

Technical paper

Smart Energy Systems Impact on Supermarkets

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Danfoss Cooling, February 2018

The energy agenda globally shifts towards reduced and zero emission scenarios and a substantial part of future energy supply will be based on renewables. To establish resiliency around a fundamentally unstable energy production flexible consumption and storage is necessary. This is smart energy systems.

Smart systems will not reduce overall consumption but they will enable renewables like wind and solar to become major energy suppliers in the most effective way.

Vapor compression systems contain a wealth of opportunities which are among the cheapest and easiest to implement into an emerging smart flexible energy system.

This paper uses a supermarket case to illustrate the win-win opportunities which can be exercised today. It shows how Heating and Cooling can be integrated - using environmentally friendly refrigerants – using Thermal networks to facilitate a hidden resource of heating and eventually cooling with modest investments. The integrated H&C system can become a major candidate for demand response. **A true smart system concept with a good business case.**

Introduction

The global energy trend focuses on an increasing carbon free or neutral energy production. It inherently means an increased amount of renewable energy sources like wind or solar and consequently also challenges in the management of electricity demand adapting to the supply fluctuations.

Energy storage is a keyword in that context and can mainly be divided into electrical, chemical and thermal storage. Thermal storage has the advantage that storage capacity often is available or built into systems e.g. in the case of thermal grids with large storage facilities for hot water and it can be adapted to heat pump based systems at relatively low cost. Typically, the cost of thermal storage is very low compared to other storage technologies.

The cost-competitive thermal storage invites the vapor compression systems to be further investigated for potential contributions to the smart integrated systems.

In figure 2 an outline of the electrical and thermal grid together with a supply plant (CHP) and traditional energy consuming supermarkets. Supermarkets have traditionally been regarded as pure consumers but now the time has come for an evaluation of that perception. It will show that today's technologies can be addressed for a smart, flexible system enabling supermarkets to become prosumers and a valid resilience tool for the electricity suppliers.

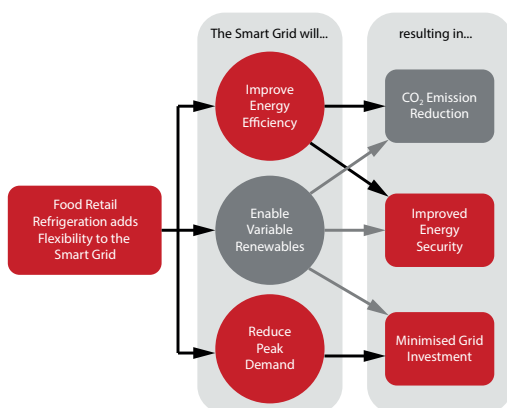


Figure 1. Schematic link between flexibility and the drivers of the energy agenda

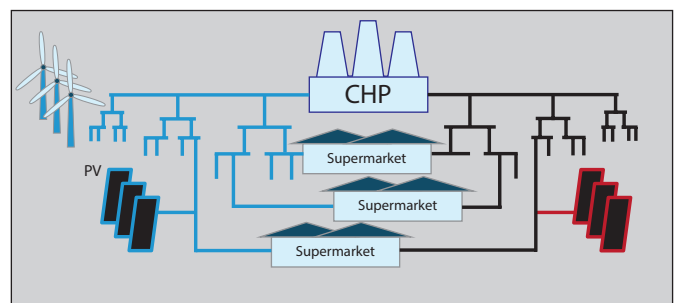


Figure 2. The Supermarket in the electrical and thermal grid

Smart grid and supermarkets

Electricity grids carrying a high percentage of renewable electricity like wind and sun are increasingly challenged in balancing the demand and the supply of electricity. In this context, it is important to notice that supermarkets account for 1 – 2% of all electricity consumption in a country like Germany [1]. A supermarket has a high thermal capacity due to the amount of food subject to cooling or freezing. This also means the sector can play a stabilizing role as ‘virtual power plant’ by adjusting electricity consumption for maintaining food temperature levels and for other electricity consuming activities like defrosting and rail heating of the display cases.

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.3. It is worth noticing that even in older systems changes in the control set-up can be done without big investments i.e. primary assets such as compressors refrigeration cases will not need to be replaced.

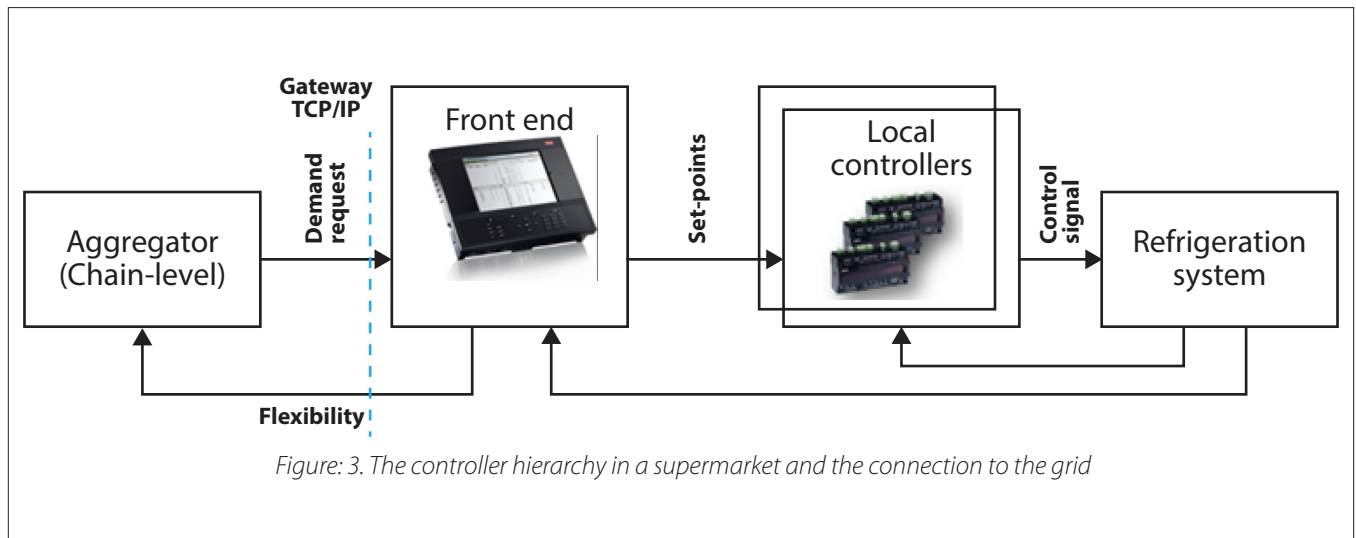


Figure 3. The controller hierarchy in a supermarket and the connection to the grid

Parameter	Value	Comment
Thermal storage of a typical supermarket	25KWH	5°C temp. change in 20 cabinets of 500 kg food, $c_p=1,7 \text{ KJ/(KG.C)}$
Compressor cooling capacity to maintain normal operation	100 KW	full capacity is 250 KW
Compressor power with a COP of 2,5	40 KW	COP will vary during the year
Time with 100 – 60% reduced power	15 – 25 min	
Time without Defrost	90 min	Defrost event is not dependent on the cooling capacity event
Defrost power flexibility	13 KW	
Total power flexibility	53 KW	For 500 stores adds up to 26,5 MW

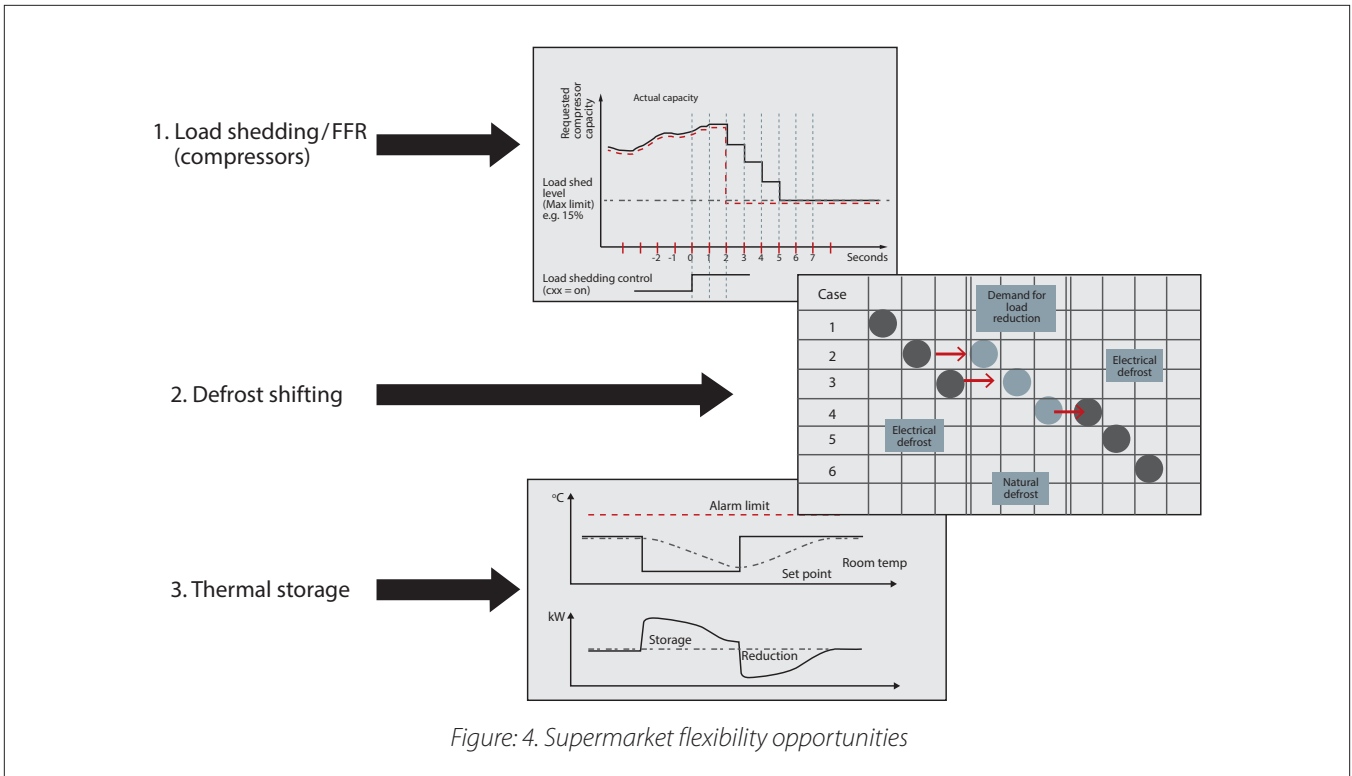
Table 1. Results and estimations on the flexibility in a typical supermarket

Flexibility services can be practiced in various variants and depends on the need of the electricity provider, see figure.4. Short-term responses are applied when the frequency in the grid drops under a certain critical value, and the compressor needs to shut down within 5 – 10 seconds. Longer and regularly scheduled consumption adjustments e.g. during peak hours can be obtained by intelligent energy storage utilization or specific tailored defrost schedules.

If properly managed, supermarkets can be 60 – 80% more flexible from their normal applied cooling capacity for around 20 minutes and most importantly react very fast on specific grid request.

Figure 4-1 shows that actual executed reaction times can be within a few seconds to minutes. Longer event durations offer smaller capacities because the thermal capacity is constant.

From the utility side, the amount of flexibility often becomes interesting in the MW range so stores must be aggregated, making supermarket chains well suited to manage this aggregation. Typically, a few hundred stores can deliver an attractive capacity to operate. It should be noted that flexibility is not always a question of reducing the load. Balancing problems in the grid are also originating from on excess electricity production e.g. wind farms may produce a lot of electricity during the night where demand is low. Curtailment of wind farms is another problem which can be mitigated with such increased demand.



Combining heating and cooling

The cooling process produces heat like a heat pump, but traditionally this heat has not been used therefore released to the surroundings. Energy efficiency stakeholders today are asking the question on how and why this waste could happen and is still occurring in the majority of installations. While the answer to this question for sure is interesting – we like to turn it around and pragmatically look at the potentials of future mitigation of this waste. In this case, the development of CO₂ refrigeration systems appears to have made the business case for heat recovery very attractive.

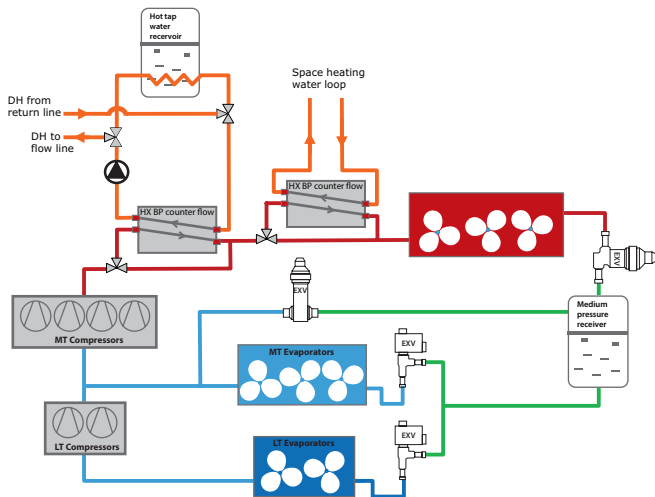


Figure 5. The concept (simplified) of the CO₂ refrigeration system with heat recovery and District Heating (DH) connection

Systems can relatively easy be retrofitted to heat recovery, and of course, specific store conditions need to be observed. The benefits of a full exploration are however tempting, and new stores should always consider maximizing this opportunity. Figure 5 shows a simplified outline of a heat recovery concept in store referred to later in the paper. Two heating circuits are applied to extract as much heat as possible. A high-temperature circuit serves hot water supply for the store and possibly also an external connection for heat

export. The second heating circuit is for low-temperature space heating in the store.

CO₂ as 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, already in 2000 political pressure for phasing down the HFC's pushed the industry in e.g. Denmark to start looking for alternative refrigerants. Specifically, for supermarkets, this implied a dramatic change from refrigerants with high global warming potential (GWP) to low GWP substances like CO₂. Once introduced in the market a continuous improvement in energy efficiency of the systems took place during the 2000's but without considering heat recovery – however once refrigeration COP's were on par with traditional systems [4], the heat recovery opportunity started to be investigated and soon appeared as very attractive due to CO₂'s high energy content at relatively high temperatures.

A case on heat recovery

To quantify the gains from combining heating and cooling also in a District Heating (DH) context a pilot store was selected and monitored. The 1100 m² store is located in the south of Denmark and was previously used as a case study for internal heat recovery [2]. From this study, see figure 6, 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% while the CO₂ emission reductions were around 34%. See also figure 6.

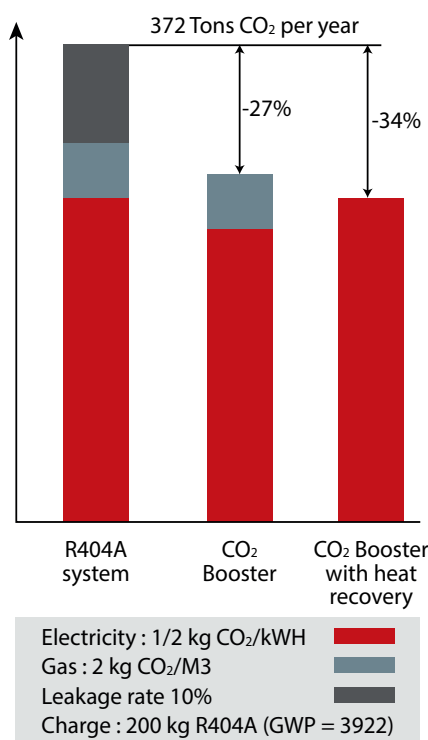
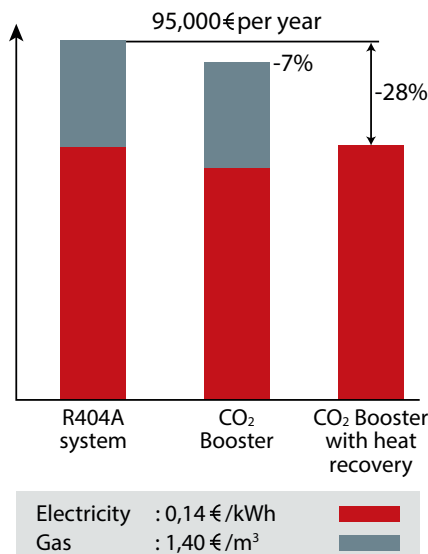


Figure 6. The Energy cost and CO₂ emission of the supermarket case

The hidden heating capacity as an opportunity

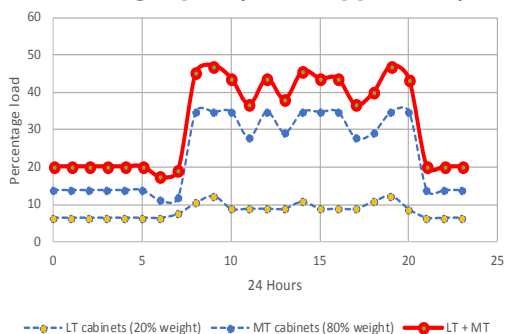


Figure 7. Calculated average load profile in a supermarket, based on data from [5]

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

$$Q_c = K \times \sum_{k=1}^n Q_{c,k} \quad (1)$$

where Q_c is the Cooling capacity of the entire system and the $Q_{c,k}$ 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 testing conditions implying a temperature of 25 °C and a humidity of 60% (EU). However, the nominal capacity is rarely fully utilized due to seasonal and daily variations or to the fact that the stores may be ventilated and air conditioned.

A thorough work [5], done at a typical but smaller supermarket in Denmark has revealed the utilization of nominal capacity. Remarkable is that even in average only 32% capacity utilization is utilized, see figure 7. 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 even lower numbers. To summarize; in average 65 – 70% of installed compressor capacity may not be used and that gives an enormous opportunity to look for utilization of these assets for additional heating and/or cooling service.

System setup for heat and/or cooling export

Once connected to a thermal grid the supermarket will face potential new opportunities beyond the traditional heat recovery. The supermarket can start selling heat as a service. The only and necessary condition is to have a customer to the service and to be able to ensure a sound business case. The distinct 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
- Upgrade low-temperature return water to the flow line temperature.

Which type of solution to be chosen depends on the particular 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 like the Danfoss heat recovery unit.

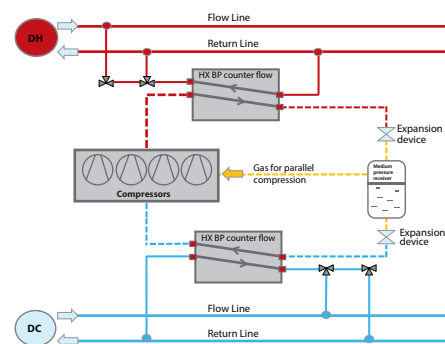


Figure 8. Principal outline of external thermal grid connectivity to District Cooling (DC) and (DH). Dotted lines are refrigerant pipes, and solid lines are water pipes

A view into the future energy scenarios - optimizing the running conditions in an integrated smart energy system

The global agenda on emission reduction will cause the energy mix in the electricity supply to change dramatically. More renewable energy as wind and solar will govern the energy mix and it implies a higher price volatility. Traditional energy consuming systems will face challenges in this regard. To make threats transform to opportunity systems can apply different measures like energy storage and utilizing excess capacity for trading energy. In the following two scenarios are compared in a full integrated supermarket system.

- A constant electricity price and two seasonal heat prices including tax on waste heat recovery (150 DKK/MWH)
- A volatile electricity price and two seasonal heat prices (as in (1)). No tax on waste heat recovery

Constant Pricing	Winter	Spring / Autumn	Summer
Elec. Night DKK/KWH	1,22		
Elec. Day DKK/KWH	1,22		
Heat DKK/KWH	550	200	0
High Variability	Winter	Spring / Autumn	Summer
Elec. Night DKK/KWH	0,3	0,3	0,6
Elec. Day DKK/KWH	1,2	2,1	2,8
Heat DKK/KWH	550	200	

Table 2. Energy prices for the two cases

A wealth of practical performance data from CO₂ based supermarkets can be found in [6]. It is thereby possible to relate realistic COP and cooling load to the outdoor temperature and to the time of the year or the day. By adding local outdoor temperature profiles it is possible to simulate local performance data as COP and thermal load.

The performance data will together with the cost for electricity and the energy storage and trading opportunities for heat determine opportunities for optimizing running conditions. Dispatch of heat production or storage of energy can become actual if a trade of in cost versus income is made. The heating dispatch mode is conditioned upon the ability to trade energy – see equation 2.

$$COP_{heat} > \frac{Cost_{elec}}{Income_{heat}} \quad (2)$$

The ice storage mode is dispatched if the energy cost for storing ice is lower than the predicted energy savings during warm parts of the day where the ice is melted and improving energy efficiency. It means that COP during night has to be higher than during the day and that sufficient capacity is available. It is also important to notice that dispatch of ice storage relies on 24 hours outdoor temperature and cooling load prediction.

$$Cost_{storage} < Value_{energy\ efficiency} \quad (3)$$

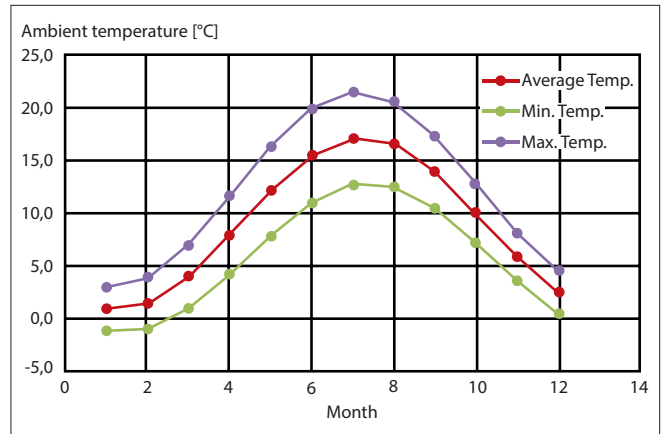


Figure 9. Thermal data from DK

In figure 10 the seasonal energy cost of a traditional system without heat recovery can be seen for the two scenarios. It is obvious that the volatile price development will result in a substantial energy cost increase as the refrigeration system has the highest load and the lowest COP during the warmer periods. It reflects also that systems have to develop to align to the future energy markets.

Using the 'free' heat recovery for sanitary hot water and space heating will reduce the energy cost with the amount of natural gas saved. This is already a widely used practice in many supermarkets today. The value is high and is shown in figure 10, left side. If the standard CO₂ system is equipped with additional feature like waste heat recovery, heat pump processing using idle compressor capacity and ice storage for improving the process efficiency during summer day operation; then a remarkable difference in the cost structure is seen in figure 10, right side.

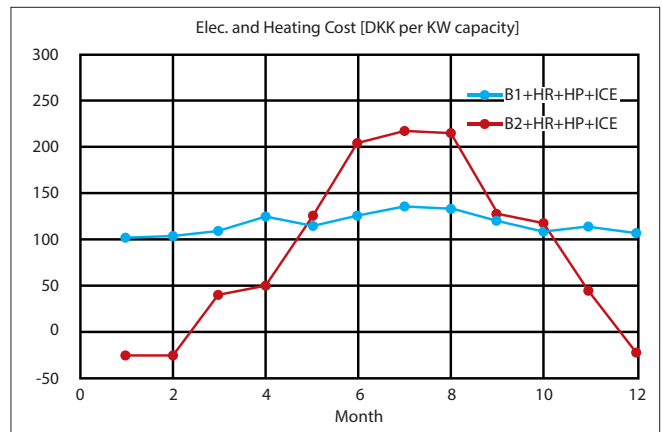
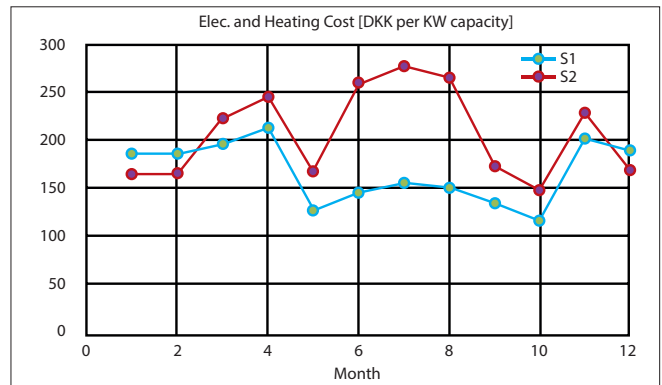


Figure 10. Cost of cooling and heating applying scenario 1 and 2. Left is standard CO₂ supermarkets and right is the same system basic but equipped with Heat recovery, Heat pump usage and Ice storage.

A yearly consumption overview can be made by accumulating the cost for 12 months. In Figure 11 the yearly income based on flexibility services are seen to be significant for the variable electricity pricing scenario while the constant electricity price has a much lower potential as only the imbalance service has a value. Figure 11 shows that variable electricity cost can be a beneficial scenario for supermarket systems – but there are important marginal Technology investments that needs to be done on top of the basic system. Heat recovery of waste heat and heat pump usage are the most dominant ones, but ice storage is also a very important contributor.

The flexibility services to help imbalance problems in the grid can also be a source of revenue. Fast response is normally traded as an agreement where the grid operator can dispatch an event with a certain capacity and duration

of time. Also 24h planning of capacity utilization versus price and planning of defrost events are known factors to optimize. It is obvious that scenario 2 with variable electricity prices will reward such technologies.

On site electricity production and storage is an interesting opportunity to reduce cost during high price periods. Supermarkets with large roof areas have the opportunity to install PV panels and the on-site produced electricity is best used when the grid electricity is high. In this case the high substation prices can be assumed. A battery can in case of variable process be very beneficial to use. Assuming a two hours battery storage would reduce the electricity cost during summer peaks hours accordingly as seen in figure 11. Furthermore, this storage would increase the fast flexibility capacity.

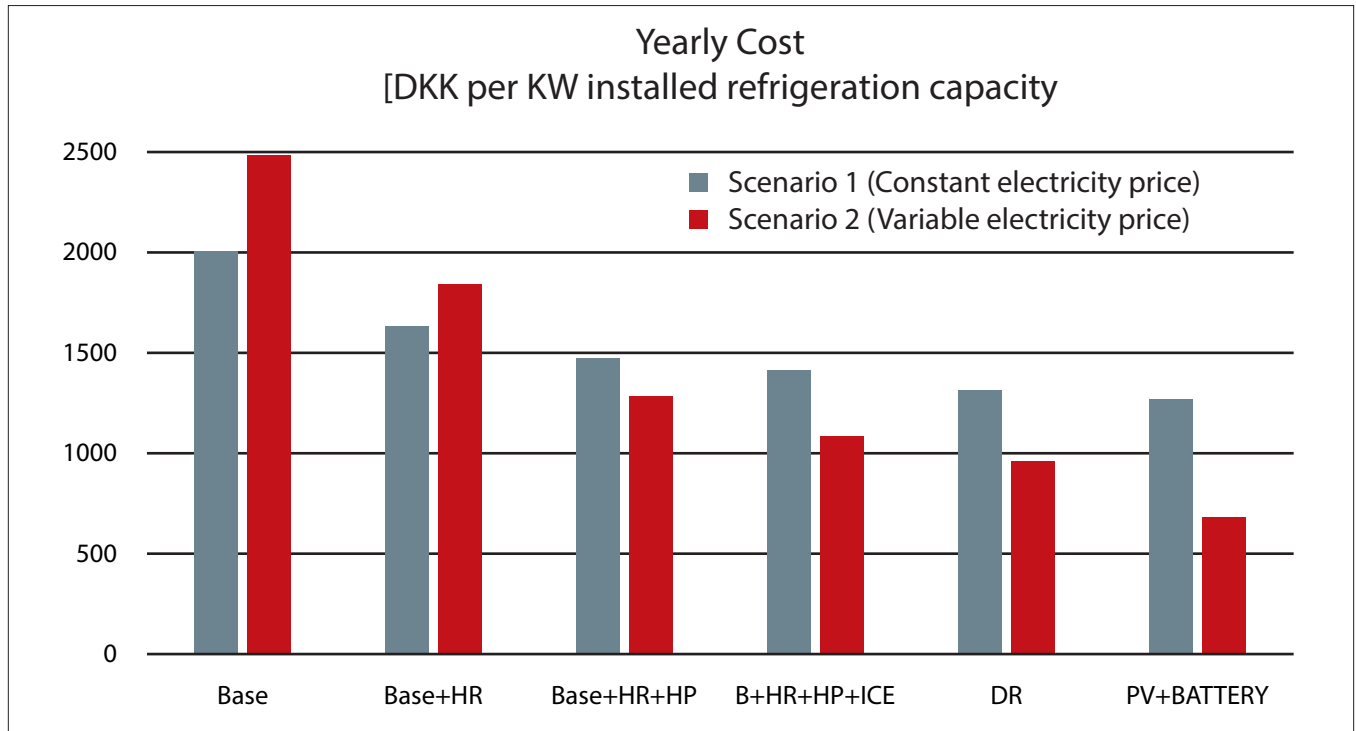


Figure: 11. Yearly cost of cooling and heating for two scenarios of electricity prices. Advanced CO₂ supermarkets appl. Scen.1 and 2

Conclusions

Traditional supermarket refrigeration systems can combine the renewable energy benefits of a smart energy system with environmentally friendly refrigerants in a new full system approach to optimally use flexibly enabled electrical and thermal networks. This new full system approach can capitalize on these benefits to ensure a positive business perspective.

The actual load conditions for supermarkets are characterized by a low load utilization. This low load usage can be exploited for extra heat pump operation that can empower supermarkets to become decentral heat suppliers.

CO₂ is a very well suited refrigerant for the integration of heating and cooling as it has superior heating and cooling properties within the existing component matrix.

The future will likely provide a much more volatile price structure for accommodating and rewarding flexible electricity consumption. It is a must that supermarkets address the opportunities like storage, heat recovery and heat pump processing. If these technologies are considered a very high reduction in running cost can be obtained.

Supermarkets can obtain substantial accumulated cost and emission savings by 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% by taking the full potential of energy savings 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 of success, specific solution guidelines are emphasized to exploit the heat recovery potentials.

References

- [1] Arnemann M. Real Energy Efficiency in Supermarket Refrigeration Systems, Institute of Refrigeration, Air Conditioning and Environmental Engineering, Karlsruhe University of Applied Science, 2014.
- [2] Funder-Kristensen T. Fösel G. Bjerg P.; Supermarket refrigeration and heat recovery using CO₂ as refrigerant, Cryogenics and Refrigeration Proceedings of ICCR2013 Paper ID: B129
- [3] Funder-Kristensen T., Green T., Bjerg P.; Supermarket refrigeration as an important smart grid appliance, 16th European conference on technological innovations in refrigeration and in air conditioning, Polytechnico of Milan, June 2015.
- [4] Mikhailov A., Matthiesen H.O., Suindykov S. Comparison of energy efficiency of systems with natural refrigerants, ASHRAE summer conference proceedings 2011. Ref number. D-ML-11-C015
- [5] Fredslund, K. Load part for supermarket refrigeration. Part of EUDP-1 ESO2 Project, Institute of Product Development, Technical University of Denmark, 2013.
- [6] Mazyar, K. Samer, S. Energy efficiency evaluation of integrated CO₂ trans-critical system in supermarkets: A field measurements and modelling analysis. International Journal of Refrigeration 82 (2017) p. 470-486