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Experimental analysis of flexibility change with different levels of power reduction by demand response activation on thermostat controlled loads

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Abstract

This paper studies the flexibility available with thermostatically controlled loads (TCLs) to provide power system services by demand response (DR) activation. Although the DR activation on TCLs can provide power system ancillary services, it is important to know how long such services can be provided for when different levels of power reduction are imposed. The flexibility change with different levels of power reduction is tested experimentally with domestic fridges used by real customers with unknown user interaction. The investigation quantifies the flexibility of household fridges and the impact of DR activation in terms of deviation in the average temperature. The maximum possible power reduction with the cluster of refrigerators is 67% and the available flexibility with the cluster of refrigerators is 10%. The resulting deviation in the average temperature is 14%.

Keywords: controllable load, demand response, demand side management, domestic energy resources, flexible electricity demands, smart grid.

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Abbreviations

BRP: Balance responsible party

COP: Coefficient of performance

DR: Demand response

ICT: Information and communications technology

QOS: Quality of service

RES: Renewable energy sources

TCL: Thermostatically controlled load

TSO: Transmission system operator

UFLS: Under-frequency load shedding

1. Introduction

The reliability of electric power system operation depends solely on the balance between power production and consumption. In a conventional power system, the balance is achieved by consumption-driven production. In such a scenario, long-term [1] and seasonal [2]load and change forecasting is used to plan new power plants and power production. As the electricity market has become unbundled, one-day-ahead demand forecasting helps to schedule the power procurement [3], [4]. The transmission system operator (TSO) is responsible for the power system balance. The errors in the demand forecast are managed by additional local procurement or consumption at short notice to avoid large deviations from the unit commitments of the power plants [5], [6]. Such services are called ancillary services and are provided by balance responsible parties (BRPs) and the regulating power providers on request from the power system operators. Due to increasing awareness of the negative environmental impacts of greenhouse gas emissions from conventional power plants' exhaust gasses, motivation for the usage of renewable energy resources (RESs) in the electric power system is high. Therefore, the participation and penetration of RESs increases as time goes on. The RES electricity

supply varies, as RESs like wind and solar power fluctuate [7]. The fluctuations in the electric power production by RESs need to be compensated either by an additional supply of power from fossil based power plants [8], [9]or by controlling demand to achieve a balance in the power system[10]. Demand response (DR) is a widely accepted operational procedure carried out by power-system operators [11], [12].

Electricity consumers can be broadly classified into three classes: industrial, commercial, and domestic [13],[14]. The demand adjustment from industrial consumers is large in comparison to the other two segments [14]. Industrial consumers can support only a scheduled demand adjustment, as the machinery used may require a complex start-up and shutdown procedure and skilled manpower to execute the procedures. But the ancillary service requirement of demand adjustment may arise at anytime. Domestic and commercial consumers are suitable for ancillary service provision by DR due to their time availability and less complex electrical gadgets, which are easy to control.

In Nordic countries, the share of domestic electricity consumption is 26%[15] and the domestic segment has great potential for DR services[16]. During appliance control, the service provided by the appliance should not be affected by the control event. Such a constraint makes thermostatically controlled loads (TCLs) most suitable for DR applications. TCLs provide a temperature service. The temperature effect is stored in the thermal mass of the TCLs, which can sustain the impact of power reduction. In a single household, the flexibility for demand adjustment may be a small quantity. When the flexibility from multiple households is aggregated, their potential is very high. To manage the massive distributed TCLs, the aggregators can play an important role similar to the BRPs[17]. The aggregator may be a separate entity or a part of the BRP.

When the power system operator requires an ancillary service related to power reduction, the aggregator will serve the request by controlling the loads of the consumers. Under control, the service provided by the loads to the consumer should not be affected or the deviation in the quality of the

service should be within the limits guaranteed to the consumers by the aggregator. The service provided by the TCLs is quantified in terms of temperature. Therefore, the deviations in the quality of service at different power-reduction levels can be analysed with the temperature variation. Also, the temperature of the TCL system represents the amount of thermal energy stored within the system, or in other words the flexibility available with the TCL. By predicting the temperature profile, the duration for which the system can support the service of power reduction can be predicted. Therefore, the variation in the available capacity with respect to different levels of power reduction can also be analysed. Further, the maximum possible power reduction by respecting the temperature limits of individual TCLs can be studied and the deviation in QOS can be analysed.

The aim of this work is to investigate the potential and capacity for power reduction by DR activation on TCLs using domestic refrigerators as an example. In Denmark, refrigerators and freezers contribute 18% of total domestic electricity demand and they are regarded as important DRs in the smart grid [18]. Refrigerators are considered for DR study in many research activities [19]–[21]. A simulation study with large-scale control of domestic refrigerators for reduction of peak demand in distribution systems is presented in [19]. In [20], a simulation study to support the primary reserve by under-frequency load shedding (UFLS) is studied. The energy consumption optimization of refrigerators is studied with a grey-box model developed using time series data from experimental measurements in [21].

The adaptive fridge model presented in [22] is used to predict the fridge behaviour for control purposes, as the model requires only two measurements and the prediction errors are within 5% [23]. The investigations of the work presented in this paper consist in:

1.   Real world application of refrigerator model.

A real world application for the black-box model described in [22] to provide power system service by load reduction is experimented. The black-box model requires only two measurements and predicts

TCL temperature close to the actual one when the dynamics of the system are not changing. The model is a generalized model suitable for any type of TCLs. Such a model is suitable for experiments with a large number of TCLs, where the number of parameters measured is limited. The analysis reported in the paper under revision allowed evaluating the range of applicability of the model.

2.   TCL control limitation due to resource synchronization.

The TCLs operation is synchronized when a group of TCLs is controlled for the aggregated power reduction. The higher is the aggregated power reduction the sooner will the TCLs operation get synchronised. The analysis presented in this paper defines the limits of the control method using the black-box model for aggregated power reduction without TCL operation synchronisation in terms of control duration.

3.   TCL flexibility definition and evaluation.

The thermostatically controlled loads (TCL) are not available for power system service provision when the thermostat switched OFF the load. This paper defines the flexibility of the TCLs in such scenario without altering the TCL. A correlation between the available flexibility and the aggregated power is given under normal operation. The change in the flexibility of group of TCLs is analysed when the aggregated power is limited to different levels compared to the normal value. The flexibility analysis discussed in the paper can be used to derive a metric about the change in flexibility for a larger population of TCLs.

The rest of this paper is organized as follows. In Section 2 the method of flexibility analysis of power reduction with DR activation and the problem outline are introduced. Section 3 explains the experimental procedure, experiment platform, the hardware devices used for control and measurement, and their configuration. Section 4 discusses the control strategy and practical limitations in detail. The results of the experiments are reported in Section 5. The discussion and conclusion are presented in Sections 6 and 7 respectively.

2. Methodology

The refrigerator is a thermally insulated box fitted with a compressor to pump heat out of the box to the ambient. The compressor is controlled by a thermostat. The temperature inside the refrigerator is maintained between two limits, namely Tmax and Tmin, by the thermostat. The thermostat switches the compressor ON when the temperature is above the temperature limit Tmax. The heat from the refrigerator is pumped out to the ambient by the refrigeration system. This causes the temperature inside the refrigerator chamber to decrease. As soon as the temperature decreases to the limit Tmin, the thermostat switches the compressor OFF. As the ambient temperature is higher than the temperature inside the refrigerator chamber, the heat flows from the ambient into the refrigerator cooling chamber through the walls and also during opening of the refrigerator door for food exchange. The heat flow causes the temperature of the cooling chamber to increase when the compressor is OFF. The heating and cooling cycles of the refrigerator can be called thermostatic cycles. The duration of the thermostatic cycle for heating and cooling depends on many parameters. The cooling duration required for the temperature to reach the value Tmin from the temperature value Tmax depends on the compressor power and its coefficient of performance (COP), the ambient temperature, the insulation parameters of the refrigerator, and the thermal properties of the cooling chamber's content (food). The duration of heating required for the temperature to rise from the value Tmin to Tmax depends on the parameters listed above, except for the compressor specifications. As the refrigerator has the ability to store the temperature effect with its thermal inertia, it can be used to provide the power system ancillary services. The method described here controls the refrigerators' state (ON/OFF) in order to keep their aggregated power consumption at a given set-point value without violating the temperature limits of the individual refrigerators. On controlling the refrigerator, one of the constraints is that the temperature Tmax of the refrigerator cool chamber should not be exceeded. The change in the available flexibility provided by the refrigerators can be analysed at different levels of power

reduction from the normal consumption.

In the presented control architecture in Figure 1, a central controller for refrigerators collects the temperature measurements and power consumption from all refrigerators. The central controller can predict the temperature of fridges and the duration for which they can be switched OFF or ON without violating the temperature boundaries with the use of a simple black-box model [22]. The black-box model considers the temperature curves of the thermostatic cycles as a piece-wise linear one and uses the slopes of the temperature curves to predict the temperature cycle duration.
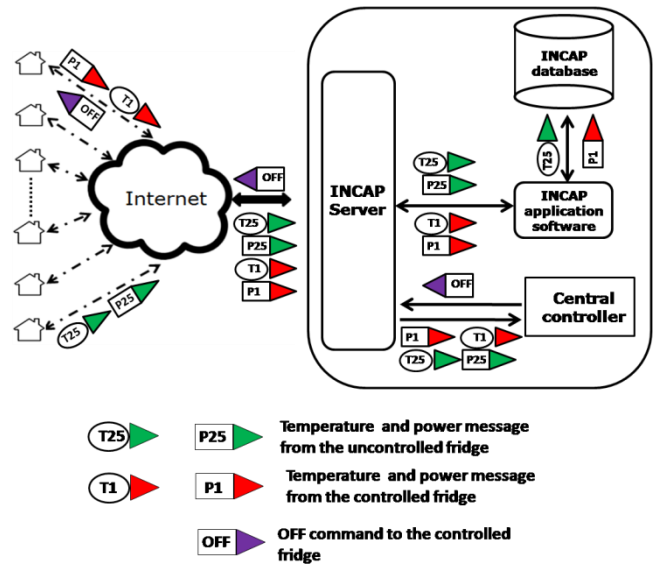

Figure 1. Control diagram and information flow.

In the proposed algorithm, the fridge flexibility is measured by the duration for which the refrigerator can be switched OFF without violating the individual refrigerator's temperature limit. The switch OFF time can be calculated by predicting the temperature inside the cooling chamber. In order to calculate the prediction of the cooling chamber temperature, the fridge's thermal behaviour has to be modelled. The black-box model [22] used in this study requires only two measurements and predicts a cooling chamber temperature close to the actual one when the dynamics of the system are not changing. It is also a generalized model suitable for any thermostatically controlled loads such as space heaters, heat pumps, air conditioners, refrigerators, and so on. Such a model is suitable for experiments with a large

number of refrigerators, where the number of parameters measured is limited.

3. Experimental procedure

3.1. Test scenarios

The experiment is conducted for four scenarios with different values of power reduction as shown in the Figure 2.

Scenario 1: Scenario 1 is the base case without any control. The refrigerator power consumption and the temperature were observed for 24 hours. The observation without control gives an idea about the variation in aggregated power consumption with time. The power limitation set-point for the control in the following scenarios is derived from the base case scenario 1.

Scenario 2: In scenario 2, the control objective is to maintain the aggregated power at the average value of power consumption in scenario 1without violating the temperature limits of individual refrigerators.

Scenarios 3 and 4: Scenarios 3 and 4 are used to understand the limits of the possible power reduction by DR activation on TCLs. The power limits for the controller are set as 50 and 25% of scenario 1 average value in scenarios 3 and 4, respectively.

The proposed method for TCL flexibility analysis is tested with refrigerators in real households with unknown user interaction. The following section introduces the experimental set-up and provides a description of the information and communication technology (ICT) infrastructure supporting the experiment and a description of the gathered measurements.
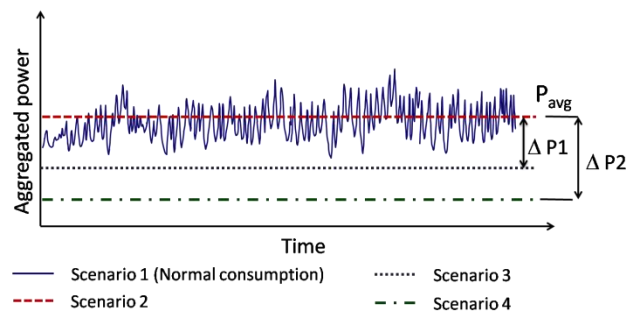
Figure 2. Scenario description.

3.2. Experimental setup

The experiment utilized the infrastructure and the refrigerators of the participants in the project INCAP. The INCAP project has established an ICT infrastructure for the real-time measurement and control of temperature and power of domestic fridges in the western part of Denmark for a field experiment. Figure 3(a) shows the experimental set-up. The block diagram in Figure 3(b)shows the devices installed for control and data collection in each household participating in the project INCAP. The devices used for control and data collection are as follows:

1. Relay unit with power measurement facility to switch the fridge ON and OFF in response to a remote command and to measure the active power consumption by the fridge.

2. Temperature sensor to measure the temperature inside the fridge cooling chamber.

3. A user interface device with red and green lights and two buttons to communicate with the user.

4. A Zigbee-Ethernet gateway device to enable interaction of these devices with the remote server.
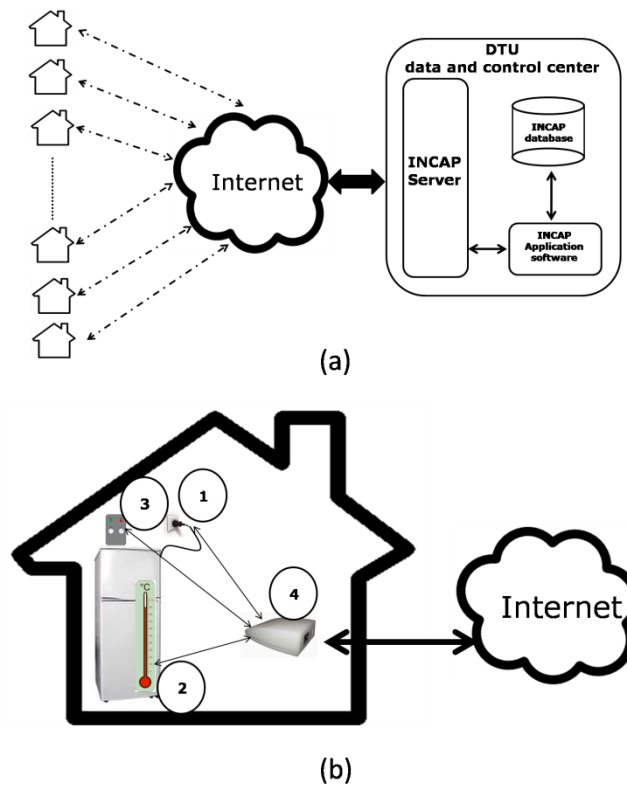

(a)

(b)

Figure 3. Data flow from the fridges to the controller and refrigerator control device installation in a

house

Develco Products A/S, one of the partners in the project INCAP, provides these devices from its Zigbee wireless home automation network products line. The Zigbee-Ethernet gateway device hosts the local Zigbee home network as a coordinator, and other devices become the child of the local Zigbee network. The Zigbee-Ethernet gateway device establishes the connection to the control server through a wired ADSL home Internet connection. Two of the devices, namely the temperature sensor and the user interface device, are battery-powered devices, while the other two are mains supply powered. For the field experiment in INCAP, devices were sent to the consumers. Once installed, the devices sent authorization requests to the server and were authorized by the server to join the Zigbee network. The temperature sensor was placed in the cooling chamber of the fridge and the relay unit was connected in series with the power input to the fridge. The measurement sampling rates for the different devices were configured by the server.

3.3. Measurement parameters and sampling rate

The temperature sensor sends the temperature measurements at two-minute intervals. The sampling interval was preconfigured by the manufacturer in order to have a longer battery life. This sampling rate cannot be changed. As the temperature inside the refrigerator changes very slowly due to the thermal inertia of the food content, the two-minute sampling rate is sufficient to appreciate these dynamics. The temperature sensor has an accuracy of ±0.5 °C. The relay unit measures the active power consumed by the fridge. The resolution of the measurement is 1 W. The RMS voltage is also measured with 1 V accuracy. The measurement is taken every 10 seconds and sent to the server.

4. Controller description

4.1. Controller architecture

The controller has the following objectives: a) to predict the switch-OFF time of the fridges using the fridge model described in [22], and b) to limit the aggregated power consumption by controlling the

fridges without violating their temperature limits. The controller execution is carried out according to the following Algorithm 1.

Algorithm
  Initialization:
        Mark all fridges that are not active for service
        Create an empty scheduling queue
  Procedure 1:
        For all fridges{
                get fridge cooling chamber temperature
                if fridge is activated for service{
                        if temperature is above T_{max} {
                                turn the fridge ON
                        }
                }
                else{
                        put the fridge into the scheduling queue
                        sort scheduling queue in descending order by length of OFF time
                }
        }
  Procedure 2:
  If aggregated power is higher than the set-point{
        calculate the power reduction required
        while power reduction is positive{
                get the first fridge from the scheduling queue
                mark the fridge to be activated for service
                subtract the fridge power from the power reduction
        }
   }
  Procedure 3:
  If aggregated power is lower than the set-point {
        calculate the power addition required
        while power addition is positive{
                get the first fridge from the activated scheduling queue
                mark the fridge to be deactivated from service
                subtract the fridge power from the power addition
        }
   }
Algorithm 1.Aggregated power control algorithm.

The controller receives temperature measurements from the fridges at two-minute intervals and the power measurements at 10-second intervals. As the model described in [22]requires the temperatures

of the previous heating cycle and cooling cycle, the control software stores those temperature values corresponding to previous cycles (heating and cooling) locally. The heating and cooling cycles were identified by the compressor power consumption. During cooling the compressor is active and consumes power; during heating, there is no power consumption by the compressor. Some of the fridges have a power consumption of a few watts for their internal electronic components and for light bulb illumination while the fridge door is open. A 30W threshold is used to separate the compressor power consumption from the power consumption by the light bulb and other components.

The aggregated power is calculated every time the power measurement from the refrigerators is updated. If the aggregated power is higher than the set limit, the coolest refrigerator among the active refrigerators is switched OFF. The procedure continues until the aggregated power reaches the control set-point. On the other hand, if the aggregated power is less than the control set-point, the hottest refrigerator among the group of controlled refrigerators is switched ON and the procedure continues until the aggregated power reaches the control set-point.

4.2. Control task timings

The temperature measurement from each fridge is received at two-minute intervals. The switch-OFF time for the active fridges (in which the compressor is ON) is calculated using the fridge model [22] every time the temperature is updated. The fridges are sorted in an order based on their switch-OFF time; the fridge that would otherwise turn off soonest would be the first priority. Although the fridge power is measured every 10 seconds, there is a time delay of 10 seconds when sensing a change in power from the fridges. When the aggregated power is limited to the reference value, the fridges which have to be switched OFF are marked internally in the software. The switch-OFF command is sent to the fridge every time, while the corresponding fridge's power measurement is received. If the temperature of the fridge reaches its Tmax, then the corresponding fridge is removed from the control list.

5. Experimental results

The experiment was conducted for 24 hours for each scenario. After the experiment for one scenario, 24 hours' relaxation time was allowed for the refrigerators to return to their normal thermostatic cycles before conducting the experiment for the next scenario. Twenty-five refrigerators participated in the experiment. The maximum aggregated compressor capacity of the refrigerators is 2500 W. The aggregated power consumption of refrigerators in scenario 1 without control is shown in of Figure 4(a) and the instantaneous temperature average of refrigerators is shown in Figure 4(b).
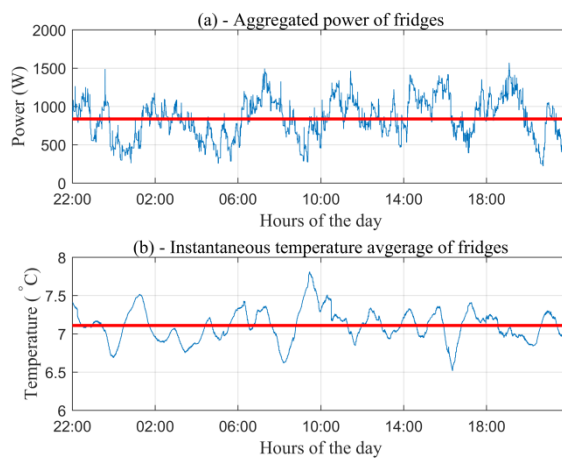

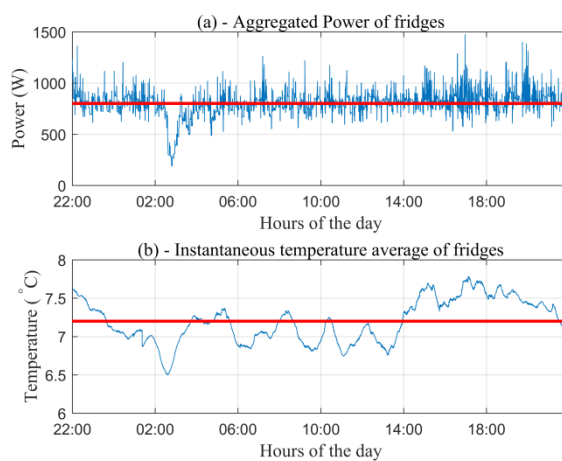Figure 4. Aggregated power and instantaneous temperature average – Scenario 1

Figure 5. Aggregated power and instantaneous temperature average – Scenario 2

Their average values are marked on the respective plots as a red line. The average value of the

aggregated power consumption of the refrigerators is 836 W. The average value of the instantaneous temperature average is 7.1 °C. The maximum value of the aggregated power is 1575 W. Therefore the experiment for scenario 2 is conducted with the power limit set at a value of 800 W for the controller. The power limit value is close to 50% of the maximum power value (1575 W) and close to the average value (836 W) of scenario 1. The aggregated power consumption of the refrigerators in scenario 2 is shown in Figure 5(a). The instantaneous temperature average of the refrigerator is shown in of Figure 5(b). Their average values are marked as a red line on the respective plots. The average value of the aggregated power is 801 W and the average value of the instantaneous temperature average is 7.2 °C.
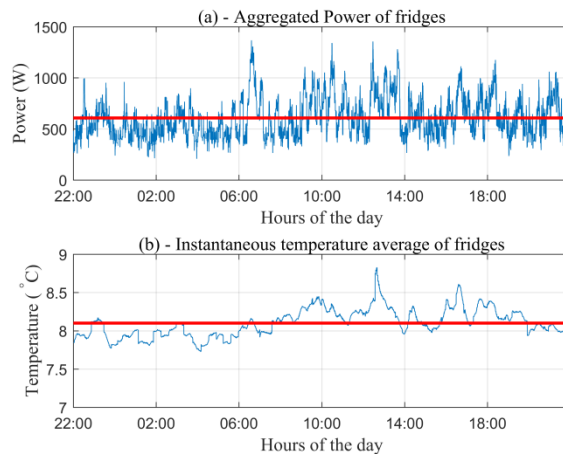

Figure 6. Aggregated power and instantaneous temperature average – Scenario 3

The experiments for scenarios 3 and 4 help to understand the change in flexibility of the overall population of refrigerators participating in the experiment. The experiment for Scenario 3 is conducted with a power limit value of 400 W for the controller. Similarly the experiment for Scenario 4 is conducted with a power limit value of 200 W for the controller. The aggregated power consumption for scenario 3 is shown in Figure 6(a). The instantaneous temperature average is shown in Figure 6(b).The power average and average of instantaneous temperature average are marked as a red line on the respective plots. The average value of the aggregated power value for scenario 3 is 607 W and the

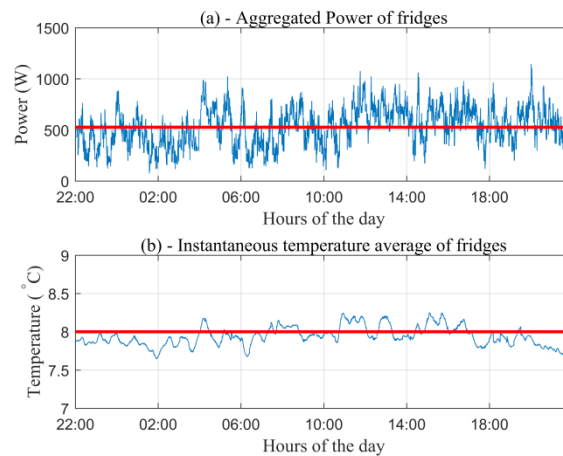average value of the instantaneous temperature average is 8.1 °C.

Figure 7.Aggregated power and instantaneous temperature average – Scenario 4

Similarly, the aggregated power consumption for scenario 4 is shown in Figure 7(a). The average aggregated power consumption for scenario 4 is 526 W. The instantaneous temperature average is shown in Figure 7(b). The average value of the instantaneous temperature average is 8.0 °C. The experimental results of the four scenarios are summarized in Table 1. The overall energy consumption for scenario 1 is 20.1 kWh and that for scenario 2 is 19.2 kWh. The difference in energy consumption is only 4.5%, taking scenario 1 as the base. In scenario 2, the controller maintains the aggregated power close to the average value of the aggregated consumption in scenario 1, which is the normal consumption. In scenario 3, when the power reduction is 50%, the overall average temperature of the population increases by 14%. The overall temperature average of the population is 8.1 °C. Although the controller aims to maintain the aggregated power at close to 50% (400 W) of the average consumption of scenario 1, the achieved average aggregated power value is 73% (607 W). This is due to one of the control constraints: that the temperature of every individual refrigerator must not exceed its Tmax value. The objective of conducting the experiment for scenario 4 is to understand the maximum limit of power reduction without violating the temperature conditions of the individual refrigerator of the population. The controller is provided with an objective power set-point value of

200 W, which is close to 25% of the average power consumption in scenario 1 (836 W). The achievable average power reduction in scenario 4 is 37% instead of 75%. The average aggregated power consumption in scenario 4 is 526 W. The temperature elevation is 13% and the average temperature of the population is 8.0 °C.

Table 1.Effect of control on the aggregated power of the refrigerators.

Scenario	Power reduction [%]	Power limit [W]	Average temperature [°C]	Average power [W]	Energy consumption [kWh]
1	NA	–	7.1	836	20.1
2	P_{avg}	800	7.2	801	19.2
3	50% of P_{avg}	400	8.1	607	14.6
4	25% of P_{avg}	200	8.0	526	12.6

Figure 8(a) shows the average value of the aggregated power of refrigerators for every 15 minutes in scenario 3. Similarly the plot for scenario 4 is shown inFigure 8(b). The controller set-point is marked as a red line in both plots. The controller is able to limit the aggregated power consumption up to 02:00 hours in the case of scenario 3. The synchronized thermostatic operation of the refrigerators starts from 02:00 hours, as most of the refrigerators reach their maximum temperature limit. Therefore, the controller was not able to limit the aggregated power after 02:00 hours. Similarly, in scenario 4, the refrigerators reach their maximum temperature limit much earlier, in less than 2 hours (at 23:45 hours), as the controller set-point is much lower. The hours of controllability are circled in green on both plots in Figure 8. Due to the synchronization of temperature cycles, as the temperature of all refrigerators reaches the maximum, the refrigerators are switched ON at the same time. Their aggregated power consumption increases, which is unavoidable. When the temperature of the refrigerators decreases, the refrigerators are switched OFF until the aggregated power limit set by the controller is reached.
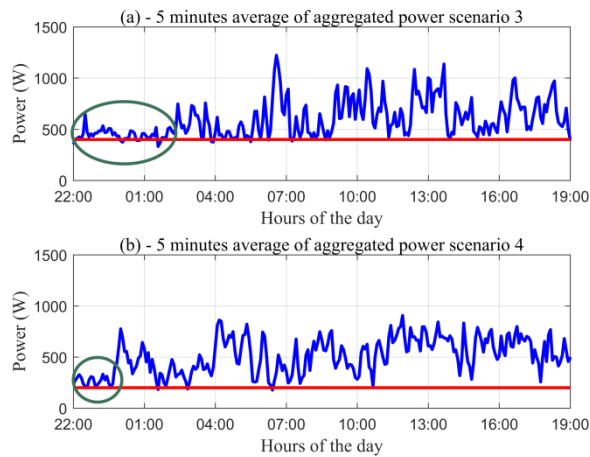
Figure 8. Aggregated power plotted with 15-minute average values for scenarios 3 and 4.

The histograms of the four experimental scenarios are shown in Figure 9. The histograms show the occurrences of aggregated power values as a probability distribution function (PDF) in the given range from 0 to 1600 W along with the mean value and the standard distribution. In scenario 1, the distribution is even around the mean value and the standard deviation is high. Scenario 2 has more occurrences around the mean, and the standard deviation decreases. The mean value is also close to the controller set-point (800 W).When control is enabled to reduce aggregated power consumption by 50% in scenario 3, the number of occurrences close to the controller set-point value (400 W) increases, but the standard deviation increases in comparison to scenario 2. The mean value is higher than the controller set-point value. Similarly, in scenario 4, the standard deviation increases and the occurrences around the mean value are evenly distributed. In both scenario 3 and scenario 4, the average power consumption is higher than the controller set-point. This is due to the synchronization of the refrigerators' temperature cycles, as shown in Figure 8. As the controller set-point of scenario 4 is lower than that of scenario 3, a greater number of refrigerators are switched OFF in scenario 4 and consequently the overall average of the aggregated power consumption is low in scenario 4. This is visible on the histogram of the aggregated power consumption of scenario 4. The number of occurrences of aggregated power below 600 W is higher for scenario 4 than for scenario 3.
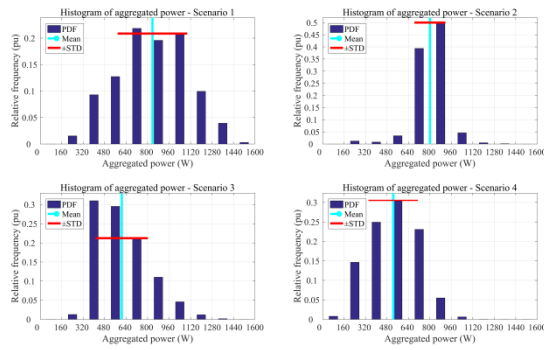
Figure 9. Histograms of the aggregated power in four scenarios.

6. Discussion

6.1. Definition and quantitation of flexibility

As the refrigerators' operations are controlled by thermostats, the refrigerator compressor will be switched OFF as soon as the temperature of the refrigerator reaches Tmin. Once the refrigerator compressor is switched OFF, the refrigerator is not available for control until the thermostat switches the compressor ON after the temperature reaches the limit Tmax. Thus, any refrigerator is available for control only during the cooling part of the thermostatic cycle, as shown in Figure 10.
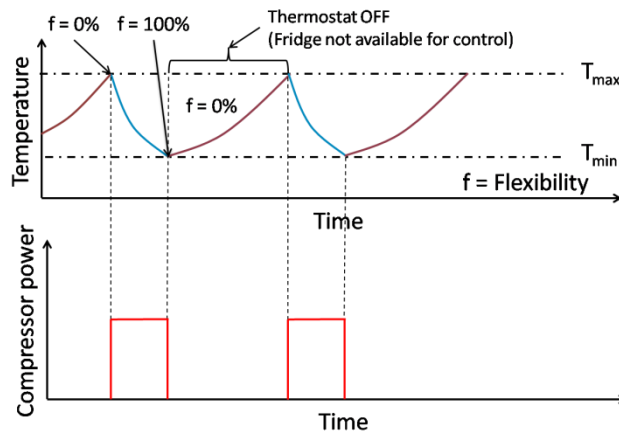

Figure 10. Flexibility change during natural thermostatic cycle.

At the beginning of the cooling, when the temperature is near Tmax, the flexibility is 0%. At the end of the cooling, when the temperature is close to Tmin, the flexibility is 100% as the refrigerator can support the maximum duration of control. All of the above statements about flexibility are valid only

when the compressor is ON. If the compressor is switched OFF by the thermostat, then the refrigerator is not available for control anymore. Therefore, the refrigerators that are switched OFF by the thermostat are considered to have no flexibility.
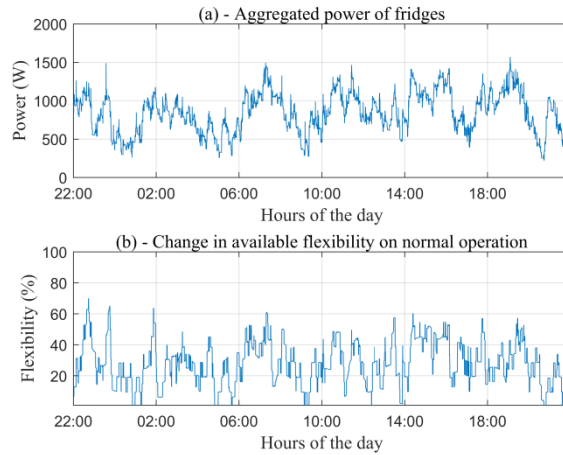

Figure 11. Change in available capacity without control

6.2. Impact on flexibility

Figure 11(b) shows the variation in the flexibility during normal consumption without control. The aggregated consumption is shown in Figure 11(a). It is interesting to notice that the aggregated power and the flexibility of the population follow a similar trend. A scatter plot of the aggregated power consumption versus flexibility is shown in Figure 12. As the power consumption increases, a greater number of refrigerators become available for control and the flexibility also increases. The coefficient of the correlation is 0.68. The overall average flexibility of the population of refrigerators is 28%. Table 2 summarizes the achieved average power consumption, average temperature, and quantized flexibility as percentages for the four different scenarios. The change in the flexibility during different levels of power reduction is shown in Figure 13. The change in the flexibility for scenario 2 is shown in Figure 13(a). The overall average of the flexibility for scenario 2 is 43%.
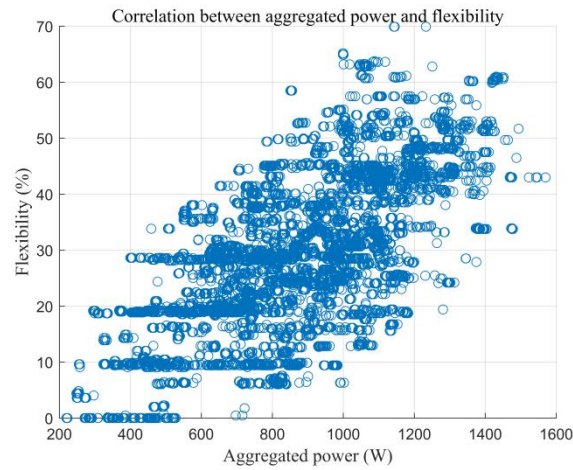
Figure 12. Correlation between aggregated power and flexibility

Table 2. Change in flexibility in different control scenarios.

Scenario	Power limit [W]	Achieved average power [W]	Average temperature [°C]	Available flexibility [%]
1	-	836	7.1	28
2	800	801	7.2	43
3	400	607	8.1	10
4	200	526	8.0	5

In scenario 2, the controller maintains the aggregated power close to the average value of the aggregated consumption in scenario 1, and the flexibility of the population increases from 28% to 43%. Therefore, flexibility in scenario 2 increases by 54% compared to the base case, scenario 1. This phenomenon is due to the control of a greater number of refrigerators to maintain the aggregated power close to the set value. The flexibility of a refrigerator is available when it is switched OFF by the controller, since it can be switched ON again if needed. On the contrary, in scenario 1, the flexibility becomes unavailable when the refrigerator is switched OFF by the internal thermostat as shown in Figure 10.The overall average temperature of the population increases by 1% in scenario 2 in comparison with scenario 1. In scenario 3, when the power reduction is 50%, the flexibility decreases by 64% in comparison with scenario 1. The flexibility of the population is 10%. The

flexibility of the population decreases to 5% in scenario 4, which can be considered as a residual capacity which cannot be utilized further. The residual capacity is due to the minimum switch-off time requirement of the refrigerator in order to avoid compressor damage due to fast switching and the high in-rush current during start-up.
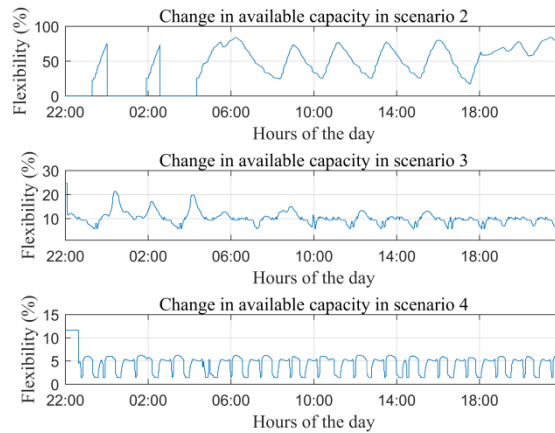

Figure 13. Change in available capacity with different power reductions.

7. Conclusions and future work

This paper studied the impact of DR activation on TCL flexibility variation with different levels of power reduction through a field experiment using refrigerators as an example case. The normal operation of refrigerators shows large variations in power consumption. The flexibility available with the refrigerators under normal operation is 28%. Due to the natural thermostatic cycles, half of the population is not available for control. The flexibility available with the population of refrigerators in terms of flexibility increases by 54% when the refrigerators are controlled for the average aggregated consumption. Therefore, if the aggregator has direct access to the compressor control, an average flexibility of 50% is possible. When the refrigerators are controlled to reduce their power to 50% of their average consumption, as seen in scenario 1, the overall average temperature of the population increases by 14% and the flexibility decreases to 10%. If the aggregated consumption is reduced by 75%, due to the temperature limit restriction, the maximum possible reduction is 37%. This causes the

maximum reduction in the flexibility: to the value of 5%.It will be interesting to carry out a further study by changing the selection criteria of the refrigerator. The controller ability for refrigerator selection can be modified by considering the available watt-hour capacity of individual refrigerators or by considering the available percentage flexibility of the individual refrigerator instead of making a selection based on the length of the switch-OFF time. The new resource selection strategy may improve the performance by avoiding refrigerator synchronization.

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