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Smart Grid Control: Demand Side Management in Household Refrigerators as a tool for Load Shifting

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Smart Grid Control: Demand Side Management in Household Refrigerators as a tool for Load Shifting

Abstract

With improved supply of renewable sources of energy the focus has shifted away from simply producing clean energy to efficient consumption of energy. Until cheaper methods of energy storage are developed, Demand Side Management (DSM) is the best option for maximising energy efficiency. This paper proposes a method of turning regular refrigerators into smart demand response fridges. First, we develop an algorithm that accounts for small fluctuations in price and switches the device for optimal performance and lowered running cost. Then, we use longer price fluctuations to predict suitable times for pre-cooling and investigate the reduction in price as a result. Finally, the two models are compared, evaluated and improvements are proposed.

Keywords

Smart Grid, demand side management, demand response, DSM, load shifting in refrigerators, grid, Refrigerator, fridge, load-shifting

Cover Page Footnote

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Smart Grid Control: Demand Side Management in Household Refrigerators as a tool for Load Shifting

1 Introduction

With the widespread use and acceptance of solar, wind, hydroelectric and other forms of renewable energy, the problem is no longer being able to produce enough renewable energy but to efficiently consume the amount we do produce.

Solar energy peaks in the middle of the day whereas wind energy peaks at night. These are both inconsistent with the energy demand peaks. The mismatch between energy production and demand in an academic building at the Technical University of Delft in the Netherlands is shown in the graph below (Cardona et al). When the excess renewable energy can not be consumed, it is dispelled or provided elsewhere in the grid.

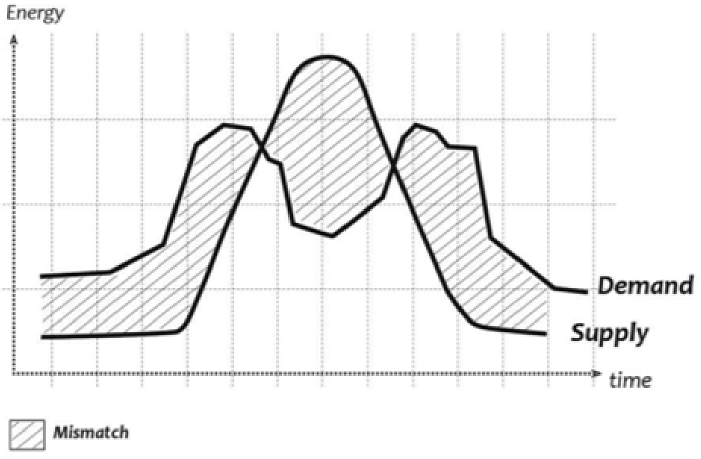

Figure 1: Mismatch in daily Energy demand and Energy Supply for a building at TU Delft in the Netherlands (Cardona et al)

There are two potential solutions to this: developing better storage options or Demand Side Management (DSM).Currently, it is cheaper and more feasibly to dissipate extra energy than to create cost effective storage methods. Thus, as we are nowhere near discovering feasible energy storage options, the last few years has seen an increased interest in Demand Side Management. Under the current model, when renewable energy sources are unable to meet demand, non-renewable resources are employed to meet the increased demand. DSM aims to spread the consumption of energy away from peak demand periods fueled by non-renewable energy to low demand and peak renewable energy supply periods. Thus, allowing for better consumption of produced energy. DSM would provide decreased energy costs for consumers and a lower carbon footprint at a potentially low price.

For our research purposes, we use the cost of energy as an indicator of increased efficiency. Firstly, lower energy prices indicate low demand periods during which time there is less usage of fossil fuel sources. Furthermore, lower energy costs also signal periods of time when there is excess energy. Usually excess energy is produced from non-renewable sources as we can not control their supply and not fossil fuel sources which we can control.

In this paper we seek to implement Demand Side Management (DSM) or Demand Response (DR) to household refrigerators to decrease the monthly cost of running said refrigerator. The main strategy used is named load shifting. Load shifting involves the shifting of energy demand away from peak demand periods to peak supply periods.

Refrigerators make up around 9 % of total energy consumption of an average household making it the most energy consuming single appliance in households worldwide (Arteconi et al). In Germany, refrigerators and freezers account for 16TWh or 5.76×104 TJ of energy consumption yearly (Stadler et al). This allows for a total load shifting potential of 800MW (Stadler et al). To put this into perspective, 1 MW of electricity would be able to supply about 800 households its average energy needs for 1 hour. Therefore, refrigerators are the single most impactful household appliance when it comes to Demand Side Management. Furthermore, refrigerators operate autonomously with little to no interaction from consumers meaning any changes to their system of operations would not interfere with consumer interactions with the appliance.

2 The Architecture of the Model and Implementation

The current household refrigerator has a rather crude up and down temperature regulation system. The refrigerator has an upper and lower temperature value. A temperature sensor routinely detects the temperature and when the temperature increases above the upper values, in our case 8 °C, the compressor in the fridge is switched on to begin cooling the fridge compartment. This continues until the temperature sensor detects a reading below the lower value, which in our case is 5 °C. Then, the compressor is switched off and the temperature in the compartment is allowed to increase gradually.

In order to implement DSM, we imagined a two-part system to integrate the refrigerator to the grid. The first part would be the compressor control side which will be built into the mechanism of the fridge. Given the current introduction of smart fridges, this can be easily accomplished through tweaking the programming of the fridge. This side can also collect user data like how many times the door is opened, how long the door is opened for, the average thermal capacity of the contents of the fridge, etc. The second part would be detached from the fridge and instead mounted externally. This will be the part that communicates with the grid through a network and can store the data collected by the compressor control side. Such a division in the architecture will ensure that the fridge does not malfunction even if there is a failure in the network or with grid connection. A similar model was imagined by Arteconi et al and the diagram below demonstrates the method of communication between the two.

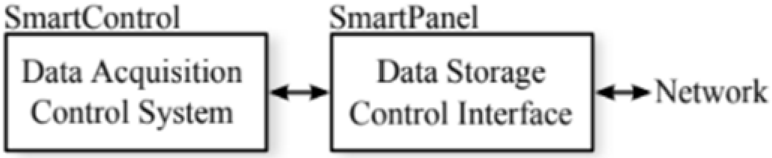

Figure 2: Arteconi et al

Next, we need to model the internal temperature of the refrigerator compartment. In their paper titled Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices, Stadler et al use the formula presented below to predict the change in temperature with respect to time in a fridge compartment.

$$T_{i+1} = \epsilon * T_i + (1-\epsilon)(T_{amb} - \frac{np}{A}) \tag{1}$$

Where ϵ is defined as follows:

$$\epsilon = e^{\frac{-\tau A}{m_c}} \tag{2}$$

Where T_i is the initial temperature, T_{amb} is the ambient temperature, n is the efficiency, P is the power of the compressor, A is the thermal conductivity, τ is the time step and m_c is the thermal mass. From sampling several fridges, Stadler et al determined that n is 3, P is between 50 and 70 Watts, A is 3.21 W/C, and m_c has an average value of 86400J or 24 Wh/C. The value of T_{amb} is the average temperature of a room (here 24 °C) and τ as 30 seconds. This data is also presented in the table below:

Variables and Values for Fridge			
Variable	Symbol	Value	Units
Inital Temperature	T_i	8-5	°C
Ambient Temperature	T_{amb}	24	°C
Efficiency	n	3	no units
Power	P	50-70	W
Thermal Conductivity	A	3.21	W/C
Time Step	τ	30	s
Thermal Mass	m_c	86400	J

Table 1: Table of Variables for refrigerator model.

These values yield a cooling period of around 30-35 minutes and a natural warming period of 100 to 105 minutes. If we run this simulation the graph of temperature vs time will look as follows:

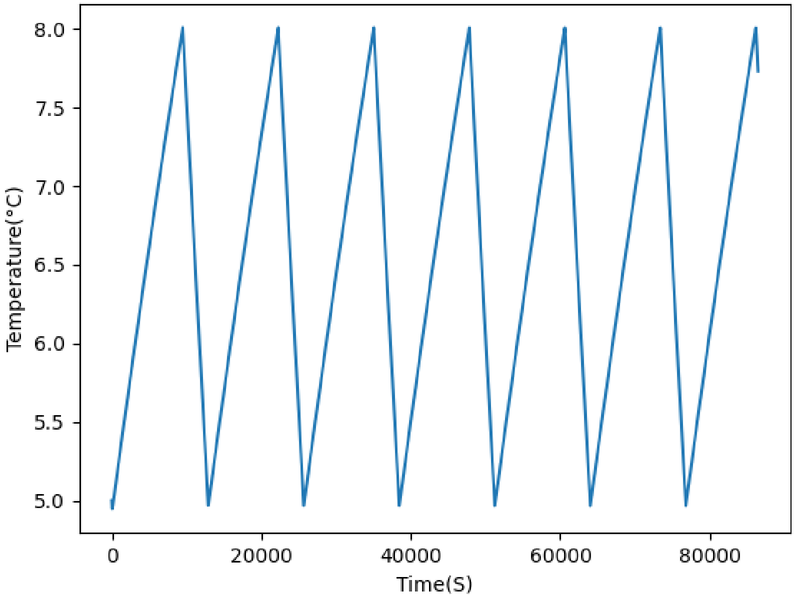

Figure 3: Demonstration of a refrigerator's 24 hour heating-cooling cycle. Temperature variance of a typical refrigerator

It is important to note that this model does not include ventilation within the fridge compartment and the effects of opening the fridge door for long periods of time. Furthermore, we have left the thermal conductivity and thermal masses constant throughout this simulation but it is indeed possible to integrate varying values for both A and m_c in the future. This gives a total cost of \$ 28.645239 to run for one month. Note that this is a large, old refrigerator. With the improved design and increased efficiency of newer refrigerators, a modern household refrigerator would cost around \$ 10-12 monthly.

3 Pricing and Grid Integration

In order to integrate the refrigerators into the grid, we need to gather information about the grid. Figure 4 demonstrates fluctuation of energy price in \$/W every 5 minutes as measured by ISO New England. The data shows price changes between 00:00 and 23:55 in households on February 7th 2022.

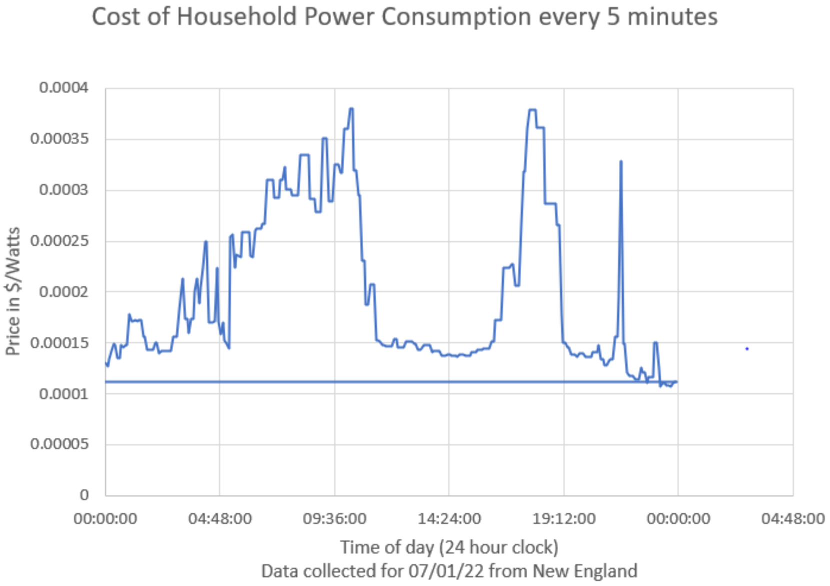

Figure 4: Cost of Household Energy as measured every 5 minutes

Whereas Figure 5 shows the general changes in price in \$/W as demonstrated by ComEd. This includes industry, businesses etc. in addition to households.

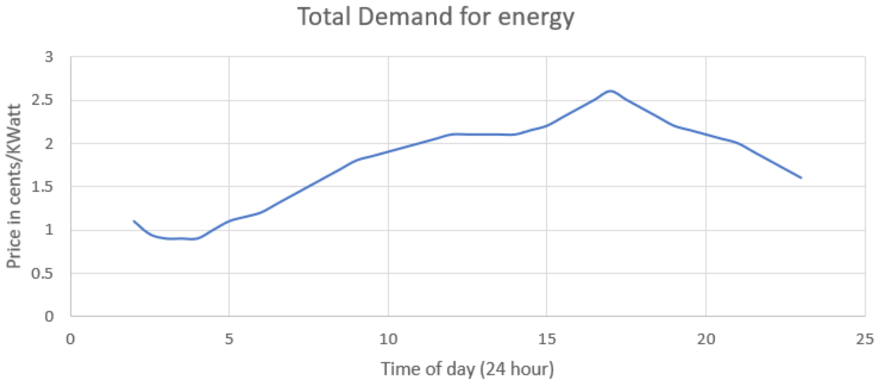

Figure 5: Cost of Household Energy as measured every hour

These graphs demonstrate the potential for load shifting away from the evening and afternoon peak between 15:00 and 17:00 towards midday.

4 Smart Algorithmic Demand Shifting

One potential method of load shifting would be modifying when the compressor turns on or off. Currently the compressor only turns on when the temperature is equal to or above 8 °C and turns off when it is equal to or below 4 °C. Note that it would not be possible to stop the compressor from running when the temperature is equal to or above 8 °C as that risks allowing the temperature of the compartment to increase above 8 °C and spoiling the contents of the fridge. However, it is possible to turn on the compressor before the temperature inside the compartment reaches 8 °C and have it begin its cooling cycle earlier. In doing so, we can encourage the compressor to run during times of low demand and stay off during times of high demand.

This was simulated in Python. The python code works as follows: if price is decreasing, the compressor is activated, if the price is increasing, the compressor is deactivated, if the price is staying the same, the function checks if the most recent change in price was positive or negative. If positive, the compressor is deactivated, because it means that the price is currently at a local high point. If negative, the compressor is activated, because it means that the price is currently at a local low point.

In doing do so, the total price is reduced to $ 28.645239 per month. This is an overall 4.6% price reduction. When the temperature and time are plotted, it yields the graph shown below:

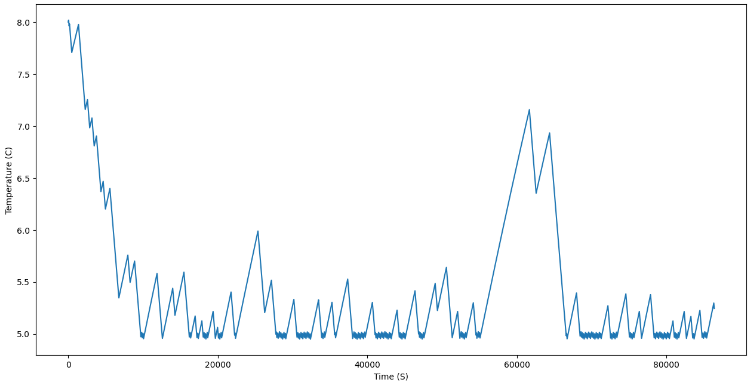

Figure 6: Refrigerator's heating-cooling Cycle when operated by the Algorithm

Here the algorithm seems to turn the compressor on before letting the temperature of the fridge increase substantially. One potential method to increase the efficiency further could be to allow for longer times of the warming period. However, despite having numerous, shorter, spardonic times when the compressor is on, the overall cost of running the refrigerator is lower because it is consuming more renewable energy (which would otherwise have been dispelled) and less non-renewable energy.

5 Precooling as a Demand Side Management strategy

Precooling involves a method of cooling a system at a point in time when it may not be required. This happens at a fixed time and usually occurs once or twice a day. Using the model of a smaller fridge with a power of 20 W, A of 1 W/C and m_c of 100J, we modeled how precooling at different times of the day would change the total price of running the refrigerator for a month. In doing so, we realized that the starting temperature of the compartment i.e., the part of the cooling cycle the fridge was in at the beginning of the day effected minimum price.

We used the price data from Figure 5 in this simulation. When the precooling is started with the fridge at an initial temperature of 6,7 or 8 °C, the lowest monthly price at, \$10.94, is obtained by precooling at 5:45 am. If the precooling is done with the fridge starting at an initial temperature of 5 °C, then the lowest price obtained is \$ 10.52 with precooling at 12:15 am. This suggests that having the fridge begin at the end of a cooling cycle at 12:00 am and starting the cycle again at 12:15 minimizes the price. Hence, the starting temperature acts as a precool itself. The graphs below demonstrate the price change as a result of precooling at different times of the cooling cycle

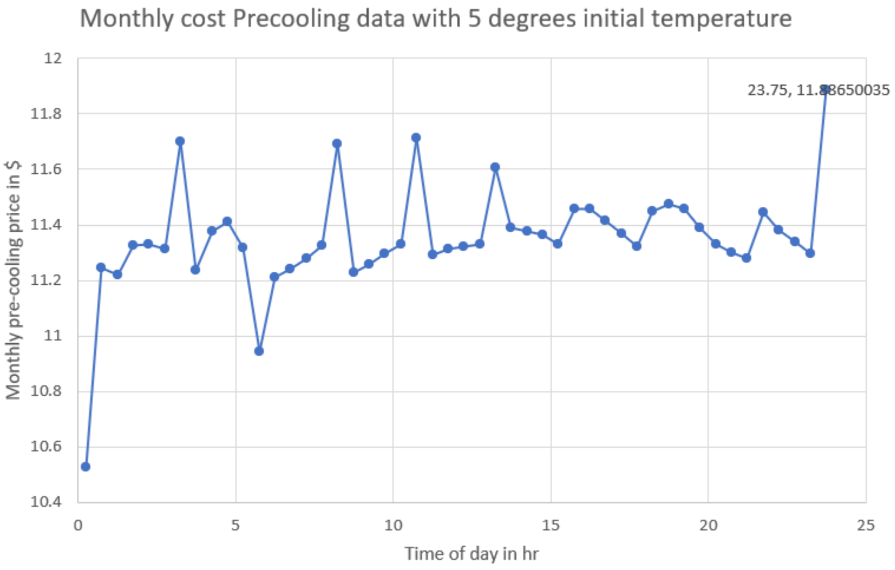

Figure 7: Refrigerator's heating-cooling Cycle when operated by the Algorithm

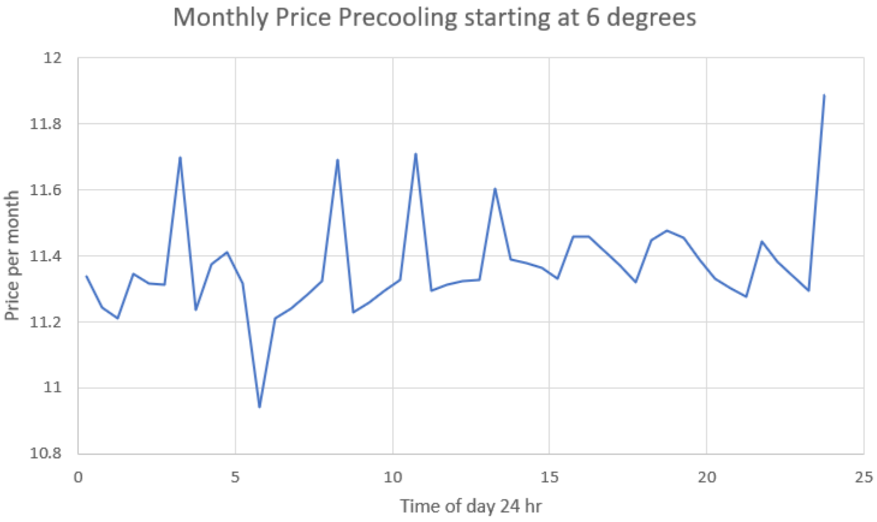

Figure 8: Refrigerator's heating-cooling Cycle when operated by the Algorithm

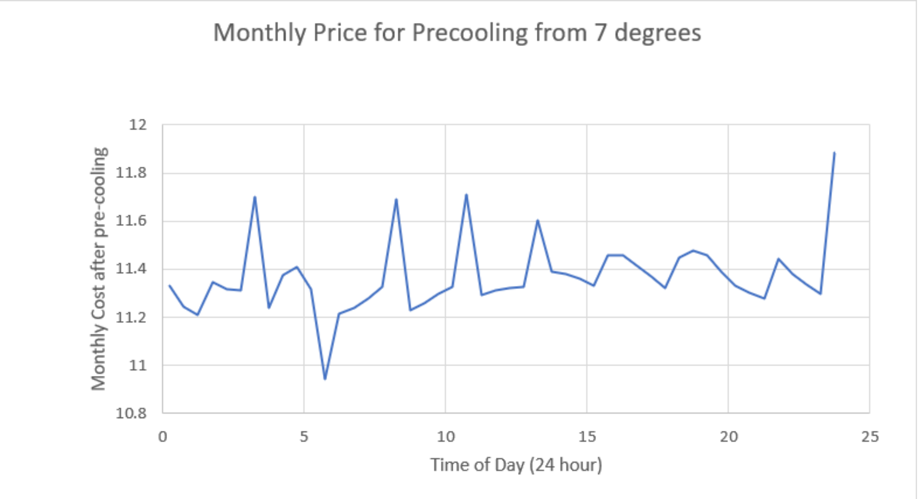

Figure 9: Refrigerator's heating-cooling Cycle when operated by the Algorithm

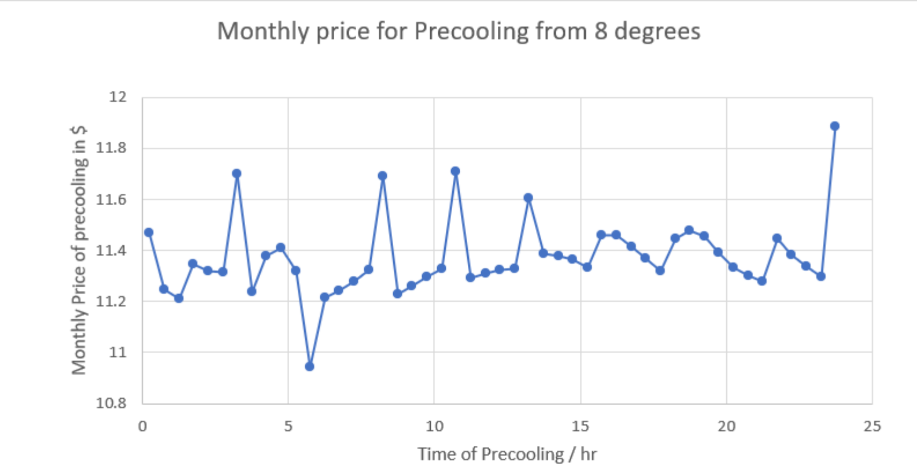

Figure 10: Refrigerator's heating-cooling Cycle when operated by the Algorithm

6 Implementation

Now that we have established that a real time smart algorithm and planned precooling can reduce the cost of running a refrigerator, we must determine the best method of wide scale implementation. The cost of the model and the energy draw to run the DSM system should be less (ideally considerably less) than the energy reduction achieved through load shifting. Although the cost of such development may initially be expensive, much like solar cells, wide scale production of DSM architecture will help reach economies of scale and hence, reduce costs in the long run.

Furthermore, wide availability and flexible programability of micro controller devices make them ideal for DSM use. While we would recommend the use of a PCB for design and development purposes because of it's ability to house both the compressor control side and communication side within a singular board, microcontrollers may be preferred for later wide scale use for their affordability once the model has been perfected. In addition to sharing historic data trends, real time price data can also be obtained either over the network on the smart panel side or measured using a current meter on the smart control side (Bigler et al).

7 Conclusion and Further Research

The first method is overall more useful than the second as it allows for more flexibility in the case of rapid price changes. Furthermore, it can respond to smaller spikes in prices and is not set at one point in time. Meaning, that regardless of which part of the cooling cycle the refrigerator is in, the algorithm can shift it to minimize costs. Overall, both methods show that it is possible to decrease the price of running a refrigerator with DSM.

For further improvement, it would be interesting to see how changing the values of thermal mass and thermal conductivity effect this model. Moreover, we can introduce variables such as opening and closing the fridge door and compartment ventilation. However, introduction of ventilation would mean that we can no longer use equation 1.

Even if we stick to the current model, it is possible to improve the smart algorithmic demand shifting model. Currently, the model rarely allows the price to even increase above 6.5 °C. For future work, it would be interesting to see how to stretch out the cycles further and use intelligent AI code to perform more specialised switching of the compressor.

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