Integration of the hidden refrigeration capacity as heat pump in smart energy systems

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Abstract

This paper describes the potentials of extending the traditional supermarket refrigeration systems to a wider energy context consisting of flexibility enabled electrical and thermal networks. Supermarket systems can become decentral heat producers and export heat to available thermal networks beyond the normal waste heat recovery by utilizing present 70% stand-still capacity in the systems. This capacity can further be utilized to help balance the production/load on the electricity grid by an efficient conversion from electricity to heat, when the production from renewable sources like e.g. wind surpass the immediate consumption. Investigations are based on real supermarket cases and technology choices in the aspect of low GWP refrigerants are evaluated. Barriers like electricity prices versus system COP and framing conditions like Thermal network temperature lift is evaluated and a method of optimizing is suggested.

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Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Keywords: Smart energy systems, Thermnal stiorage, District Heating, CO2 refrigerant, Supermarkets

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1. Introduction

Heating and Cooling accounts for more than 50 % of the energy usage in the EU. The heating demand in China is notoriously known as a main contributor to the severe airborne pollution in the big cities and is necessarily looking into a transformation of its energy source. Heat pumps are well acknowledged clean energy providers which fit well many of the new energy paradigm mainly introducing carbon free energy production and increased electrification. It inherently means an increased amount of renewables and consequently also challenges in the management of electricity demand adopting to the supply fluctuations caused by wind and solar plants. Energy storage is a keyword in that context and storage can mainly be divided into electrical, chemical and thermal storage. Thermal storage has the advantage that it may already have the storage capacity available e.g. in the case of thermal grids and large storage facilities or it can be relatively low cost adapted to heat pump based systems. Typically, the costs of large scale thermal storage are a factor 100 – 1000 lower compared to electrical storage [6]. The cost perspectives of thermal storage mainly relate to the conversion technology i.e. the heat pump.

Supermarkets account for a relatively large share of total electricity consumption. In Germany 1-2 % of all electricity use can be assigned to supermarket refrigeration [1]. Most supermarkets are energy managed by a central controller connected to multiple cooling cases to control temperature levels. The hierarchy of the controls in a supermarket and the communication to the grid operator can be seen in fig. 2. It is worth noticing that even in older systems changes in the control set-up can be done without big investments i.e. main assets as compressors refrigeration cases will not need to be replaced.

2. Combining Heating and Cooling

The cooling process produces heat like a heat pump but traditionally the heat has not been used but instead released and wasted to the surroundings. Energy efficiency stakeholders are today asking the question on how this could happen and actually still is happening in majority of installments. A reasonable explanation could be the trajectory of technology development has emerged in times where energy costs were low. As energy cost increased the likelihood of exploring new efficient methods increased but with a certain business resistance barrier before technology trajectories change. Often a secondary technology development can initiate the spark to a new trajectory – in this case the development of CO_2 refrigeration systems appears to have made the business case for heat recovery very attractive.

2.1 CO_2 as the preferred refrigerant

From January 2015 the new EU F-gas Regulation has been in force and as from 2019 a global phase down of HFCs will commence. However, pressure for phasing down the potent greenhouse gases already in 2000 pushed the industry in e.g. Denmark to start looking for alternative refrigerants. Especially for supermarkets this implied a dramatic change from refrigerants with high global warming potential (GWP) to low GWP substances like CO_2. Once introduced in the market a continuous improvement in energy efficiency of the systems took place during the 00’s without considering heat recovery – however once refrigeration COP’s were on peer with traditional systems [4], the heat recovery opportunity appeared as an obvious low hanging fruit. Recently CO_2 systems have been further optimized for warmer climates by using ejector technologies [8]. This technology will further improve the efficiency of CO_2 based heat recovery.

To recap on CO_2, it has low Carnot efficiencies – but this is more than counterbalanced by the thermos-physical properties like improved heat transfer; enabled smaller system dimensions and a high heat content at high temperatures facilitating efficient heat recovery. Furthermore, CO_2 has a GWP value of 1 and is regarded as a safety refrigerant considering the minimum room size versus the charge amount.

It is feasible to show the combined heating and cooling COP (often named COSP) as a function of the relative heat recovery potential also named the Heat Factor (HF). HF is the energy above a certain temperature level on the discharge side divided by the cooling energy, see figure 1 (left). Thereby the cooling capacity relates to the usable heat recovery. Normal compressor isentropic efficiencies and operating maps are considered which limit the pressure and temperatures. Calculations are based for a single compression cycle with an evaporation temperature of -5°C and a final condensing temperature of 12°C. The input is then a value of HF for heat delivered above 65°C and the output is the COSP and shown in figure 1 (right) for R404A, R32 and CO_2 (R744). It shows CO_2 becomes superior when high amounts of heat at high temperatures is to be delivered.

Observe the COSP only drops slightly for CO2 even at high HR ratios due to the fact that at CO2 has a heat capacity which increases more than the extra compressor work when pressure is increasing, see figure 1 (left). R404A is low in COSP even at low HF ratios as the ‘natural’ discharge temperature is far below 65°C. Thus forcing the process into a 65°C heat recovery stage means the efficiency becomes very low. R32 has a high COSP at lower HF ratios and could be a candidate for certain applications with lower amounts of heat delivery. It should be noted these calculations are very simple and idealized therefor only indicative towards real system performance.

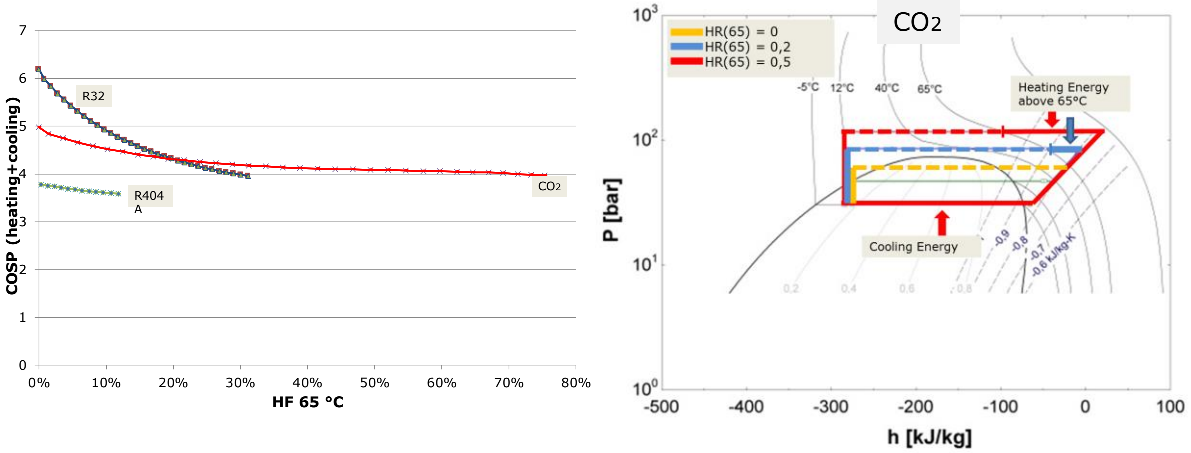


Fig. 1. Left: COSP versus amount of HR above 65°C (evap.temp -5°C). Right: Log P-H diagram showing increasing HR levels for 65°C

2.2 How much heat can be recovered

To answer the question on how much heat can be recovered several parameters need to be considered. The temperature of the CO2 refrigerant and the temperature level(s) of the water used for heating are the main parameters but due to the nature of the CO2 refrigerant the heat capacity varies heavily with temperature and pressure. This nonlinearity must be exploited if optimized heat recovery has to be achieved. If only a single temperature level is demanded one counter-flow plate heat exchanger is sufficient. However, the water flow will be limited by the high temperature due to the CO2 heat capacity is decreasing with increasing temperature. If two temperature levels can be utilized, then two serial heat exchangers should be used to capture the increased heat capacity of CO2 at lower temperatures, see figure 2 for a technical outline.

Temperature levels in the heating systems depends on the system layout and safety issues. Hot water for sanitary purposes needs temperatures above 65 °C while closed heating systems in buildings uses temperatures between 30 and 80 °C. New buildings are normally based on low temperature heating due to lower heat loads and more efficient heat transfer. The lower the temperature for space heating the higher the amount of possible heat recovery and the higher the efficiency of the system becomes. To illustrate the possible heat recovery a case is described in the next section.

2.3 Case on heat recovery

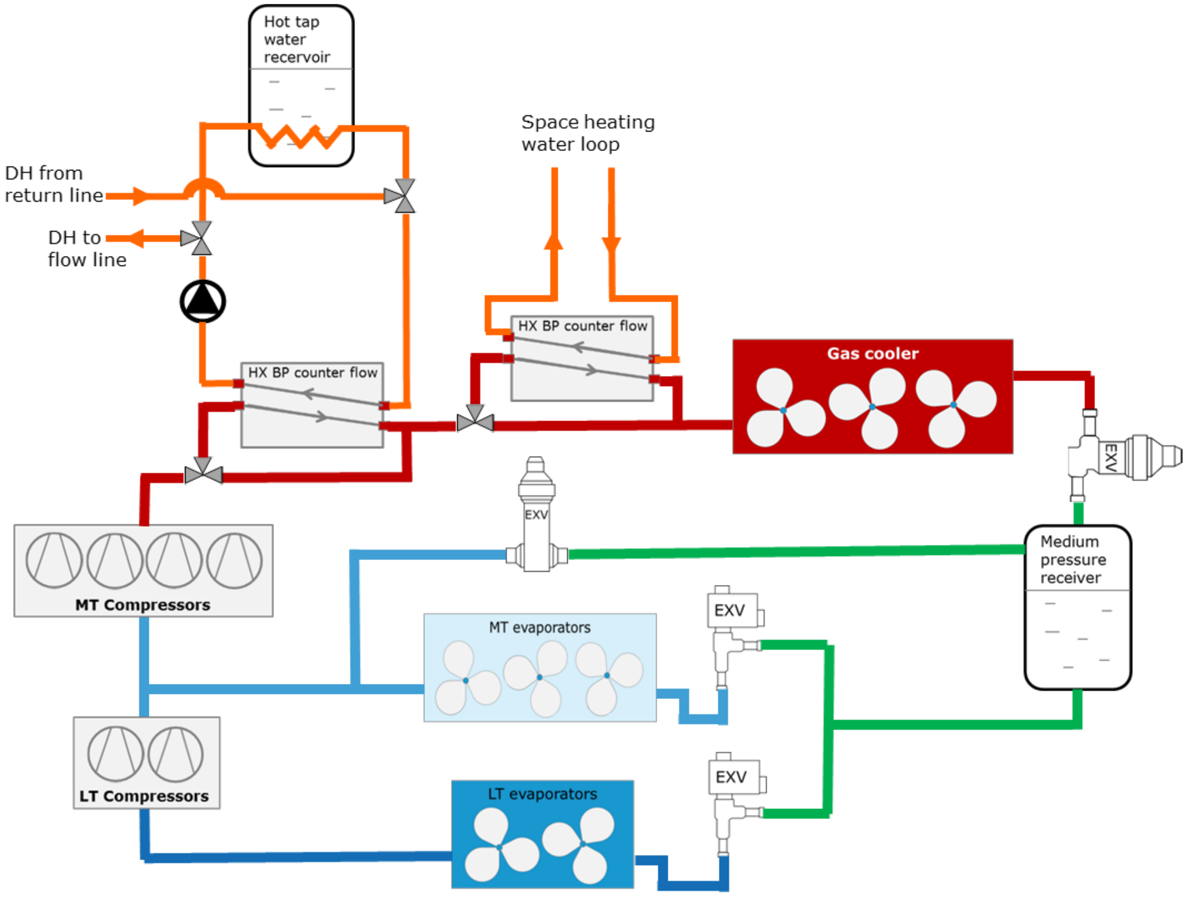


Fig. 2. The concept of the CO2 refrigeration system with heat recovery and District Heating (DH) connection

To quantify the gains from combining heating and cooling also in a District Heating (DH) context a pilot store was selected and monitored, see figure 2. The store is located in the south of Denmark and was previously used as a case study for internal heat recovery. From this study it was concluded that the heat recovery for the store eliminated the need for natural gas heating previously used and the heat recovered reduced the total energy cost by 28%. [2].

In a following study [3], the DH system amendment was done without interrupting the refrigerant high-pressure part and there no down time was encountered in the store. Only the water circuit to the high-temperature tap water reservoir is rebuild connecting the flow and return lines of the DH system. To overcome up to 6 bar pressure difference between the DH flow and return line a pressure pump was installed.

DH is in general at the level of the 3rd generation, heading towards the 4th generation. [6]. One important parameter is the flow temperature of the DH network. Towards the 4th generation its envisioned to be reduced to 55°C-60°C for the main part of the season. This provides a great synergy with supermarket heat recovery. A number of 4th generation, or low temperature DH, projects have been implemented with good results. [7]. The overall control system of the compressor rack takes care of the heating priorities of the store. 1st priority is to serve the basic heating needs in the store i.e. keeping comfort temperatures within the building while 2nd priority is to have enough hot sanitary water. 3rd priority is to serve the DH network with excess heat. The DH return line water is heated from 35°C to 65°C by the hot CO_2 refrigerant using a counter flow plate heat exchanger and is then feed back into the flow line. The DH feed water flow is controlled to achieve the demanded flow line temperature. In figure 3 different heat recoveries are recorded during one week in April 2015. The need for space heating was very low due to relatively high ambient temperatures (10°C) meaning other electrical heat sources in the store were sufficient to keep the desired comfort level. Consequently, the majority of the heat was delivered to the district heating system. No big differences are seen for colder periods as the space heating water only needs a temperature around 35°C to heat the store even at 0°C ambient temperature which corresponds well with the CO_2 temperature leaving the DH heat exchanger. Heat exported to the DH grid was around 4.5 MWh per week in April 2015 while in August 2016 it was up to 11 MWh per week due to warmer weather.

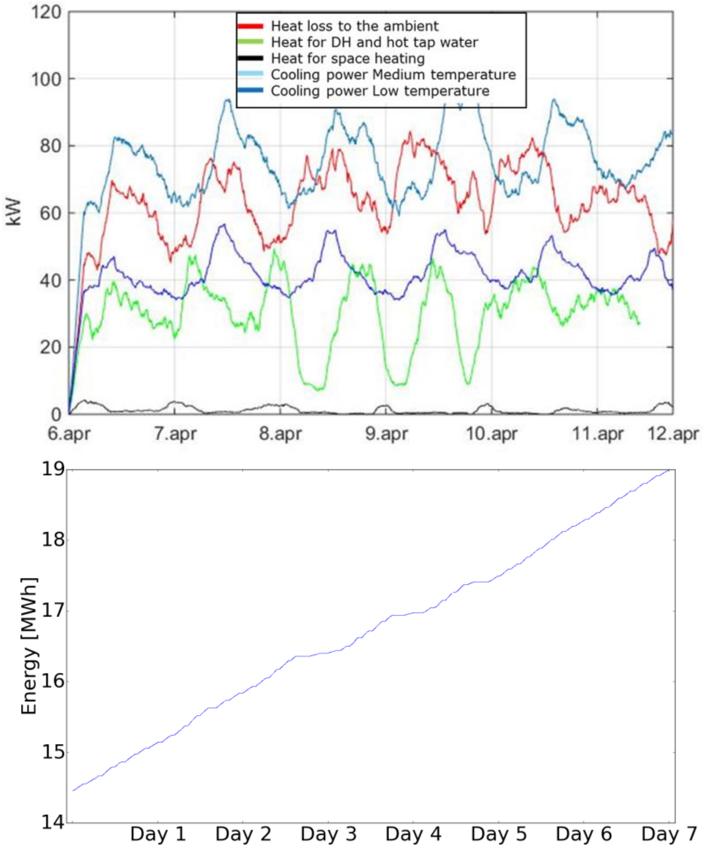


Fig. 3. Heat energy flows in the case study supermarket

3. The hidden heating opportunity

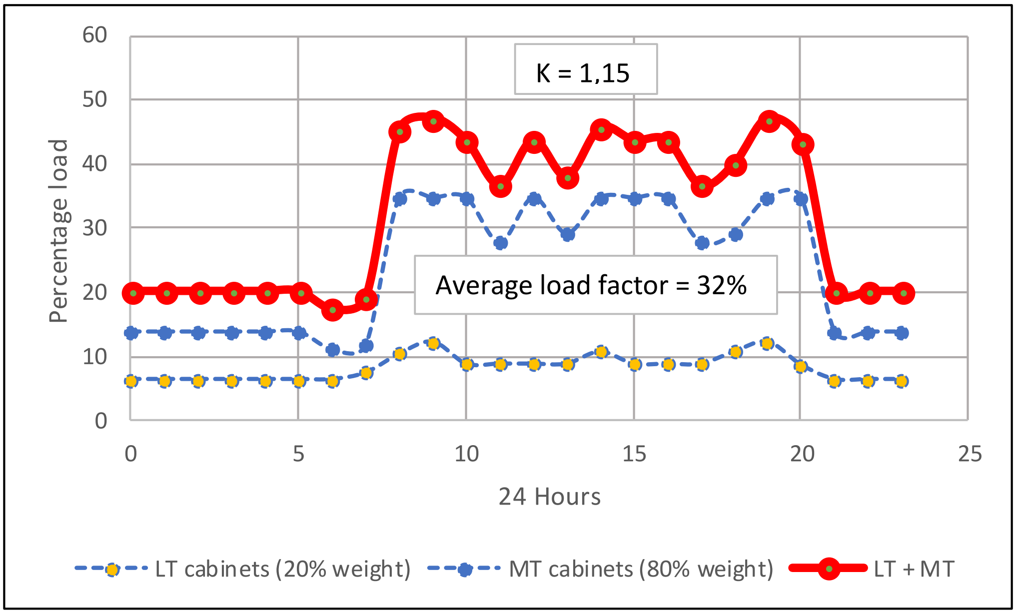


Fig. 4. Calculated average load profile in a supermarket, based on data from [5]

Traditionally supermarkets are designed for a high cooling load respecting extreme summer conditions with high temperatures and high humidity or more explicitly

$$Qc = K * \sum_{k=1}^{n} Qc,k \qquad (1)$$

Where Qc is the Cooling capacity of the entire system and the Qc,k the single display cases in the store. K is a safety factor which usually can be taken as 1,10 – 1,15. The cooling capacity of the display cases relates to certain test conditions which can be found in e.g. ISO 23953. The rating condition relies on temperature of 25°C and a humidity of 60% (EU).

However, the nominal capacity is rarely full utilized due to seasonal and daily variations or to the fact that the stores may be ventilated and air conditioned. There is not much data available on actual load utilization, but as reference is taken a thorough work [5], done at a typical supermarket in Denmark. Variations will of course be seen towards other supermarkets. Remarkable is that even in average only 32 % capacity utilization is utilized, see figure 4. During closed store conditions i.e. low indoor temperature and closed display cases capacity utilization may even go down to 20%. Winter conditions would probably yield lower numbers. To summarize; in average 65-70% of installed compressor capacity may not be used and that gives a huge opportunity to utilize these assets for additional heating and/or cooling service. Once connected to a thermal grid the supermarket will face potential new opportunities beyond the traditional heat recovery. The only and necessary condition is to have a customer to the service and to be able to create a business case.

4. System setup for heat or cooling export

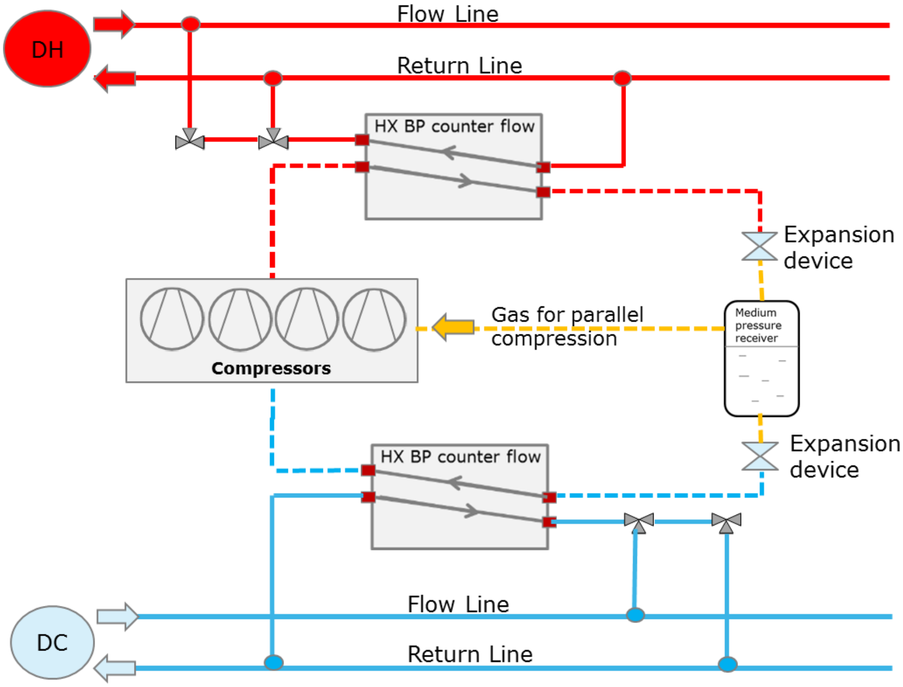


Fig. 5. Principal outline of external thermal grid connectivity to District Cooling (DC) and (DH). Dotted lines are refrigerant pipes and solid lines are water pipes

The specific outline of the heating system depends on the heating needs to serve. There are mainly two different methods:

- Increase the temperature of the return line – this can be an arbitrary increase or a specified.
- Upgrade low temperature return water to the flow line temperature.

Which type of solution to be chosen depends on the specific value that can be attained and accepted by the thermal network or DH operator. A certain amount of pragmatism also needs to be considered when designing the system. Easy and robust adaption to existing systems while looking at return on investments are governing parameters while new stores more easily can use ‘from the book‘ optimized concepts.

Service people are almost divided into their respective technical areas and the implications of merging the cooling and heating systems must not be underestimated. Who has the main control and how is this influencing on the ‘new’ connected system. To overcome these potential pitfalls standard setups are recommended.

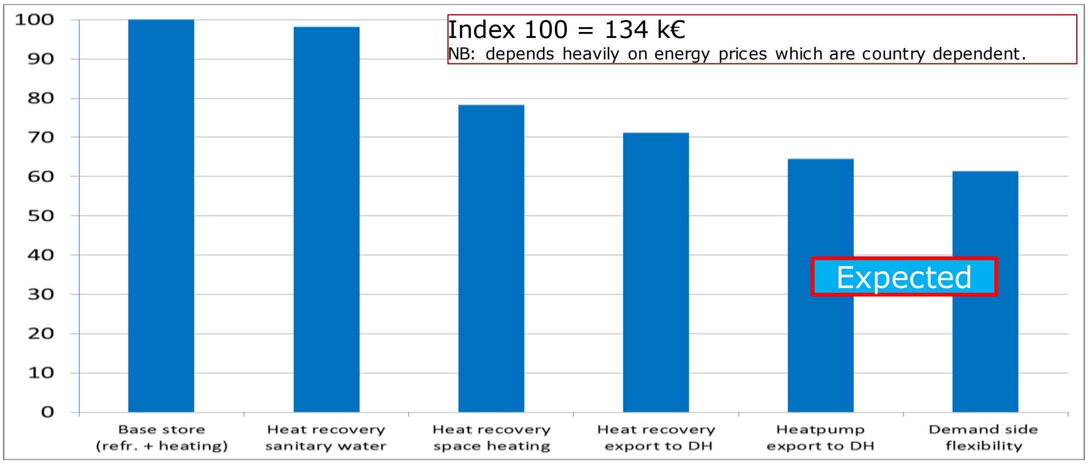
5. Optimization of the running conditions in smart energy system

Heat recovery is per definition based on the energy obtained in the cooling units in the store and can be regarded as ‘free’ bonus energy. Traditional heat pump processing is a ‘fait a comply’ because heat is needed. However, the utilization of the extra compressor capacity is a trade opportunity which is dynamic throughout 24h. Consequently, an automated evaluation on when and how to operate needs to be in place. An attractive cost balance for a certain minimum time is needed before activating the extra capacity. The cost balance is positive if the relative heat remuneration (C_h) exceeds the relative electricity cost (C_e) divide by the $COP_{h,u}$ which is the energy of usable heat divided by the energy for running the system, see equation 2

$$C_h > \frac{C_e}{COP_{h,u}} \qquad (2)$$

This implies that the operator knows these parameters and has an online measurable COP factor [1] giving an estimation of the COP development in the near future.

6. A case considering the cost optimization and emission reduction



Index 100 = 134 k€

NB: depends heavily on energy prices which are country dependent.

Electricity (base)	0,14 € / kWh
Electricity (HP mode)	0,04 € / kWh
Gas	0,55 € / m^3
District Heating	0,05 € / kWh

DSF	KW reductn	Min. per event	Events per day	Value per KWh	SUM year €
Defrost	13	90	3	0,03	570
Capacity reduction	20	30	4	0,03	390
Imbalance Service	53	15	n.a.	60	3200

Fig. 6. Cost reductions accumulated

Based on the supermarket case previously described in this paper further cost validations have been made. Benchmark is a conventional CO2 refrigeration system without heat recovery. The actual store has heat recovery internal in the store and also exports heat to the local DH network. Based on the actual running conditions and estimations on the extended heap pump processing an energy cost calculation can be made, see figure 6. The first and second cost saving comes from the internal heat recovery which are used for the store only and relates directly to the abundance of the old gas heating system. The third saving consist of an income from selling heat to the district heating system based on the surplus of energy under normal load conditions i.e. around 30% capacity utilization.

The fourth saving is then designated the further utilization of the available compressor capacity not used for refrigeration. It is assumed that in 25% of the time the electricity price is attractive due to the amount of renewables and that the $COP_{h,u}$ is 1,5. This saving can likely be higher but is dependent on local conditions.

Finally, the fifth cost reduction is an income based on selling demand side flexibility (DSF) to the electrical grid operator. DSF is about optimizing the timing of electricity usage to have the lowest electricity bill by shedding defrost and loads during peak hours. Imbalance services relates to fast load reductions to help keeping the grid frequency. The DSF services relates also to the extended possibilities for heat pump processing. Many times in the year renewable energy production exceeds the planned amount and loads need to be introduced. Indirectly this is already taken into account with low electricity price in the fourth saving but additional fast an unplanned ramp could be an incentive for the future.

The associated CO2 emission reductions can be estimated calculating the CO2 content of the saved gas consumption and for the DH export part (fifth column) the CO2 difference between electricity and heat production. The DSF part (sixth column) is regarded as having zero CO2 emission influence directly because it is only moving energy consumption. However, from the electricity supply side emissions are likely saved to due to a lower CO2 emission based energy mix.

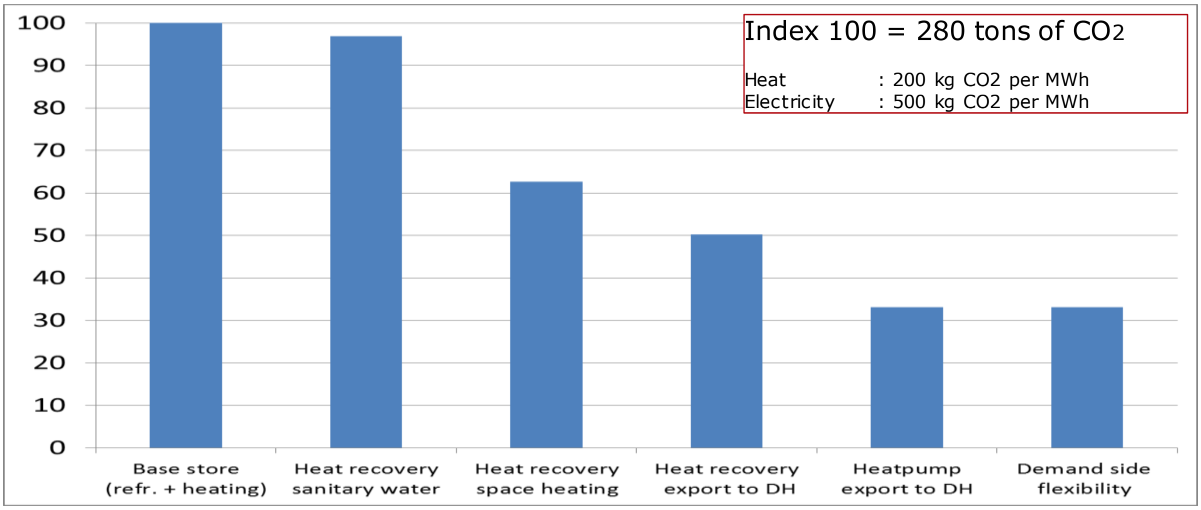


Fig. 7. CO2 emission reduction accumulated

7. Conclusion

The potentials of extending the traditional supermarket refrigeration systems to a wider energy context consisting of flexibility enabled electrical and thermal networks can be done by extending the traditional refrigeration systems. The actual load conditions for supermarkets are characterized by a low load utilization. This low load utilization can be exploited for extra heat pump operation and supermarkets can become decentral heat suppliers.

CO2 is a preferred refrigerant for the integration of heating and cooling as it has superior properties within the existing components technologies.

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Supermarkets can obtain substantial accumulated cost and emission savings addressing the full potential of utilizing the compressor capacity in the context of variable electricity prices. Accumulated savings are in the range of 40%. Accumulated CO2 savings can be in the range of 60-70% taking a full potential of energy savings into account into account. Further savings could be made if a combination of District Cooling and District Heating could be utilized.

The specific set up for energy system integration will depend on local conditions and opportunities. A thorough business case needs to be developed in each case. To increase the certainty for success specific solution guidelines are emphasized to exploit the heat recovery potentials.

Acknowledgements

This paper has been made as a part of the Danish EUDP-project (64016-0106) ‘Super Supermarkets’ work package 1.

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