Delivery no. 3.8 b:
Demonstration of heating flexibility in smart homes

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Preface

EnergyLab Nordhavn – New Urban Energy Infrastructures is an exciting project which will continue until the year of 2019. The project will use Copenhagen's Nordhavn as a full-scale smart city energy lab, with the main purpose to do research and to develop and demonstrate future energy solutions of renewable energy.
The goal is to identify the most cost-effective smart energy system, which can contribute to the major climate challenges the world are facing.

Budget: The project has a total budget of DKK 143 m (€ 19 m), of this DKK84 m (€ 11 m) funded in two rounds by the Danish Energy Technology Development and Demonstration Programme (EUDP).

Forord

EnergyLab Nordhavn er et spændende projekt der løber til og med 2019. Projektet vil foregå i Københavns Nordhavn, og vil fungere som et fuldskala storbylaboratorium, der skal undersøge, udvikle og demonstrere løsninger for fremtidens energisystem.
Målet er at finde fremtidens mest omkostningseffektive energisystem, der desuden kan bidrage til en løsning på de store klimaudfordringer verden står overfor nu og i fremtiden.

Budget: Projektets totale budget er DKK 143 mio. (EUR 19 mio.), hvoraf DKK 84 mio. (EUR 11 mio.) er blevet finansieret af Energiteknologisk Udviklings- og Demonstrationsprogram, EUDP.

Project Information

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Executive Summary

The focus of WP3 is to study energy flexibility potential in buildings connected to district heating grids. Based on multiple simulation studies conducted at earlier phases of the project, a demonstration of flexible heating demand in smart homes was conducted in the last heating season of the ELN project. From November 2018 until March 2019 field tests in 19 apartments were conducted, using the existing ICT systems to manage heating systems operation for flexible demand. Based on residents' feedback, algorithms were tested to control temperature setpoints of individual rooms during defined period of the day. The algorithms are generic using two inputs, i.e. room inside temperature and room temperature setpoint, and providing on/off signal to valves of individual heating loops. These methods can be applied to other smart homes where heating supply is controlled using a room thermostat. The low energy concrete apartment has shown to be flexible that can maintain thermal comfort for a long time period, i.e. in this demonstration it was up to 6 hours without heat supply for space heating.

1. Aim of the report

According to the Copenhagen 2025 Climate Plan [1], the City of Copenhagen aims to be the world's first carbon neutral capital by 2025. One of the targets is to make its district heating carbon neutral, as 98% of the buildings in Copenhagen is supplied by district heating network [2]. For heat production in district heating, currently, fossil-fueled boilers are brought into use during peak-load periods, i.e. 6:00-9:00 and 17:00-20:00, in particularly cold days. Therefore, a more flexible heating demand in buildings plays an important role in reducing CO2 emissions of district heating. The use of ICT to enhance the operation of buildings' energy systems is a topic that has attracted attention in recent years. In the EnergyLab Nordhavn – New Urban Energy Infrastructures project, Copenhagen's Nordhavn district is used as a full-scale smart city energy lab to demonstrate how electricity and heating, energy-efficient buildings and electric transport can be integrated into an intelligent, flexible and optimized energy system. As part of the EnergyLab Nordhavn project, we focus on heating demand management in buildings to enabling heating flexibility for the reduction of fossil fuel use in district heating.

The aim of this report is to describe the demonstration of heating flexibility in smart homes in Sundmolen apartment building in Nordhavn. In the demonstration, the heating systems in these homes were made responsible to the requested services from district heating grid which is morning peak load reduction. The demonstration results are displayed using online visualization software, Grafana. In addition, a poster of the demonstration is displayed in the showroom of the project.

2. Methodology

Demonstration of flexible heating demand was conducted through field tests in 19 apartments in Nordhavn, aiming to gain insights into the use of ICT to manage heating systems operation for flexible demand. The apartments are equipped with sensors and devices interfaced to an ICT system composed of blocks responsible for data storage, monitoring and control.

2.1 Apartments characteristics

The apartments are located in a newly built multi-story residential building with a total of 72 apartments. The building was constructed in accordance with building class 2020 of the Danish Building Regulation BR15. This permits for a maximum energy usage of 20 kWh/m^2 per year for heating, ventilation, cooling and domestic hot water [3]. The apartments are thus expected to be very energy efficient with a high degree of insulation in both windows and external walls and a high level of air tightness. Each apartment consists of a main kitchen/living room area, one to four bedrooms, one large bathroom and for some apartments also one small toilet.

2.2 Heating system

The space heating and domestic hot water of the apartments are provided by district heating grid with a heat substation installed in the basement of the building. Heating in each room is provided by floor heating system with the supply water temperature maintained at 35°C and water flow rate of each thermal zone is controlled by individual valves and respectively thermostatic controllers. The valve opens when the difference between the room temperature setpoint and the indoor temperature is larger than 0.5°C.

2.3 ICT system description

The smart apartments are equipped with KNX systems, which connect sensors and devices for monitoring of indoor environment, occupancy detection and operation of heating, ventilation and lighting systems. Each KNX system is interfaced to a data management system located at PowerLabDK, DTU. The database is connected to a visualization tool, built on top of Grafana and InfluxDB, which allows real-time data verification. There is also an integration between the KNX systems and a MQTT broker, which can be used to publish messages to the KNX buses. The MQTT interface is used for controlling and reading data of KNX devices. The thermostatic controllers are KNX devices, so the temperature setpoint can be remotely adjusted by publishing messages to the MQTT broker. For the experiments, a Python script was used to communicate with the MQTT broker and remotely adjust temperature setpoints of living rooms using individual reference set points. Figure 1 shows the diagram of the ICT system.

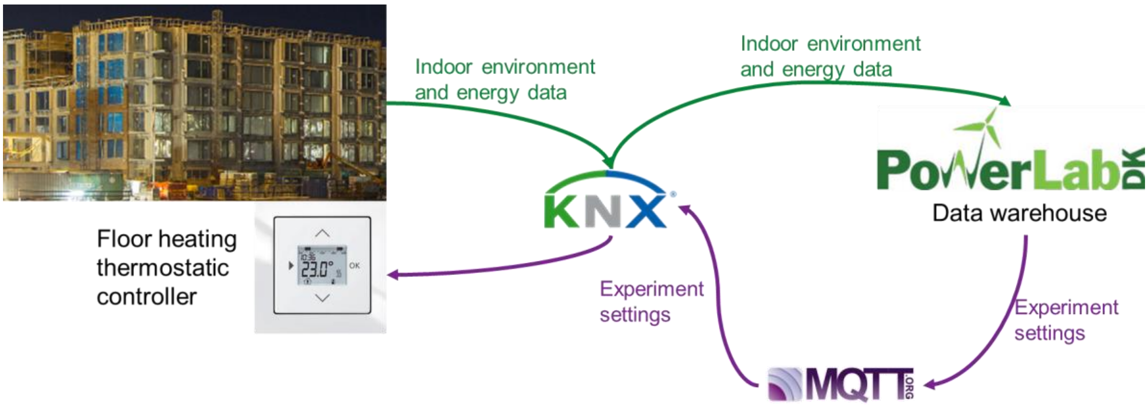
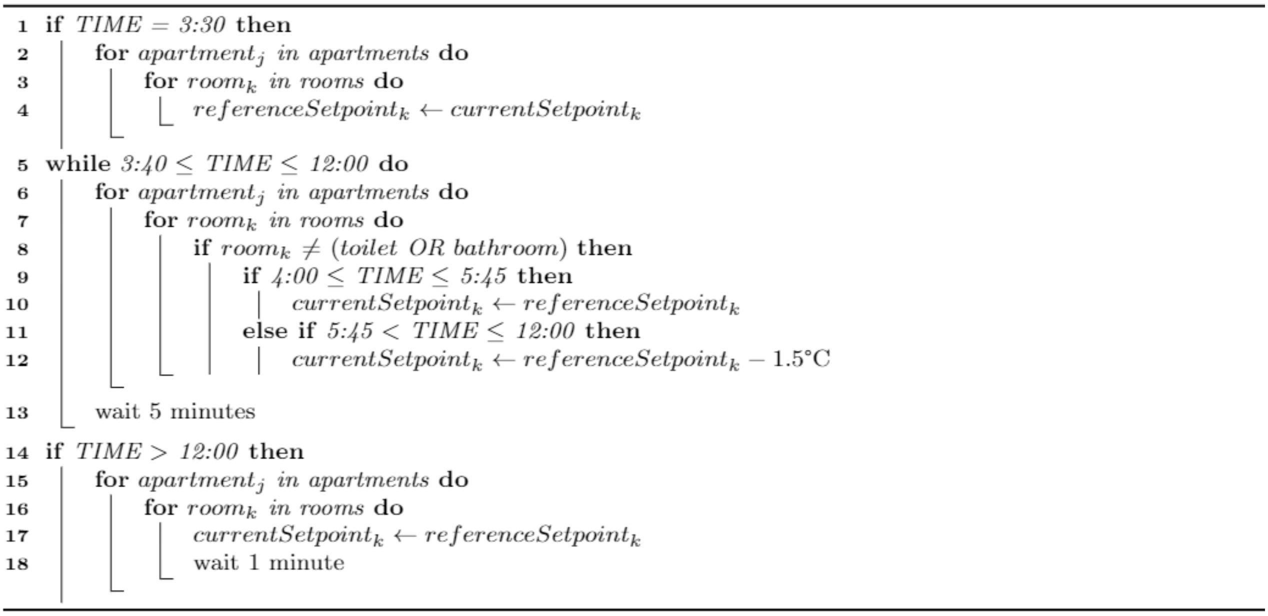


Figure 1 Diagram of ICT system used in the demonstration

2.4 Control strategy

In the demonstration, algorithm was developed to reduce morning peak load by switching off space heating in apartments from 6:00 to 9:00 or 12:00. We controlled temperature setpoint of individual rooms during defined period of the day, and continuously developed control strategies throughout the tests in the heating season 2018/19. As different rooms have different temperatures, for each room, we scheduled to read the current setpoint at 3:30 as reference setpoint, between 5:45 and 12:00 to reduce setpoint by 1.5 °C from reference setpoint, at last to return the setpoint back to the reference value. To reduce the rebound effect, i.e. demand peak created if the setpoints of all rooms are increased at the same time, in the last step, a time delay of 1 minute was added to increase the temperature setpoint of each room to its original setpoint. The choice of 1 minute is for practical reason. With 1-minute delay among 90 rooms, the process to return the temperature setpoint of all rooms takes 90 minutes. This means, the last room's setpoint changed back at 13:30 not at 12:00. If longer delay is applied, the last rooms will have to wait for much longer time to have their setpoints changed back.

The control strategy used in the experiments evolved according to the results obtained throughout the project including feedback from residents, aiming to optimize the operation of the system. In the last test, more improvements i.e. including user feedback in the control and reducing rebound effect, were added to the control loop and it evolved to the process described in Figure 2. The virtual machine (VM) was scheduled to read the reference setpoint at 3:30, to run the script with the control loop between 3:40 and 12:00, and to run an extra step after 12:00. This last step was added to the control strategy in order to reduce the rebound effect, i.e. demand peak created if the setpoints of all rooms are increased at the same time. To mitigate it, a time delay of 1 minute was added after the setpoint of each room is changed. In this phase, the preheating was completely removed from the experiments, since it was verified that the thermal inertia of the building was capable to maintain the indoor temperature in an adequate level during heat cut-off, even without the preheating. Moreover, the setpoint was reduced for a longer period -- between 5:45 and 12:00, and by a larger factor -- reduction of 1.5°C. Lastly, based on user feedback from previous tests, bathrooms and toilets were excluded from the experiment as residents prefer to have warm floors in these rooms although the decrease in room temperature was not noticeable.



```
if $TIME = 3{:}30$ then
    for $apartment_j$ in $apartments$ do
        for $room_k$ in $rooms$ do
            $referenceSetpoint_k \leftarrow currentSetpoint_k$
while $3{:}40 \leq TIME \leq 12{:}00$ do
    for $apartment_j$ in $apartments$ do
        for $room_k$ in $rooms$ do
            if $room_k \neq (toilet\ OR\ bathroom)$ then
                if $4{:}00 \leq TIME \leq 5{:}45$ then
                    $currentSetpoint_k \leftarrow referenceSetpoint_k$
                else if $5{:}45 < TIME \leq 12{:}00$ then
                    $currentSetpoint_k \leftarrow referenceSetpoint_k - 1.5°C$
    wait 5 minutes
if $TIME > 12{:}00$ then
    for $apartment_j$ in $apartments$ do
        for $room_k$ in $rooms$ do
            $currentSetpoint_k \leftarrow referenceSetpoint_k$
            wait 1 minute
```

Figure 2 Control algorithm

3. Results

3.1 Result display of demonstration

Demonstration results are shown in Grafana to show real time information, e.g. room temperature, temperature setpoints, valve opening of heating loop in each room and heating power of the entire apartment. As an example, the figures below show the demonstration data of two days for one apartment. Figure 3 shows the heating power of the apartment which was completely eliminated from 6:00 till afternoon. The reason can be seen in Figure 4, which shows that from 6:00 till afternoon, valves were closed. This is due to the room temperature setpoints were more than 1°C lower than the room temperatures, so valves were not asked to open, as shown in Figure 5 - Figure 8.

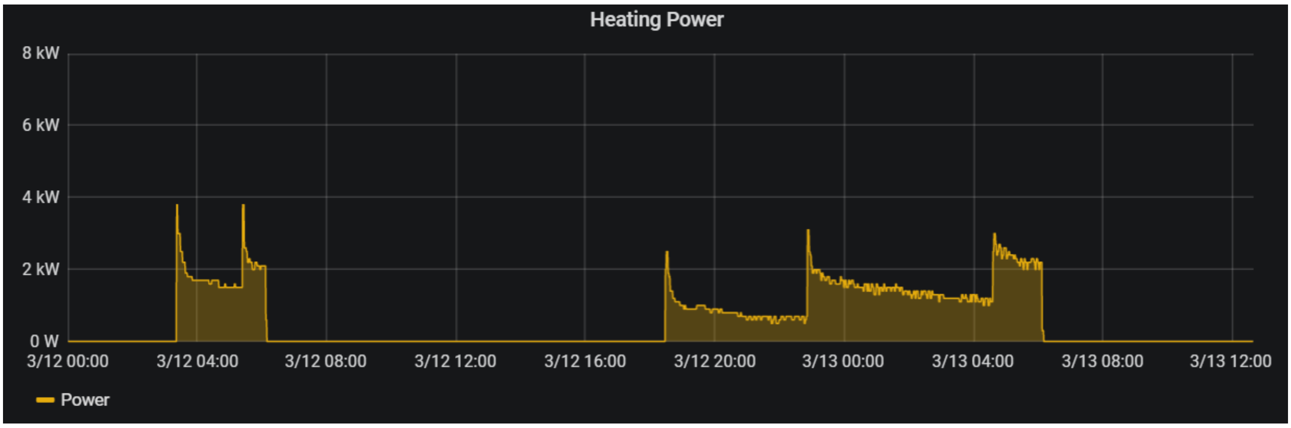


Figure 3 Heating power of the apartment

Figure 4 shows the stack view of valve opening status. The valve only has on/off controls with 0 means closed and 255 means fully open. If a valve is open, it has the value of 255, e.g. at 4:00 on 12/03, valves in both kitchen/living room and bedroom 3 were open. There is fluctuation in the heating power curve because the power is calculated based on the temperature difference of supply and return water and the flow rate. The temperature difference is dynamic because heat transfer from the floor heating system to the room is dynamic.

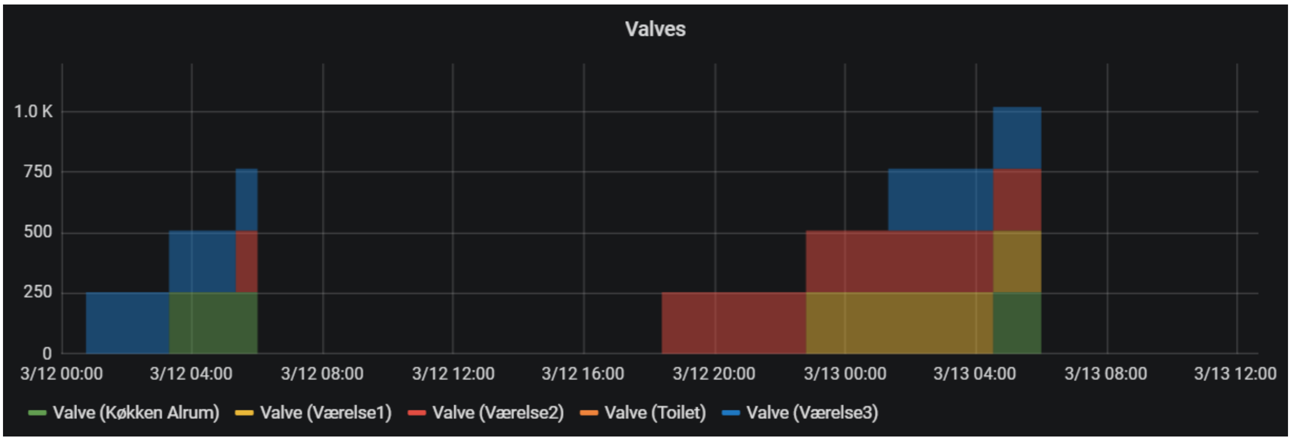


Figure 4 Stack view of on/off status of floor heating valves in all rooms of the apartment, 0 = closed valve, 255 = opened valve

In Figure 5 - Figure 8, each room's heating settings are displayed. The yellow lines show the controlled setpoints in the demonstration and the blue dots are the setpoints displayed on the home display. In the kitchen/living room, the setpoint changes to 12 °C when the balcony door is opened, but turns back to normal setpoint when it is closed. The dashed curve is the heating power of the apartment (as shown in Figure 3), but not of the room, as there is no heating power measurement in each room.

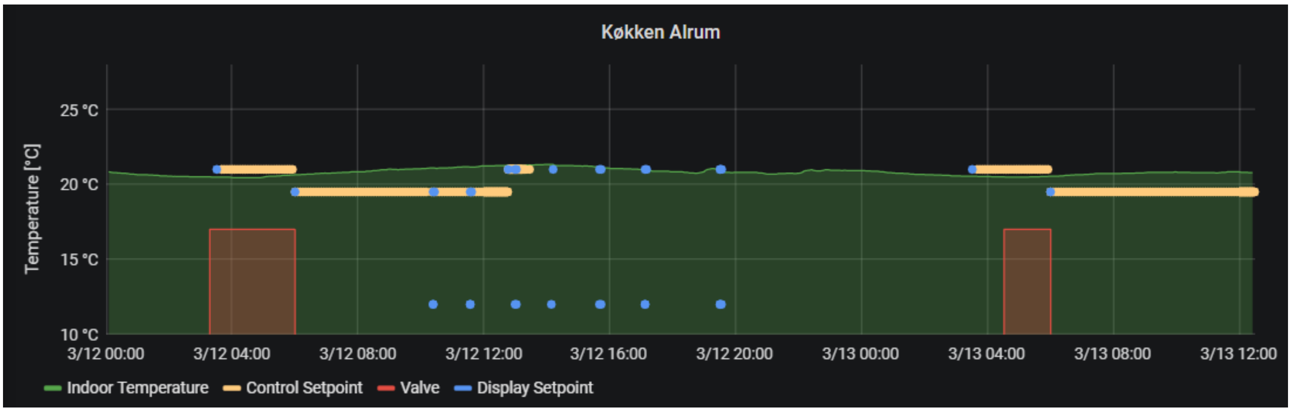


Figure 5 Heating settings and room temperature of kitchen/living room

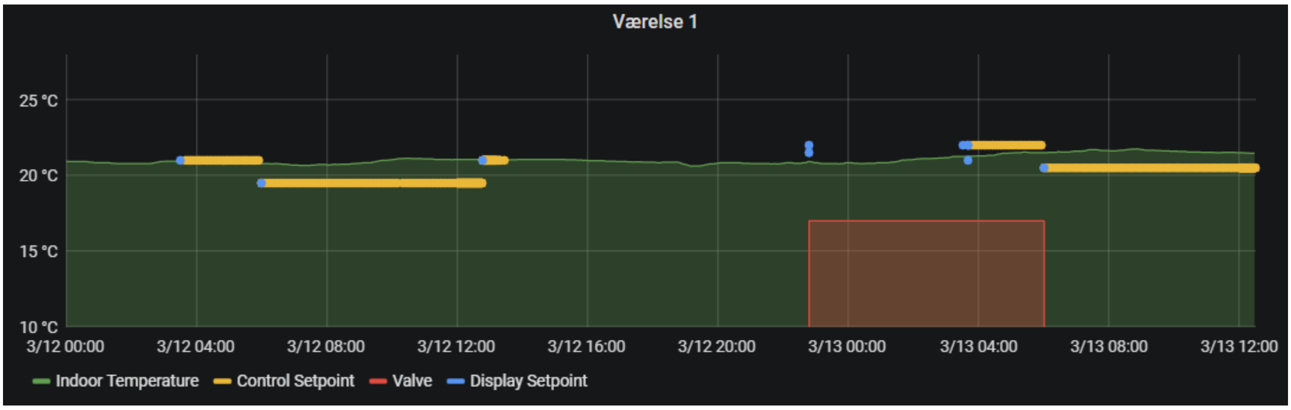


Figure 6 Heating settings and room temperature of room 1

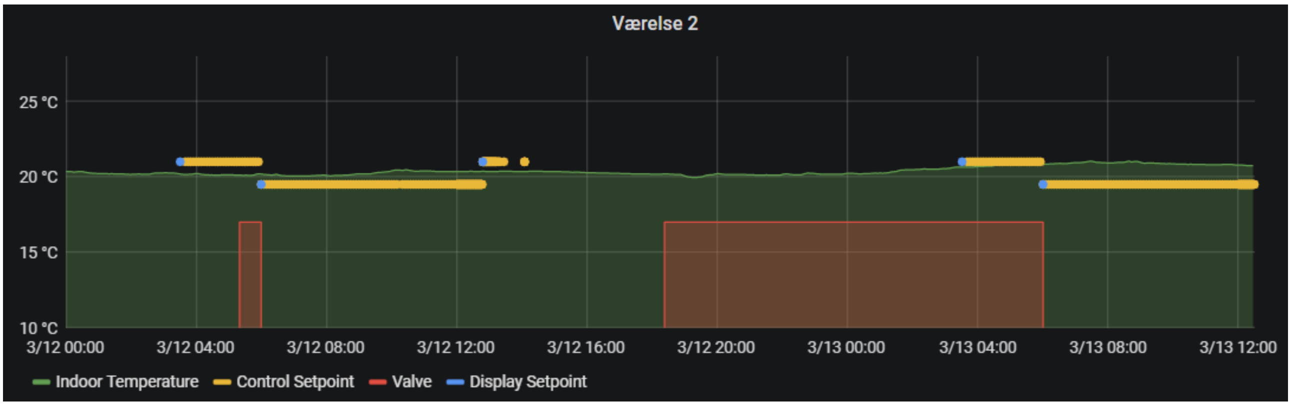


Figure 7 Heating settings and room temperature of room 2

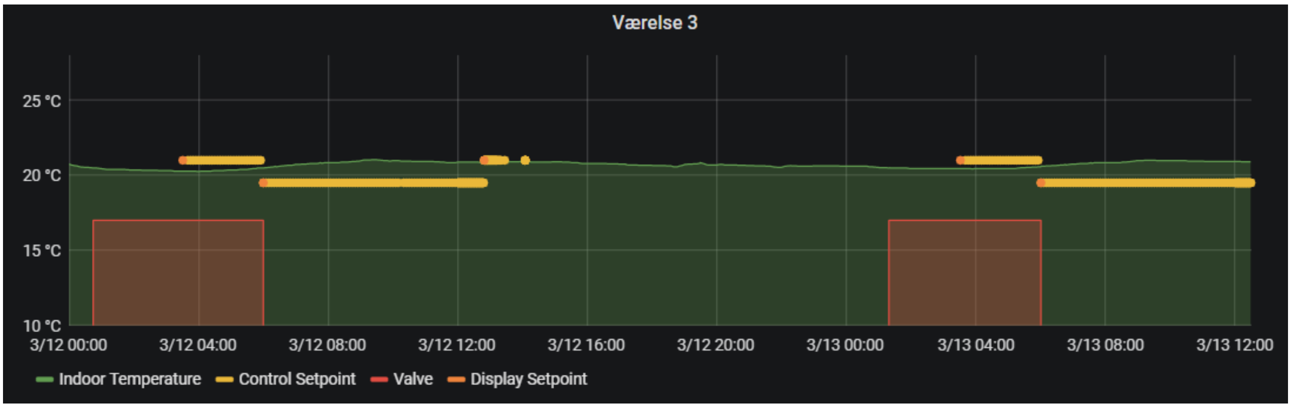


Figure 8 Heating settings and room temperature of room 3

3.2 Peak demand shaving

The effect on peak demand shaving is shown in Figure 9. Heating power of the home is much lower during 6:00-12:00 on experimental days (11-15/03/2019) in comparison with reference days (05-08/03/2019) when heating is controlled by residents, as in the mornings of experimental days only in bathrooms and toilets heating was permitted to use. Although the amount of peak demand reduction varies among homes, on average a reduction of 68% was reached in comparison with peak demand of the homes on non-experimental days with similar weather conditions. On average, in these apartments, the heating supply for space heating could be cut off from 6:00 for 6 hours with room temperatures decreasing by no more than 0.5 °C.

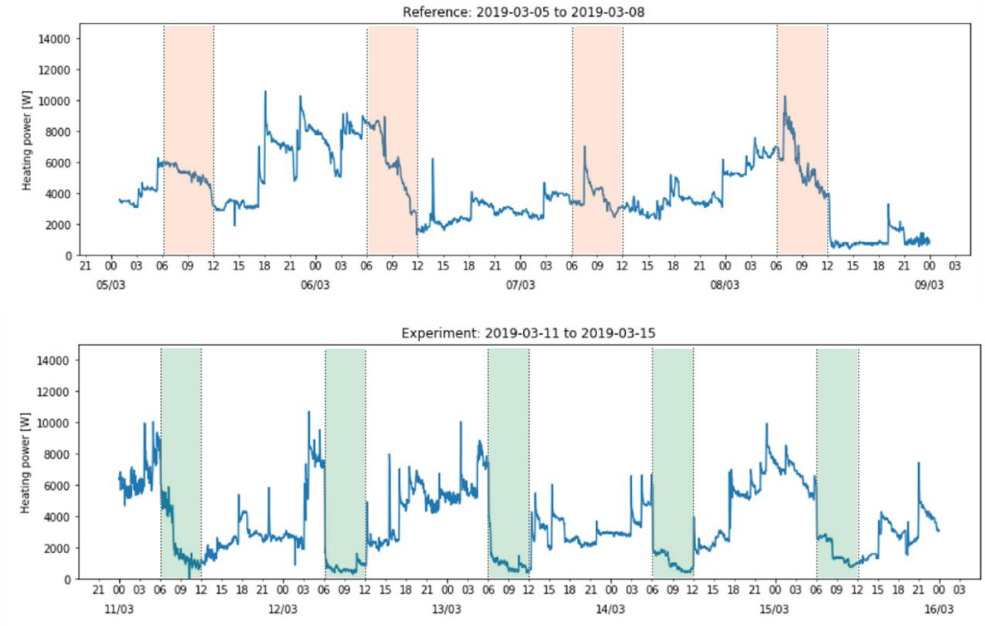


Figure 9 Results of peak demand shaving

4. Conclusions

Demand side management in the heating system plays a key role in the elimination of carbon emissions from our society, and the use of ICT to improve the operation of heating systems brings new resources for implementation. In this project, field tests in 19 apartments were conducted, using the existing ICT systems to manage heating systems operation for flexible demand. Based on residents' feedback, algorithms were tested to control temperature setpoints of individual rooms during defined period of the day. The algorithms are generic using two inputs, i.e. room inside temperature and room temperature setpoint, and providing on/off signal to valves of individual heating loops. These methods can be applied to other smart homes where heating supply is controlled using a room thermostat. The low energy concrete apartment has shown to be flexible that can maintain thermal comfort for a long time period, i.e. in this demonstration it was up to 6 hours without heat supply for space heating.

Reference

[1] "Copenhagen 2025 Climate Plan," 2012.

[2] HOFOR, "District heating in Copenhagen: an energy efficient, low carbon, and cost effective energy system."

[3] The Danish transport and construction agency, Danish Building Regulations 2015. 2015.

Quality Assurance

Author(s)	Reviewer(s)	Approver(s)
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