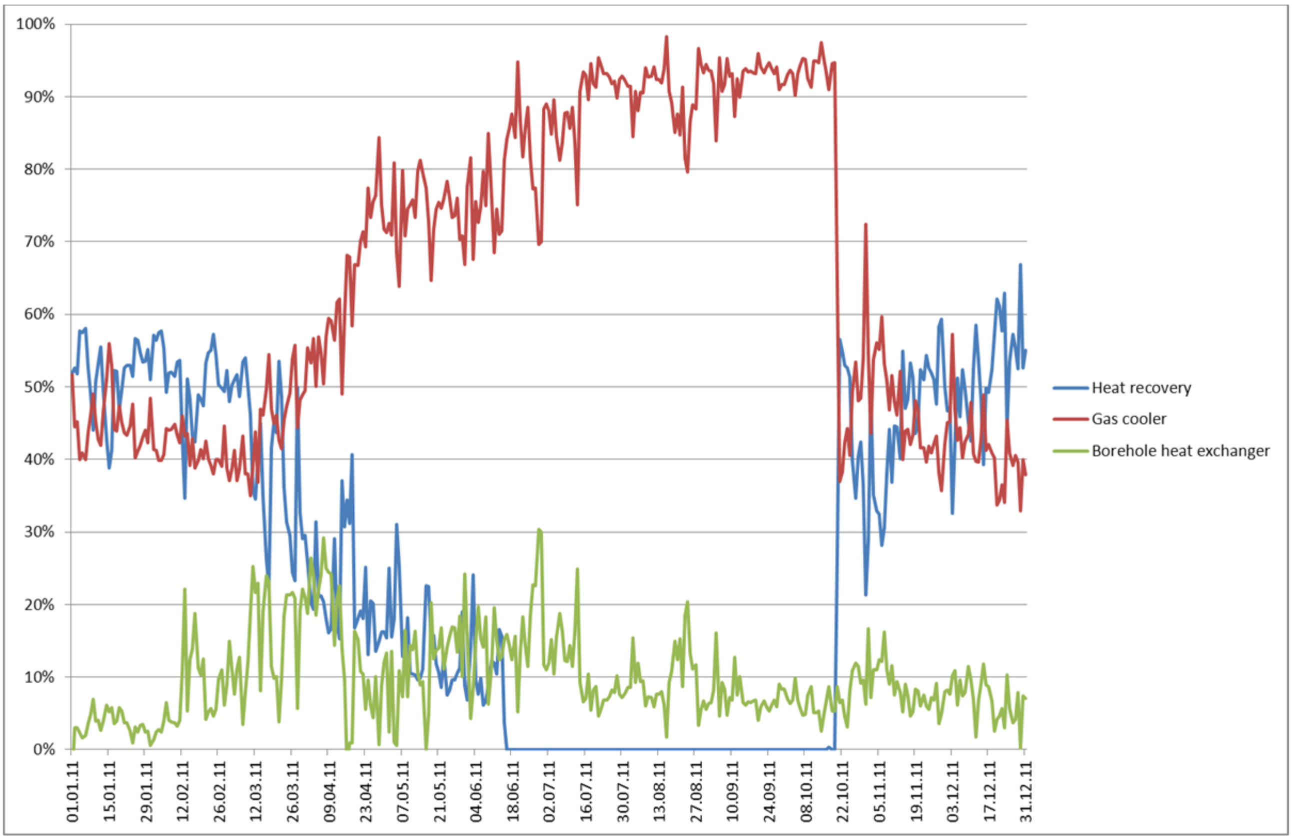

Figure 4 Shares of R744 enthalpy differences of the heat recovery system, the gas cooler and the borehole heat exchanger during year 2011

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.

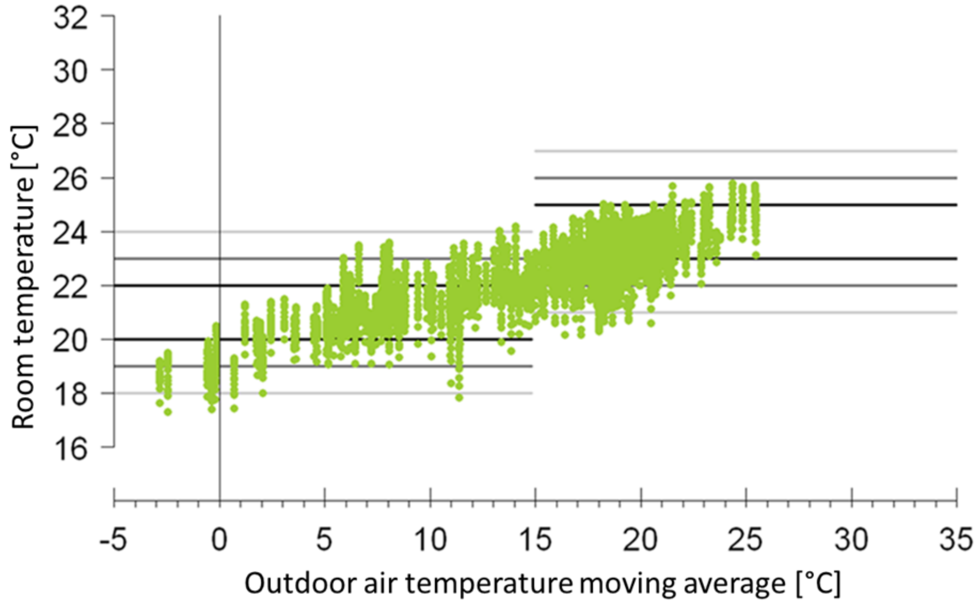

Figure 5 Relationship between hourly average of the room temperature and moving daily average of the outdoor air temperature

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.

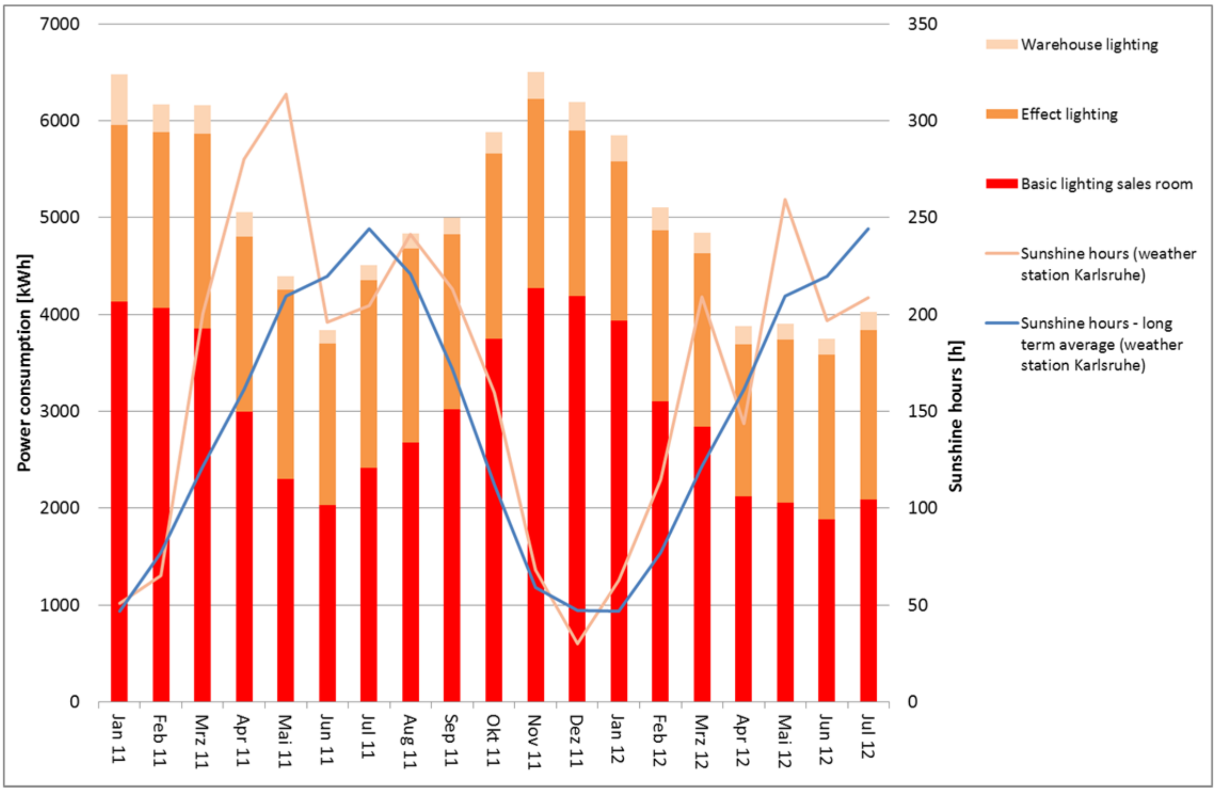

Figure 6 Electrical power consumption of lightings from Jan. 2011 to July. 2012

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.

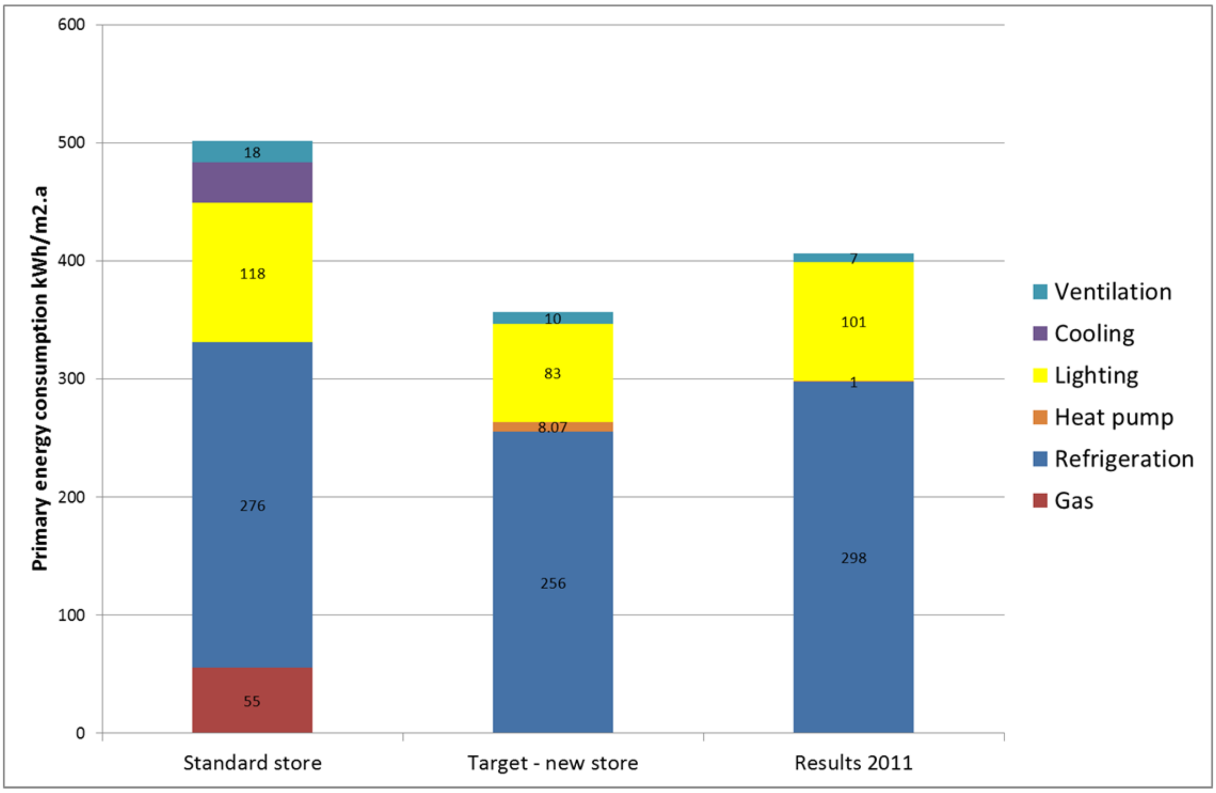

Figure 7 Comparison of the energy consumption targets with measurements after one year

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.

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