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Potential of Supermarket Refrigeration Systems for Grid Balancing by Demand Response

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Abstract: The environmental goals of European Union demand a larger share of renewable energy sources for electrical energy generation. With the increasing share of renewable energy sources such as solar and wind, the utility grids has an increasing need for energy storage and/or demand side management. With a high energy intensity and a large thermal inertia, the refrigeration systems of supermarkets appear as an attractive actor for demand response in such scenario. Theoretically they have the capability to absorb vast amounts of electrical energy as stored compressor work, lowering the temperature of the food goods in the refrigerators. Alternatively supermarkets have the capability of reducing their energy demand by allowing the food goods temperature increase to its upper limit, reducing electrical power demand for the grid. This positioning paper will further discuss the attractiveness as and feasibility to use supermarkets for electrical energy balancing by demand response in a smart grid.

1 BACKGROUND

The European Union (EU) Commission launched the European Climate Change Programme in 2000 to develop strategies to implement the Kyoto protocol in EU. In short the programme aim is to reduce the release of anthropogenic greenhouse gases (GHG) to the atmosphere and thereby mild the effects of global warming and climate change. The commitment was further strengthened by the Paris agreement from COP21 in 2015 where 195 UNFCCC members agreed to limit the global warming to less than $2°C$, while aiming at $1.5°C$ compared to pre-industrial levels.

EU has set ambitious goals towards a more sustainable future and by 2050 EU aims to reduce the GHG emissions by $80-95\%$ compared to 1990 levels(European Commission, 2012). The EU is pursuing these goals through both financial support and revised regulations as will briefly be introduced below(Union and Action, 2017). Milestones for 2020 is a 20% reduction in GHG, 20% reduced energy usage and a 20% increased energy efficiency.

The financial support is agreed as at least 20% of the EU's budget for 2014 to 2020 (€ 180 billion) shall be spent on actions helping to achieve the ambitious goals for 2050(European Union, 2018). Additionally individual countries and company initiatives are also funding parallel actions and projects.

The introduction of EU emissions trading system in 2005 that limits the maximum amount of GHG that the EU countries is allowed to release has created a platform for businesses to trade with their GHG-reduction. Companies and countries can trade their rights to release GHG, which becomes an incentive to reduce emission to increase profit.

Additionally, all EU countries are required to support renewable energy generation such as solar, wind and biomass as a part of the Green energy targets. Following the Revised Energy Directives (REDII) the EU should have reached an overall share of 27% of renewable energy by 2030, with some members performing significantly better(Comission, 2018). However, an increased share of uncontrollable and slower responding renewable energy sources creates an issue for the utility grid to balance the supply and demand.

In a traditional electrical grid, the supply is adapted to the demand by adjusting the electrical energy generation. The variations are often balanced by the use of smaller gas turbines, hydroelectric etc. that has the possibility to adjust their power outtake rapidly. However, gas turbines most commonly are using fossil fuels and the hydroelectric capacity is

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geographically limited to regions with a satisfying topology.

Therefore in a national, continental or global scenario where the share renewable energy sources are increased and the use of fossil fuels are to be minimised, these problems of balancing will become more severe. Implementing energy storage in combination with demand side management to adapt the demand to the available supply of energy is therefore needed (Farhangi, 2010).

1.1 Needed Energy Storage and Demand Response

In Germany, the implementation of renewable energy sources has been progressing in accordance with the goals of EU and the need of storage solutions in increasing. In (Sinn, 2017) the author concludes a storage capacity demand of $5,800$ GWh at 68% share of renewable energy and $16,300$ GWh with a share of 89% for the German context. In (Zerrahn et al., 2018) the authors instead conclude a 55 GWh need at a 68% share, and a 436 GWh need at 88% share. Already today and since years back Germany is facing issues with balancing the grid, resulting in negative electrical energy tariff(Deloitte, 2015).

If batteries or pumped hydro is used, it has the capability of storing electrical energy to be released later, but it is costly and also the materials used in batteries has a negative environmental impact(Sandén, 2014).

By introducing demand side response, the needed storage capacity will be lowered accordingly(Balijepalli et al., 2011). Instead of demanding energy when there is a deficit, the energy user will postpone the demand to a more favourable time for the supply side.

(Haider et al., 2016) ,(Costanzo, 2015) , (Gelazanskas and Gamage, 2014) ,(Gelazanskas and Gamage, 2014) and (Baharlouei and Hashemi, 2013) amongst others have discussed the benefits and challenges with demand response. They conclude one challenge to be the communication between a vast amount of appliances to schedule their loads optimally. By identifying large and energy intense systems, the amount of involved units can be reduces and this challenge is thereby reduced.

This is where supermarkets and their refrigeration systems appears as an attractive actor (Månsson and Ostermeyer, 2013)(Funder, 2015)(Pedersen et al., 2014)(Hovgaard et al., 2011).

2 POTENTIAL DEMAND RESPONSE BY SUPERMARKETS

Supermarkets are inherently intense energy users due to all food goods that demands refrigeration (Tassou et al., 2011). The thermal inertia of the refrigeration system is a great benefit as it would allow the supermarket to “charge” by transforming electrical energy into stored compressor work by temperature reduction of the food goods(Månsson, 2016). Additionally the supermarket would be capable of reducing the electrical power demand for refrigeration to nil within seconds if requested by the supply side.

In Germany alone, there are about $38,000$ supermarkets with an accumulated energy demand of 10 TWh (Funder, 2015), translating to an average of 30 kW of electrical power demand per market or 1.14 GW nationally. This represents about 2% of Germanys electrical energy demand, which is also a representative number for both Sweden (Arias, 2005) and UK(Tassou et al., 2011). With refrigeration representing approximately 50%(Statens Energimyndighet, 2010) of a supermarkets energy demand it is reasonable to estimate that the average power demand would be correspondingly large. And most certainly the rated power of the accumulated refrigeration systems is significantly larger, which is advantageous when acting as a energy sink for the grid.

2.1 Available Buffering Power and Energy

A supermarket refrigeration system could potentially run its refrigeration system at maximum rated capacity at any given time. This action would result in all refrigerated display cabinets decreasing in temperature at maximum rate. Several models for estimation of this rate and the energy demand exists (Smale et al., 2006) but are all dependent on accurate input parameters for the thermal properties of the food and refrigeration system. From the authors experience this rate is in the magnitude of $1°C/min$. As the temperature of the refrigerated display cabinets in general vary in time with $\pm 2°C$ around the set point temperature, the possible buffering capacity measured in time would be $0-4$ minutes, depending on the individual temperature levels of the cabinets in the supermarket.

Another scenario is to partially increase the compressor work above the needed heat extraction rate for the refrigerated display cabinets. This would result in a slower decrease of temperatures in the cabinets i.e. longer discharge time for the supply side. However, the energy buffered by the refrigerated display cabinets is equal for the maximum rate and partial rate scenario. The energy storage capacity is limited to the accepted lower limit temperature and the thermal inertia of the food goods and refrigerated display cabinets.

2.2 Available Electrical Demand Reduction

A supermarket could potentially also turn the compressor completely or partially off, resulting in a temperature increase of the food in the refrigerated display cabinets. The temperature increase rate is however lower than the temperature decrease rate. Following that the cabinets are developed to be energy efficient, the insulation capacity is high. From field observations and laboratory measurements an estimated temperature increase rate between $0.2-0.8°C$ per minute can be expected depending on the cabinet type and quality. For low temperature cabinets a lower rate is likely.

With the same reasoning as above, this gives a potential complete shut off time of $0-20$ minutes depending on the actual individual temperature and quality of the cabinets. In a scenario where the supermarket just has been charged and all cabinets are at their lower limit temperature and they are of highly energy efficient type, the upper figure of 40 min is true. This figure is however also influenced by the customer behaviours, i.e. if the doors are frequently opened or not.

If instead of completely turning the compressors off the supermarket keeps them at a reduced power, the supermarket should be able to run at reduced capacity for significantly longer times.

2.3 Example Store from Germany

To exemplify the potential, we present data from a $1,300\ m^2$ supermarket built in 2011 just outside Hannover in Germany. The refrigeration system serves a total of 22 doored freezers, 15 chest type freezers and 62 doored medium temperature cabinets as well as 12 meter of refrigerated deli desk. The rated electrical power for this system is approximately 50 kW.

In Figure 1 the electrical power demand by the refrigeration system is shown. Here it can be seen that the system uses on average about 25 kW over the week. Only at a few times a week the demand is above 30 kW and it never goes below 20 kW on the 15 min averaged data that is shown. The fluctuations in the low temperature compressors that causes the daily peaks is a consequence of synchronised defrost schedules for the low temperature refrigerated display cabinets.

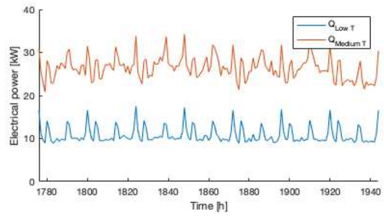

Figure 1: Stacked line graph showing one week of the 15 minute average electrical power demand by the $1,300\ m^2$ supermarket used in this example.

For medium temperature refrigerated display cabinets in the store, the setpoint temperature range is $6\pm2°C$ allowing for $4°C$ variation of temperature. For low temperature cabinets the set point is $-20°C$ with the same allowed variations.

To estimate the storage potential, the temperature decrease and increase rate must be known. The authors therefore performed a test on the medium temperature cabinets of the store to find the maximum temperature decrease rate. And a representative temperature increase rate for $23°C$ ambient conditions, which is slightly higher than the actual store temperature, making the results conservative. The results from the experiment is presented bellow in Figure 2.

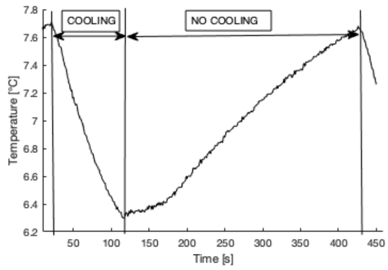

Figure 2: Temperature development in a refrigerated display cabinet during maximum cooling followed by no active cooling. Results are from a pilot experiment by the authors.

In Figure 2 it can be seen that the temperature decrease from 7.7 to $6.3°C$ occurs during approximately 100 seconds. Resulting in an temperature decrease rate of $0.84°C/min$. In analogy with the decrease rate the increase rate was calculated to be $0.24°C/min$.

2.3.1 Absorbing or Postponing Energy

From Figure 1 we see that the electrical power demand at any given time is within the range of $20-30$ kW. Meaning that the remaining power to reach the maximum power of 50 kW is $20-30$ kW too. With a temperature decrease rate of $0.84°C/min$, the market would be able to absorb energy for a maximum of

4.76 minutes resulting in $1.59-2.58\ kWh$ of excess energy stored.

If assuming that all components of the refrigeration system is at their respective lower temperature limit and that all cabinets have the same temperature increase rate we can calculate the maximum postponed energy use. From the experiment presented the authors concluded a temperature increase rate of $0.24°C/min$, meaning that it would take 16.7 minutes to increase the temperature by $4°C$. During this time the supermarket would under normal conditions ($20-30\ kW$) have used $5.3-8\ kWh$, which is the amount of energy that was shifted.

With the large number of refrigerated display cabinets it can be assumed that the distribution of their individual temperature is evenly spread within the upper and lower limits. This implies that a complete shutdown of the refrigeration system is only possible if the refrigeration system actively has cooled down all cabinets before the shutdown. Otherwise the warmer cabinets will exceed the upper temperature limitation and the food must be discarded. Running the system on partial load, serving only the warmer cabinets is however a more realistic scenario.

3 DISCUSSION

As shown in the example above and by the previous argumentation, supermarket refrigeration systems could potentially be utilised for demand response in the electrical grid. In the example the quantities of stored energy is rather low while the available electrical power is high and almost instantly accessible, making the supermarkets attractive as a short time energy buffer for the grid. One missing part to realise this today lay in the communication between the supermarkets and the electrical grid, both for the business agreements and digital signals to allow the grid to use the capacity.

In today's supermarkets the main objective of the control systems is to keep the food temperatures within the temperature limits and to make the heat extraction demand even for the compressors to be able run at an energy efficient level. Some system actively plans the cooling cycles to avoid peak power events to occur when the electrical tariff is high. Meaning that the refrigeration system today already uses the thermal inertia of the food goods, but for a different purpose then demand response. But due to the low accuracy of the control system the safety margins must be high to ensure the food safety. Meaning that the full range in allowed temperature variation is almost never used but rather limited to a few degrees.

When designing a supermarket refrigeration system they are made to be redundant to ensure that heat extraction demand never is larger than the installed capacity. This has led to that the supermarkets has significant amounts of spare cooling power capacity, which most certainly would benefit the electrical grid to have as buffering capacity.

Following that the four largest supermarket companies Aldi, Netto, Lidl and REWE represents 14 640 (Statista, 2013) of these stores, the sector becomes easily addressable. Meaning that if the companies find incentives to implement demand response, the accumulated effects would be very large.

With low profit margins ($2-3\%$)(Arias, 2005), the supermarkets are prone to adapt cost reducing actions in their markets(Retail Forum for Sustainability, 2009). Potentially being offered by the electrical grid companies to sell buffering capacities or benefit of reduced energy prices might be an attractive incentive. With the trade of Carbon-emission rights the supermarkets could claim to have lowered the GHG emissions and therefore sell parts of its emission rights. Creating a second revenue stream for the supermarket companies.

From a technology implementation perspective, the larger organisations are often using standardised solutions which would mean that the demand response technology that is necessary would have fewer variations. Adapting the technology of one system that is used for thousands of similar stores makes it more attractive for developers to find a business case.

The businesses case is however rather complex and must involve benefits for two actors, both the supermarket and the energy producer. Fiscal and economical incentives for increased energy efficiency and lower climate impact for the energy producers are obvious. But these benefits must also be transferred to the supermarkets to motivate the initial investment in systems allowing for the demand response to be implemented.

An interesting aspect is that the driving force that makes supermarkets attractive for demand response is their high energy intensity. Meaning that any energy efficiency measures that lowers the energy demand for refrigeration will negatively affect its capacity as a resource for demand response. Yet it will lower the local energy demand and thereby the energy bill. Therefore, finding a balance between the incentives here is crucial.

Another aspect of the utilisation of the refrigeration system for demand response is the fact that the thermal mass is highly valuable food. The accumulated monetary value of the stored food in the cabinets is monumental. This demands that the implemented technologies are safe against failures and the highest priority must always be the food safety.

Depending on the business model of the supermarket companies and the incentives provided by the electrical grid, the installation of additional cold thermal storage for the refrigeration system might be beneficial(Ochieng et al., 2014). As presented earlier the duration for which the refrigeration system can be turned off or ran at maximum capacity is limited to the thermal inertia of the food. If installing additional thermal energy storage units, the duration and stored energy could be increased. Additionally depending on on chosen technical solution for thermal energy storage, this would also allow for complete shutdown by allowing the valuable food goods to cool directly from the thermal energy storage instead of increasing its temperature. The optimal sizing of such a storage depends on the energy demand by the supermarket and the business agreements with the utility grid. However, the storage is one directional as the stored compressor work cannot be converted back to electricity. Meaning that there must be a balance between the supermarkets heat extraction and the stored electrical energy over the chosen storage period which could be stretching from minutes to seasons.

4 CONCLUSION

With the above presented arguments and discussion we conclude that utilising supermarket refrigeration systems as a part of the grid balancing mechanism is feasible. The technology is there and the incentives could be created via the right business model. In theory almost any centralised refrigeration control system would be capable of providing this buffering capacity to the grid, the main barrier is the business models and control system accuracy and communication.

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