AFSLUTNINGSRAPPORT CASE 1

FUTURE

FUTURESSOURCER ENERGI

REnewable Energy Lolland

DTU

NEOGRID TECHNOLOGIES

Projektleder

GATE 21
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FUTURE
FREMTIDENS INTELLIGENTE ENERGI- OG RESSOURCESYSTEM

FUTURE-projektet består af syv visionære casesamarbejder på tværs af de tre regioner i Greater Copenhagen. De syv cases tester og demonstrerer forskellige teknologier, værktøjer eller forretningsmodeller indenfor vedvarende energi eller udnyttelse af ressourcer:

- **Case 1: Fleksibel energilagring i individuelle bygninger**
- Case 2: Integration af vedvarende energi i komplekse bygninger
- Case 3: Forbedret energihusholdning gennem balanceret varme og køling i sygehusbygninger
- Case 4: Energioptimering gennem smarte grids i bygninger
- Case 5: Cirkulære løsninger, der integrerer energi, ressourcer og affald
- Case 6: Resttekstiler som en del af fremtidens byggeri
- Case 7: Intelligent brug af produktdata, der forbedrer og fremmer genbrug i cirkulære samfund

Vedvarende energi

Projektet vil:

- Udnytte, integrere og lagre vedvarende energi bedre, så vi får et mere fleksibelt energisystem
- Fremme energieffektive løsninger i bygninger

Derfor skal vi designe løsninger og infrastruktur, der kan bygge bro mellem behovet for forsyningssikkerhed på den ene side, og det faktum at vedvarende energikilder ofte fluktuerer.

Ressourceudnyttelse

Projektet vil:

- Øge ressourceeffektiviteten og skabe en cirkulær omstilling af samfundet. Vi skal forlænge levetiden af materialer, genanvende affald og rester så de indgår i nye kredsløb.
- Begrænse produktionen af jomfruelige materialer og dermed også energiforbruget

Derfor demonstrerer projektet, hvordan man lokalt kan styre produkt- og materialestrømme, så man fremmer en mere intelligent materialeanvendelse

Læs mere her:
https://www.gate21.dk/future/

Introduction

FUTURE is a project funded by the EU program Interreg and has the overall goal to increase the usages of renewable energy. The project is divided into different cases, where case #1 focuses on storage and smart controls of energy systems for individual buildings.

The purpose of case #1 is to test a number of different heat pump systems installed with a storage and controls, in order to support and balance the electricity consumption. By utilize private dwellings and their energy systems to decrease the fluctuation in the electricity consumption during peak hours, the usages of renewable energy are increased.

Case #1 will investigate the effects of heat pump systems installed with storage tanks in order to offer flexibility the electricity grid.

This report gives an overview of the gained knowledge and conclusions from case #1.

Content

1. System description Lolland Falster Airport

In the following, the installed system in Lolland Falster Airport is presented along with measurements from the system. Evaluation of the energy performance is given, and added control for the system is described with the effects on the flexibility.

1.1 Airport – Lolland Falster

The airport in Lolland Falster is located in the southern part of Lolland. It is a commercial building, with one individual working the controls for the runway, from 8 am to 5 pm during weekdays, and no activity during the weekend, see Figure 1.1-1. The building is a one-storey building, with large glass surfaces and wooden structure.

Figure 1.1-1 Aerial photo of the airport and picture of the heat pump installed at the airport.

The building consists of a control room, meeting room, canteen, kitchen, and various smaller utility rooms. The heating system is a water based radiator system with individual thermostats on the radiators. The indoor temperature sensor is placed in the control room where the person working at the airport is sitting. The set point for the sensor is 20°C, decided by the user. The set point for the radiators in the canteen and kitchen is lowered to 17 °C, since these rooms are seldom used, this is also decided by the user.

In Table 1.1-1 some key parameters are given for the building and the system installed at the airport. The heat loss from the building is here not determined as described in DS418, but from the measurements based on energy delivered to the building for space heating during stable indoor temperature periods.

Table 1.1-1 Descriptive figures for the airport.

Airport Lolland Falster		
Building area	342	[m²]
Year of build	1973	[-]
*Building heat loss**	0.476	[kW/K]
Building time constant	57	[hour]
Building heat capacity	27.4	[kWh/K]
Size heat pump	13	[kW]
Size buffer storage (water)	300	[liters]
Measurements from	1/11-2018	[dd/mm-yyyy]

** the building heat loss is determined based on measurements of the delivered space heating during periods with a constant indoor temperature.*

The system installed at the airport is a Bosch system, with a 13 kW heat pump and a 300 liters buffer storage, see Figure 1.1-2. The system is only connected to the space heating loop in the building, since the domestic hot water is delivered separately, heated by an electrical heating element.

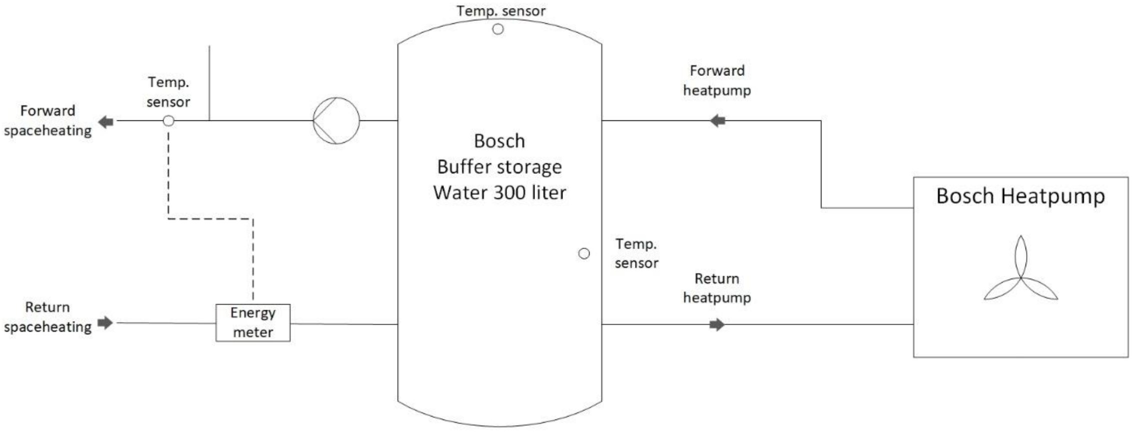

Figure 1.1-2 Diagram of the system installed at airport delivered by Bosch.

This configuration has its advantages and disadvantages. It is here possible to allow the heat pump to be shut down for longer periods and thereby lowering the temperature in the buffer storage to temperatures below domestic hot water temperatures, because it is not necessary to standby with a heated volume of hot water for domestic use. This offers more flexibility in terms of the electricity used by the heat pump and a greater potential for avoiding peak hours. The disadvantages are that the domestic hot water is heated by a simple heating element, which has a much lower efficiency than a heat pump. Also, the on/off controls for the heating element are not connected to any smart controls and is thereby only controlled by demand.

Although there are disadvantages a system only connected to the space heating loop is still very appropriate for a commercial building where the operating hours often for a majority of the time is outside the morning and evening peak hours. Also, the hot water consumption is low in smaller commercial installations where there are no shower facility and industrial kitchen activity.

Space heating

The needed energy for space heating is given in Table 1.1-2. Here it is seen that the yearly consumption is between 26 MWh - 33 MWh for the measured period, dependent on the weather conditions during the winter.

Table 1.1-2 Energy for space heating at the airport from the 1/11-2018 to 1/6-2021.

Airport Lolland Falster	*2018* *1/11 – 31/12*	*2019* *1/1 – 31/12*	*2020* *1/1 – 31/12*	*2021* *1/1 – 1/6*
Degree days [-]	701	2535	2366	1774
Energy space heating [MWh]	9.84	32.77	26.32	23.87
Energy heat pump [MWh]	3.42	11.53	8.31	8.17

On Figure 1.1-3 the daily need for space heating is given as a function of the time of the year The colour indication shows the mean daily outdoor temperature. As expected, the need for space heating is highest during the winter where the outdoor temperature low.

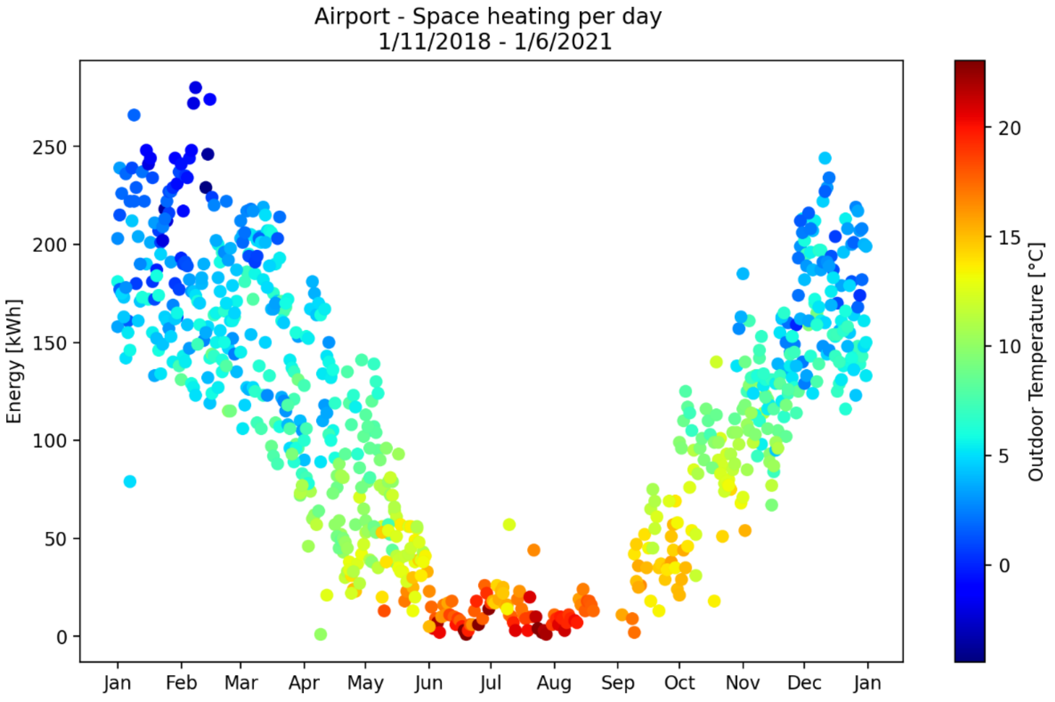

Figure 1.1-3 The daily need for space heating in the airport measured during the project.

Performance

The performance of the heat pump system installed at the airport is shown on Figure 1.1-4. The figure shows the daily variation over the course of a year of the System COP, derived by the energy consumption for the heat pump and the energy delivered to the space heating loop. The size of the circle on the figure are proportional to the energy delivered, where the larger circles are during the winter months corresponding to when the most heat is delivered through the space heating loop.

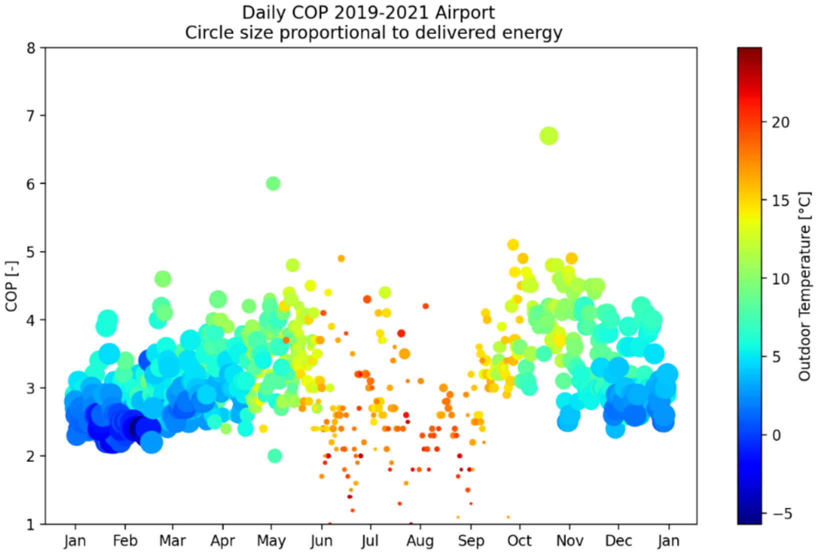

Figure 1.1-4 System COP for the heat pump installed at the airport.

The efficiency of the Bosch system in the outdoor temperature interval from -5°C to 17°C is a COP of 2.0 – 4.5, which is considered within acceptable ranges for an air/water heat pump.

The overall performance of the system is given in Figure 1.1-5, where weekly performance indicators are plotted. At low outdoor temperatures the operation time is almost all day, meaning the heat pump is running continuously. When the outdoor temperature increases, the operation time decreases allowing for longer periods without heat pump operation.

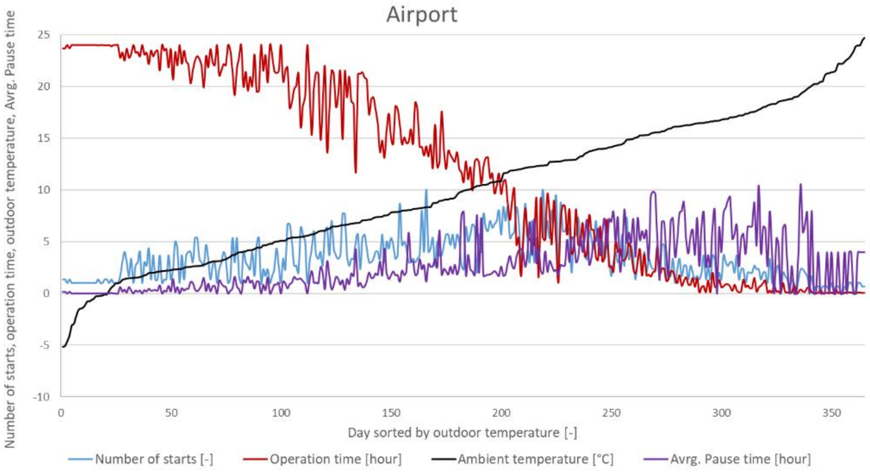

Figure 1.1-5 Performance of the system installed at the airport.

1.2 Added control system installed in the airport

The Bosch heat pump runs on its internal control strategy but in this project three relays are designed and implemented for external control purpose. If relay 1 is activated the heat pump is shut off. If relay 2 is activated the pump supplying the airport with heat is shut off. If relay 3 is activated the heat pump is turned on for force running of the heat pump lifting the heating profile controlling the heat pump.

The API control program was set up remotely controlling Relay 1 and Relay 2 according to the indoor and outdoor environment.

First, it will connect Neogrid Gateway and ask for the real time data of the indoor and outdoor temperatures. Second, by comparing the indoor and outdoor temperatures with the threshold temperatures, the control signals for Relay 1 and 2 will be calculated according to the control strategy. Then the control signals will be sent out to the Neogrid Gateway and implement the control signals to the Relays. The control start time, stop time and the time step can be specified by users. The API control is deployed in the DTU server and runs continuously 24 hours per day.

Reduce run time for the heat pump when the outdoor temperature is high

It was observed that the heat pump would start up during periods where there was no need for heating since the indoor temperature was well above 20°C. This is because the heat pump does not look to the indoor temperature, but is controlled by a profile based on the outdoor temperature as well as other internal algorithms where time plays a role. The unneeded starting of the heat pump can be seen on Figure 1.2-1 where the red curve is the indoor temperature and the grey curve is the energy consumption of the heat pump. The blue curve is the outdoor temperature and the yellow curve is the solar radiation, which shows these days were sunny days with high temperatures during the day.

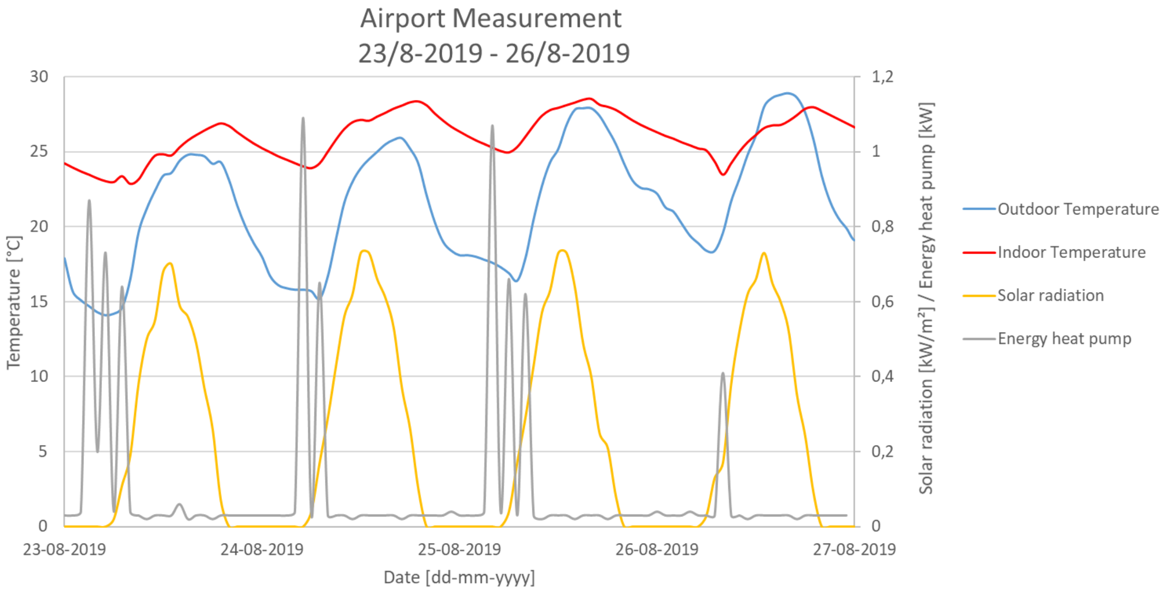

Figure 1.2-1 The in- and outdoor temperature as well as the solar radiation and energy consumed by the heat pump from the 23/8-2019 to 26/8-2019.

The added control implemented the1st of July 2020, simply states that if the indoor temperature is above 20°C, relay 1 is pulled and the heat pump is blocked from starting. When the indoor temperature drops below 19°C the block is lifted and relay 1 is released meaning the heat pump is returned to its normal controls. The effect of this can be seen on Figure 1.2-2 where the energy consumed by the heat pump is reduce to a minimum, which is needed for running the control system internally in the heat pump.

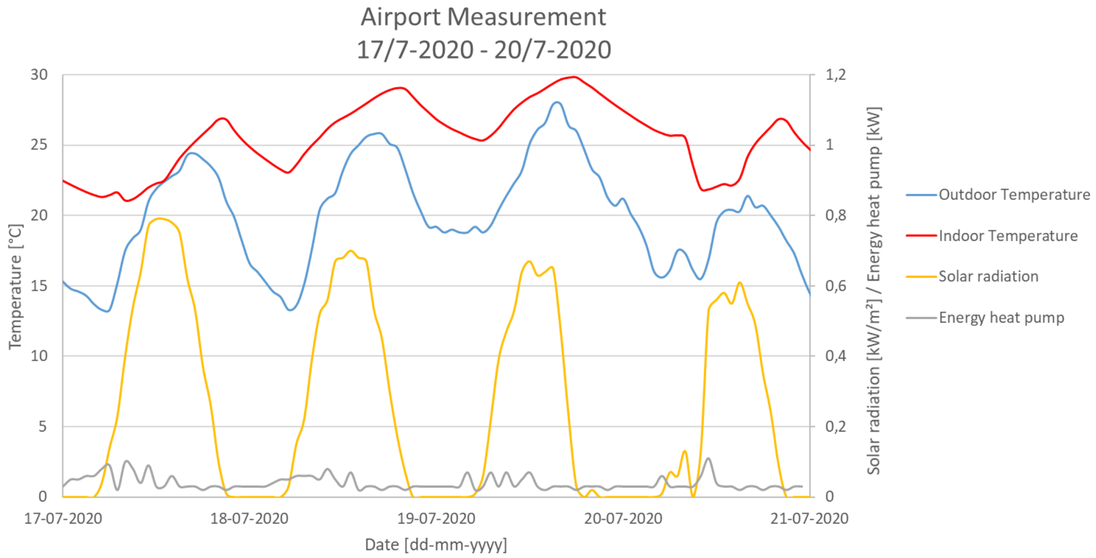

Figure 1.2-2 The in- and outdoor temperature as well as the solar radiation and energy consumed by the heat pump from the 17/7-2020 to 20/7-2020.

Reducing the energy consumption during peak hours in the winter period.

To utilize the flexibility the storage tank offers additional controls were implemented. The control states that the heat pump shuts down at hour 17:00 to hour 20:00. If the room temperature drop below 17°C the heat pump is released and returned to its normal control.

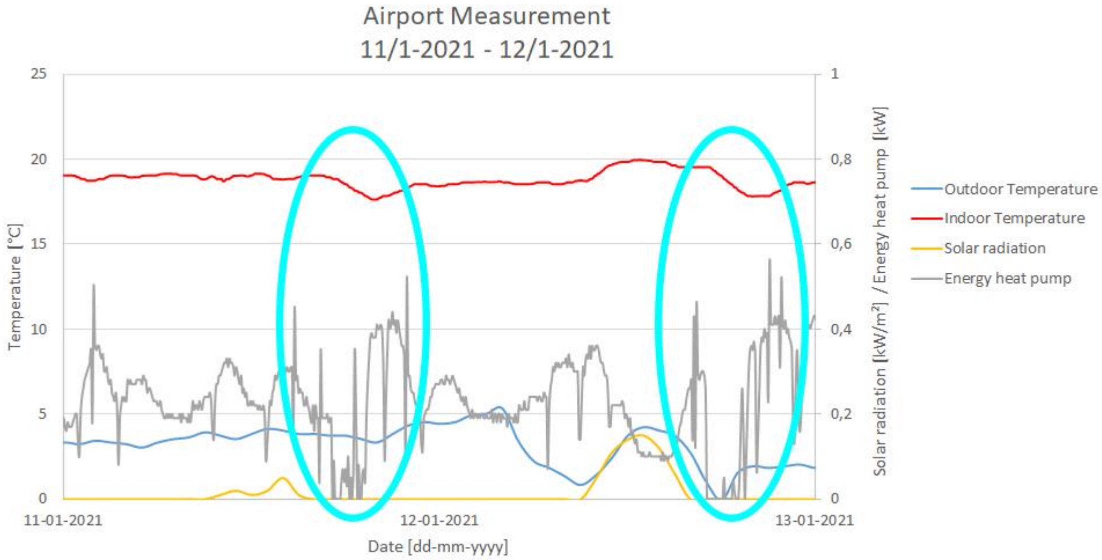

Figure 1.2-3 The in- and outdoor temperature as well as the solar radiation and energy consumed by the heat pump from the 11/1-2021 to 13/1-2021.

The effects of the added controls can be seen in Figure 1.2-3. The two circles show the time periods where the heat pump is forced to shut down. The grey curves indicate the energy consumption of the heat pump, and show it is lowered in this time period. The red curve shows the indoor temperature and here the effects of the forced shut down on the indoor temperature. It can also be observed that there is a delay in the drop in indoor temperature, which is the effects of the storage tank. The storage tank continues to deliver energy to the building after the heat pump is shut down. When the tank temperature is below the room temperature the building is no longer supplied with heat and therefore the indoor temperature drops. When the lower limit of 17°C is reached the heat pump is released and the consumption of the heat pump shows it turns on and starts supplying the building with heat again.

On Figure 1.2-4 the effect on the system COP before and after the control were added are given. Here it can be seen that the added control has a positive effect on the system COP. During the summer months unnecessary run-time is reduced. During the winter months the system COP is increased.

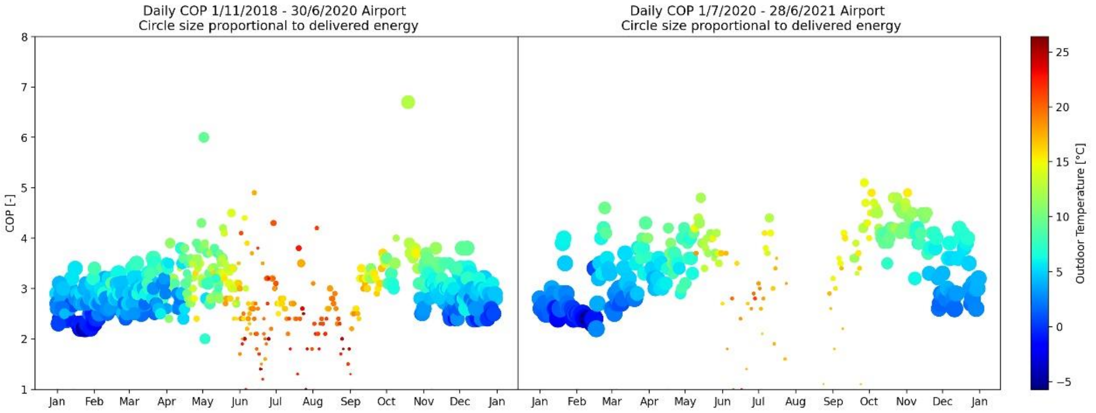

Figure 1.2-4 The system COP before and after the controls are added to the system.

Experiences running the heat pump through relays and API controls

In order to maintain a robust control system, the API control is further designed with the following extra functions.

1. Automatic fallback control signal. When a signal is calculated and sent out to the relay, the signal always contains two parts. The first part is the current control signal and then followed by a 0 signal for the next time step. This is to make sure that once the control collapses or fails, the relay can fall back to its initial condition.
2. Automatic notification. The control system can automatically send emails to notify users that the control starts, stops and errors found.
3. Hold on period. It appears that sometimes the Bosch system are offline due to WIFI problems. Then the control system cannot request the real time data from Neogrid Gateway. Then the control system can hold on for a period that user specified and attempt to connect again. The total attempt times before error reporting can also be specified.
4. Control file. The control system can automatically record all the control signals, control status and time steps and write to a log file with the name of the start date.

2. System description private dwellings

2.1 House 1

House 1 is a brick house built in 1947, located in Lolland, see Figure 2.1-1. The occupants are a family with three adults and one child. The space heating loop consists of radiators with a forward and return temperature of 55°C and 45°C.

Figure 2.1-1 Location of House 1 and a picture of the house.

The house was previously heated by an oil burner, with a yearly consumption of 2000 liters. In September of 2019 the house was fitted with a new system from Suntherm, consisting of a 7kW heat pump and a 400 liters water and PCM storage. Key figures for House 1 and the system installed is given in Figure 2.1-1. The measurements used in the analysis are from 1st of November 2019 to the 1st of June 2021.

Table 2.1-1 Key figures for House 1 and the system installed.

House 1		
Building area	125	[m²]
Year of build	1947	[-]
*Building heat loss**	0.265	[kW/K]
Building time constant	57	[hour]
Building heat capacity	15	[kWh/K]
Size heat pump	7	[kW]
Size buffer storage (water/PCM)	400	[liters]
Measurements from	1/11-2019	[dd/mm-yyyy]

** the building heat loss is determined based on measurements of the delivered space heating during periods with a constant indoor temperature.*

A sketch of the system installed is shown on Figure 2.1-2. The system is design to cover both space heating and domestic hot water. On the figure, the heat pump is shown to the right with connections to the storage in the middle. The system is designed with a by-pass option so the heat pump can deliver directly to the house. The additional energy meters installed in the system are also shown in the figure.

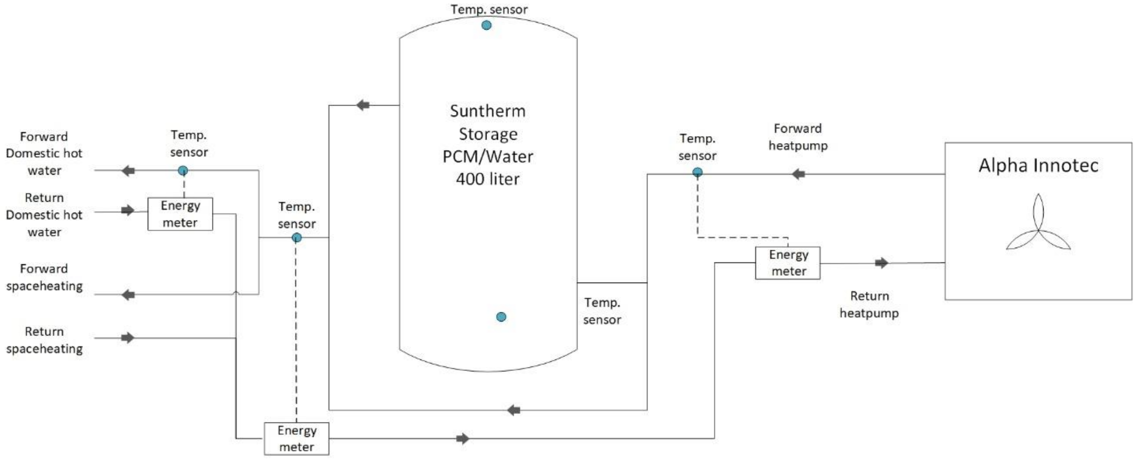

Figure 2.1-2 Sketch of the system installed in House 1 delivered by Suntherm.

Space heating

Based on the collected measurements the energy used for space heating is determined and given in Table 2.1-2. The energy consumption for space heating is of course dependent on the weather conditions during the heating season. For house 1 the space heating need is approx. 20 MWh per year.

Table 2.1-2 Energy for space heating House 1 from the 1/11-2019 to 1/6-2021.

House 1 – Space heating	*2019*	*2020*	*2021*
	1/11 – 31/12	*1/1 – 31/12*	*1/1 – 1/6*
Degree days [-]	692	2370	1764
Energy Space heating [MWh]	4.96	19.68	11.30

The daily space heating need is also shown on Figure 2.1-3 over the course of a year. The mean daily outdoor temperature is indicated with colour corresponding to the outdoor temperature, see scale to the right. When the outdoor temperature increases the energy for space heating decreases and comes close to 0 kWh at outdoor temperatures of 17°C.

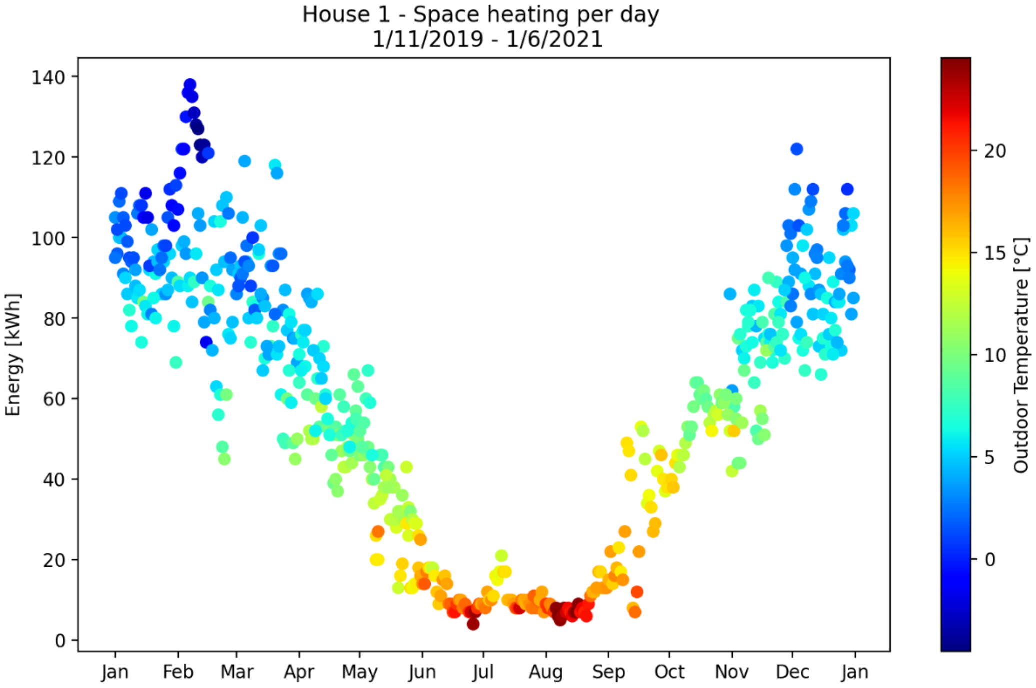

Figure 2.1-3 The need for space heating for house 1 as a function of the time of the year, with the colour indicating the outdoor temperature.

Domestic hot water

The same way the energy for space heating is measured so is the energy for domestic hot water. The family has yearly energy consumption of approx. 1.0-1.5 MWh, see Table 2.1-3. Also, their daily consumption is between 119 liters and 151 liters.

Table 2.1-3 Energy for domestic hot water for House 1 from the 1/11-2019 to 1/6-2021.

House 1 – Domestic hot water	*2019* *1/11 – 31/12*	*2020* *1/1 – 31/12*	*2021* *1/1 – 1/6*
Energy domestic hot water [MWh]	0.28	0.93	0.95
Average draw off per day [liters]	119	127	151

The measurement also gives information of the pattern for the domestic hot water draw off. On Figure 2.1-4 the average draw off over the course of 24 hours is given, along with the probability of different sizes draw off based on all the measurements.

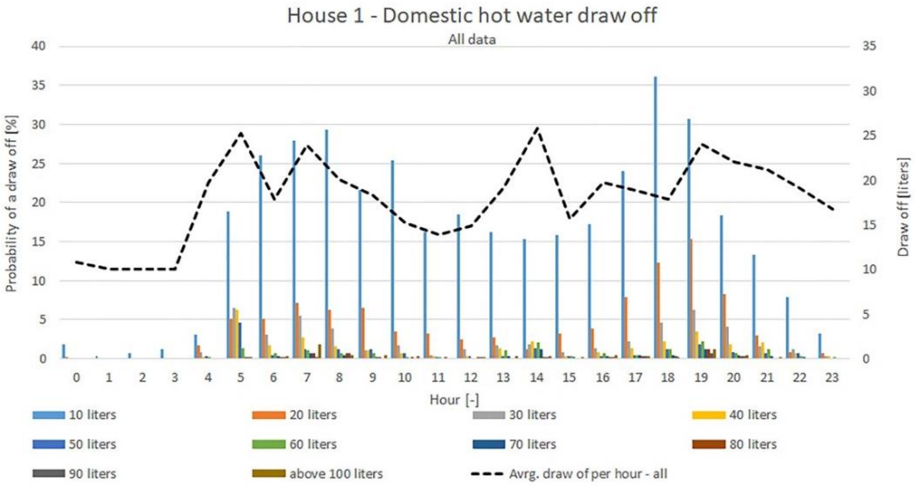

Figure 2.1-4 Probability of a draw off from House 1 and the average draw off based on all data.

The vertical bars give the probability of a certain size hot water draw off within a specific hour, excluding the hours where there are no draw off. The blue bars indicate a 10 liter draw off and therefore is the most common draw off in all the hours. This gives an indication of when there are large hot water draw off and if there are hours where it is unlikely there are hot water draw off. Larger draw off are seen in the morning hours and dinner time hours.

The average draw off per hour show on the figure with the dotted curve gives the average size of the hot water draw off only take during periods with draw off. Here it is seen that there are large hot water draw offs during the morning hours from 5 to 8 am and again at 2 pm. In evening there are again large draw offs around 7 to 8 pm.

Based on the measurements collected it is also investigated if there are different profiles for the different days of the week. For House 1 the profiles for weekdays and weekends are much the same, which can be seen on Figure 2.1-5 and Figure 2.1-6.

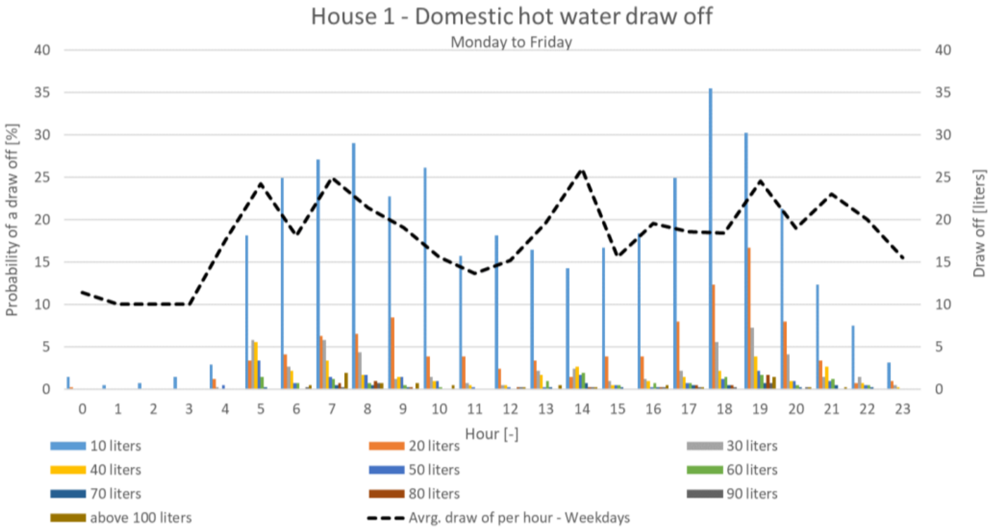

Figure 2.1-5 Probability of a draw off from House 1 and the average draw off based on data from Monday to Friday.

On weekdays there are less large draw offs in the evening compared with the weekends, at the same time there is a higher probability of a 10 liters draw off during the night in the weekdays as oppose to the weekends.

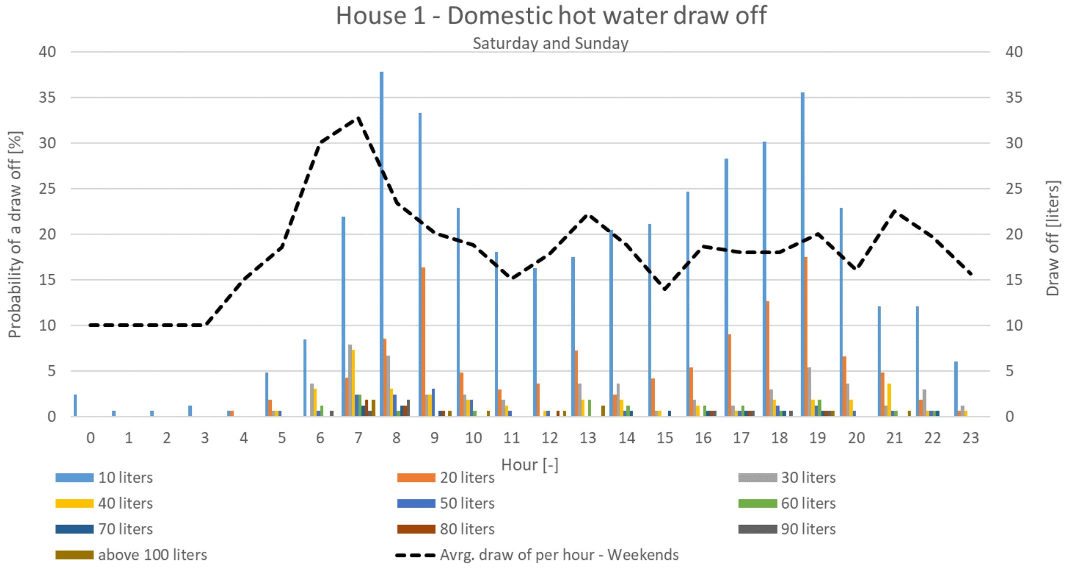

Figure 2.1-6 Probability of a draw off from House 1 and the average draw off based on data from Saturday and Sunday.

Figure 2.1-7 shows the difference in the weekdays and weekend profiles, where it becomes clearer that there is a higher probability for larger draw offs during the morning in the weekends.

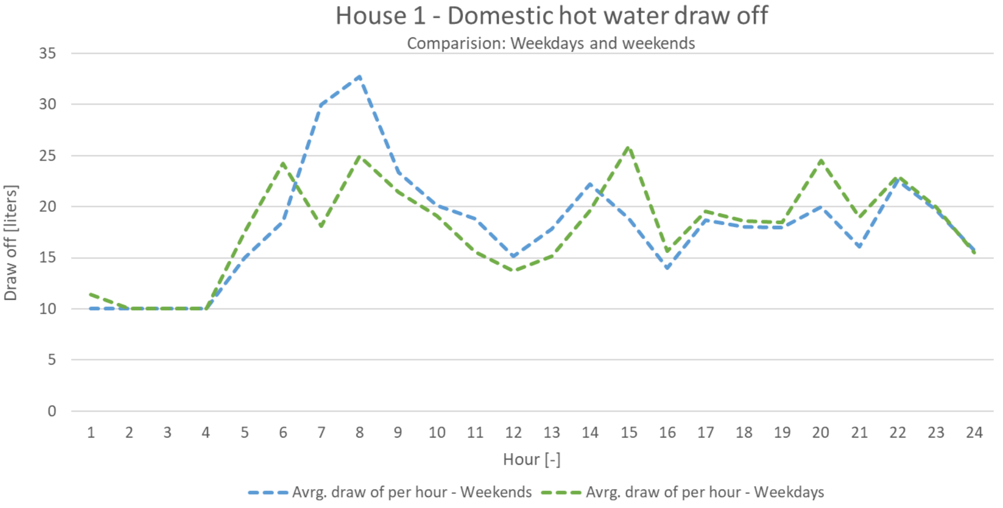

Figure 2.1-7 Comparison between weekdays and weekend profiles for House 1.

Performance

The efficiency of the system installation in House 1 is given on Figure 2.1-8. The System COP is shown over the course of a year where the outdoor temperature is indicated with the colours. The sizes of the circles correspond to the energy delivered to the house by the heat pump.

The System COP is between 3 – 7, which is considered as a well operating heat pump. The System COP is temperature dependent as it is seen on the figure, with higher performance at warmer outdoor temperatures.

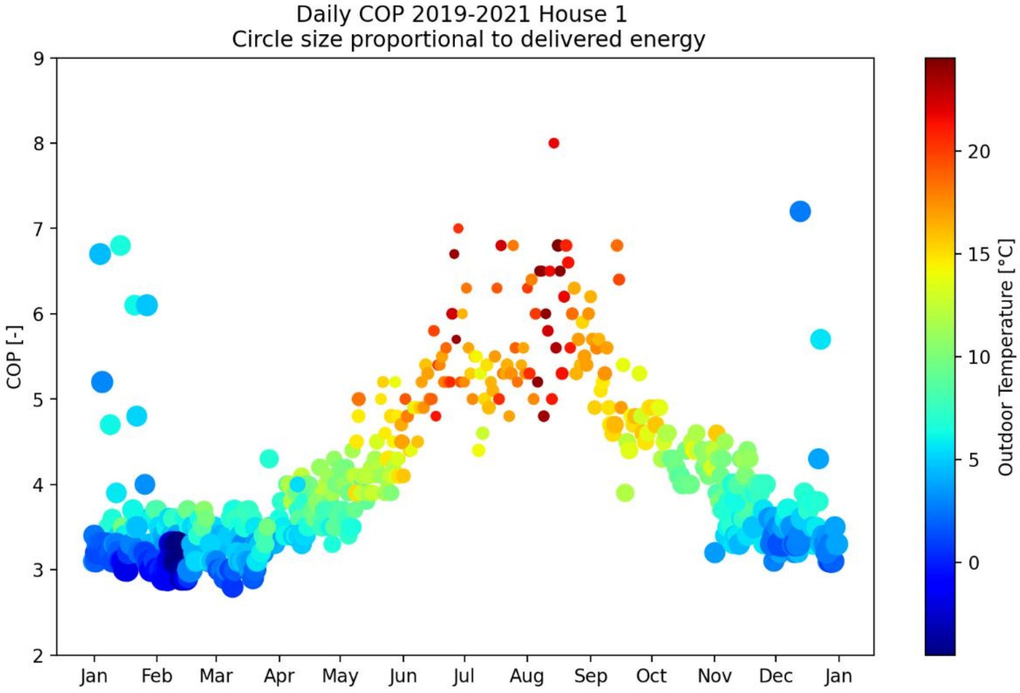

Figure 2.1-8 System COP for the heat pump system installed at House 1

On Figure 2.1-9 the overall performance of the Sunthem system is given. Here it can be seen that the operation time at low outdoor temperatures is approx. 16 hours, with avg. pause time around 1-2 hours. At increasing outdoor temperatures, the operation time decreases and the avg. pause time increases. This indicates that there is a potential for flexibility.

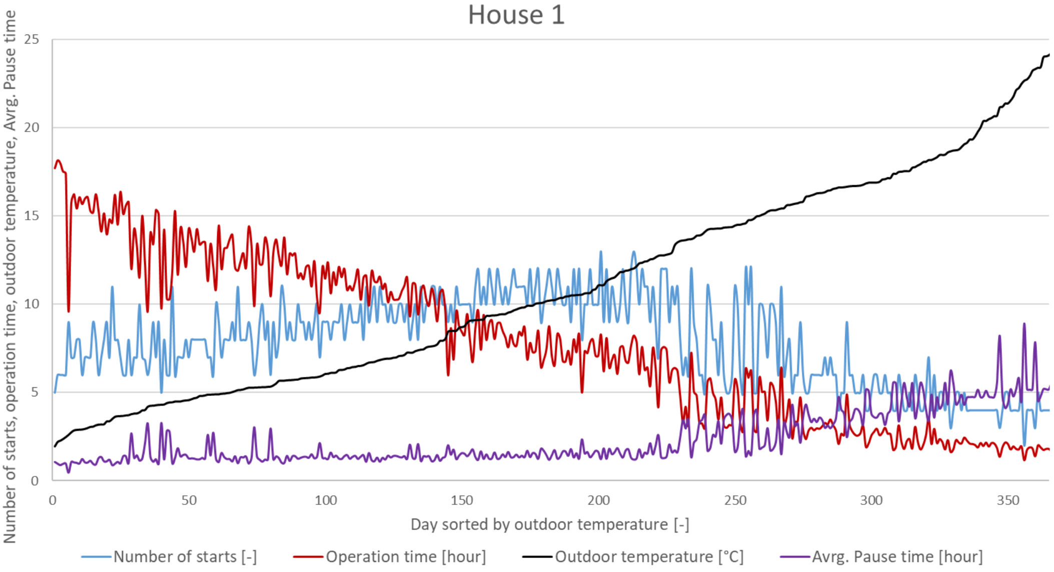

Figure 2.1-9 Performance of the system installed at House 1.

2.2 House 2

House 2 is located in the southern part of Zealand on Bogø, see Figure 2.2-1. It is a wood house build in 2005. Two adults with one child occupies the house. The previous energy source before the installation of the Suntherm system was electricity with a yearly consumption was 19.000 kWh. Radiators heat the ground floor of the house and the first floor is heated by floor heating.

Figure 2.2-1 Location of House 2 and a picture of the house.

Key figures for the house and system installed for House 2 is given inTable 2.2-1.
The heat pump installed is a 7 kW heat pump with a 400 liters water and PCM storage. The measurements are available from 1st of December 2019.

Table 2.2-1 Descriptive figures for House 2 and the system installed.

House 2		
Building area	179	[m²]
Year of build	2005	[-]
*Building heat loss**	0.170	[kW/K]
Building time constant	84	[hour]
Building heat capacity	14.32	[kWh/K]
Size heat pump	6	[kW]
Size buffer storage (water/PCM)	400	[liters]
Measurements from	1/12-2019	[dd/mm-yyyy]

** the building heat loss is determined based on measurements of the delivered space heating during periods with a constant indoor temperature.*

Space heating

Table 2.2-2 shows the measured energy for space heating in House 2 along with the number of degree days. The yearly energy consumption for space heating is approx. 10 MWh per year.

Table 2.2-2 Energy for space heating House 2 from the 1/12-2019 to 1/6-2021.

House 2 – Space heating	*2019* *1/12 – 31/12*	*2020* *1/1 – 31/12*	*2021* *1/1 – 1/6*
Degree days [-]	377	2368	1788
Energy Space heating [MWh]	1.74	9.52	6.16

The energy for space heating over the course of a year is shown in Figure 2.2-2. The dependency of the outdoor temperature can be seen with the colour scale indicating the variation of the outdoor temperature. It can also be seen that House 2 has a much lower heat demand for space heating compared to House 1, which is because the house is more recently build with more insulation according to the harder restrictions in the Danish build code.

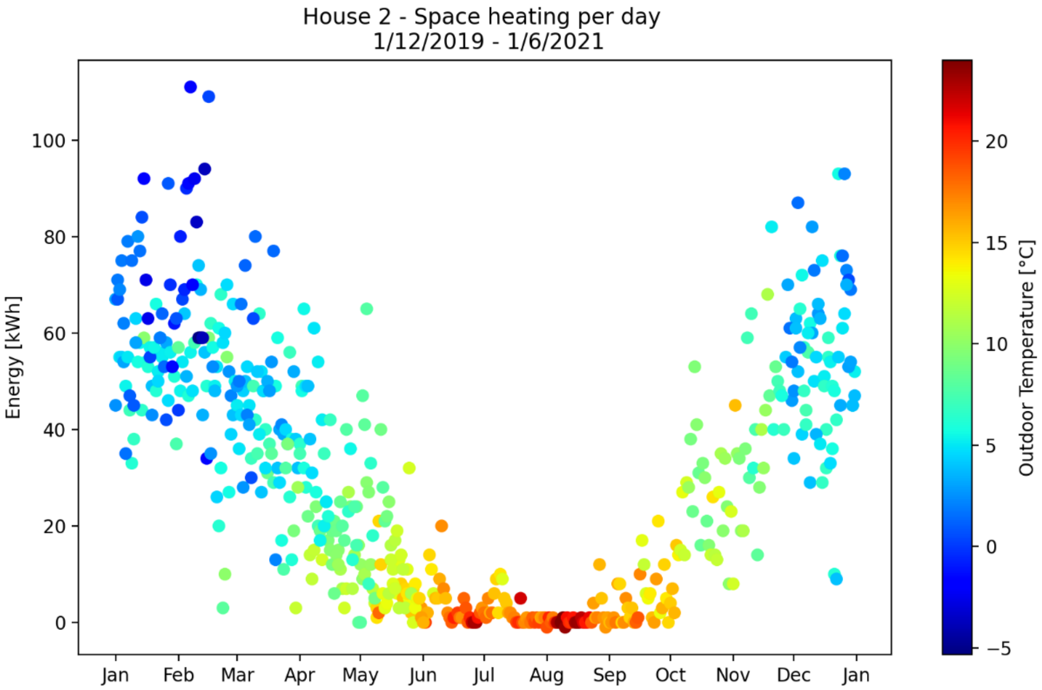

Figure 2.2-2 The need for space heating for house 2 as a function of the time of the year, with the colour indicating the outdoor temperature.

The energy for domestic hot water usage for House 2 is approx. 1.4 MWh per year, with an average daily consumption of just under 100 liters per day, see Table 2.2-3.

Table 2.2-3 Energy for domestic hot water for House 2 from the 1/12-2019 to 1/6-2021.

House 2 – Domestic hot water	*2019* *1/12 – 31/12*	*2020* *1/1 – 31/12*	*2021* *1/1 – 1/6*
Energy domestic hot water [MWh]	0.12	1.39	0.61
Average Tap per day [liters]	95	98	90

The profile of the domestic hot water consumption in House 2 can be seen on Figure 2.2-3 based on all the data available from House 2. The figure shows a high draw off in the early morning hours. Also in the morning, occurrence of small taps of 10 liters is almost no existing. The figures show most often the taps in the morning are larger ranging from 30 liters to 50 liters.

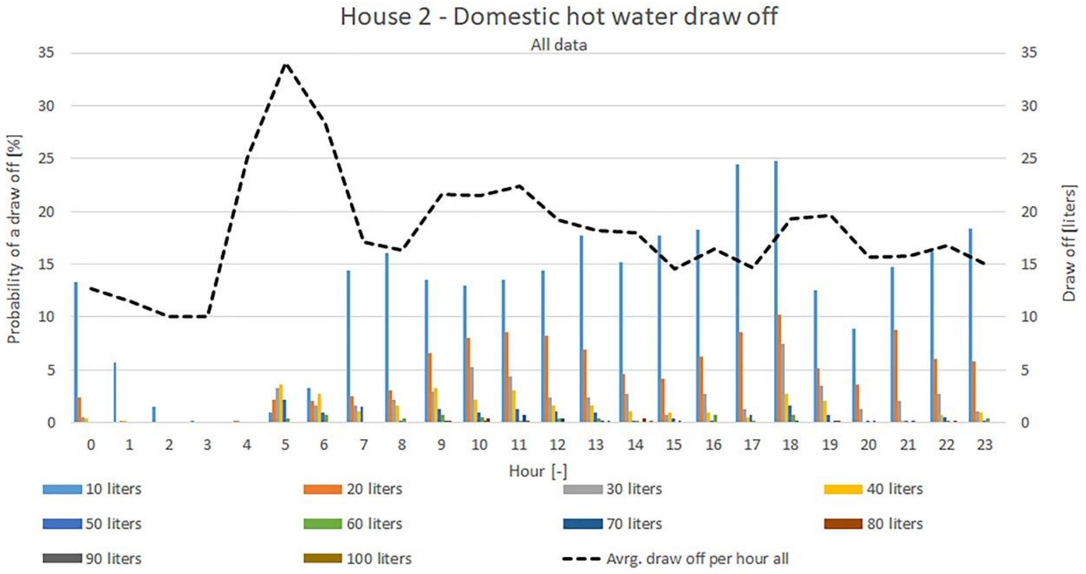

Figure 2.2-3 Probability of a draw off from House 2 and the average draw off based on all data.

The evening peak where larger tap occurs can be seen from hour 18 to hour 19, with taps of 30 liters and more.

When the data is spilt into weekdays and weekends and profiles are created it appear that the early morning draw off does not occur in the weekends, see Figure 2.2-4. The consumption of hot water is moved from the early morning hours at 5-6 in the weekdays to the hours of 8-12 which is seen with the increase in the average usages in the profile for the weekend (blue curve).

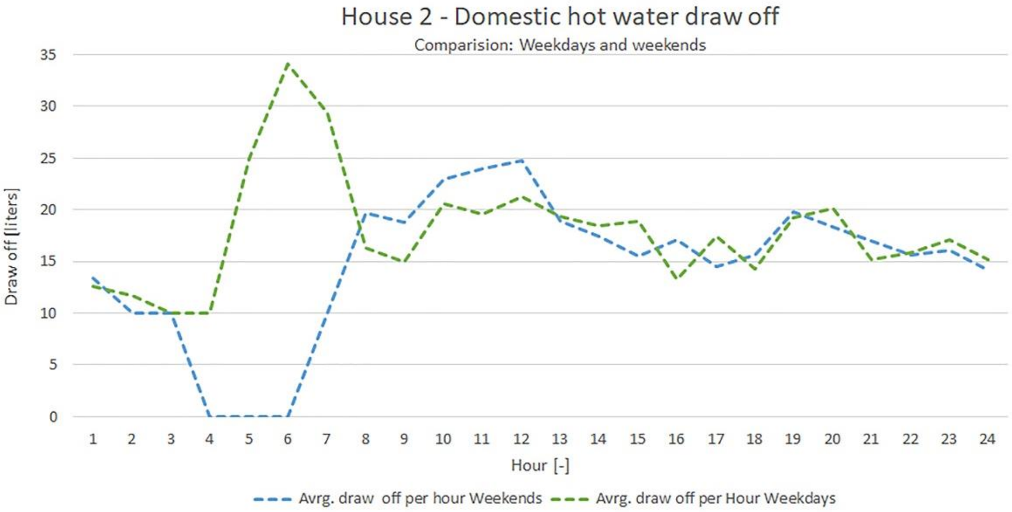

Figure 2.2-4 Comparison between weekdays and weekend profiles for House 2.

Performance

The system COP for the Suntherm system installed at House 2 is given in Figure 2.2-5, where it can be seen that the system COP is between 2.0 and 5.0 dependent on the outdoor temperature. In the figure, the size of the circles corresponds to the delivered energy by the heat pump to the house. It can be seen that as expected the most energy is delivered during the winter months where the space heating needs are highest.

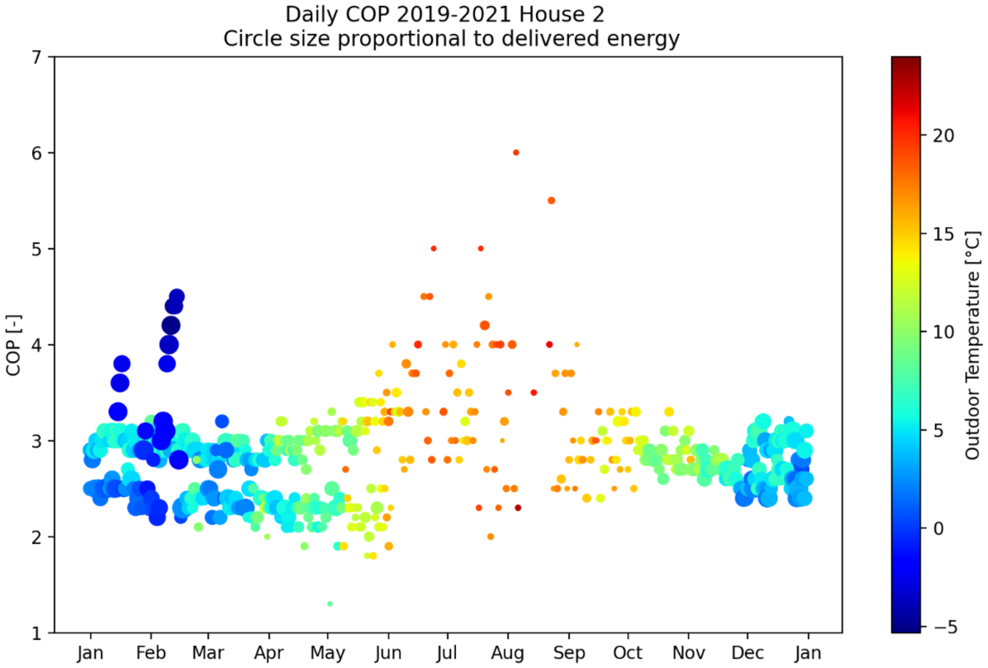

Figure 2.2-5 System COP for the heat pump system installed at House 2.

The overall performance of the system installed in House 2 is given in Figure 2.2-6. Compared with the system installed in House 1, it can be seen that the operation time is lowered, also there is an increase in the duration of the periods without heat pump operation which means that there is a greater potential for offering flexibility. The measurements show that the average duration of the periods without heat pump operation reaches 5-6 hours when the outdoor temperature is above 10°C. At outdoor temperatures around 0°C the daily operation time is approx. 13 hours and the average duration of periods without heat pump operation is 3 hours.

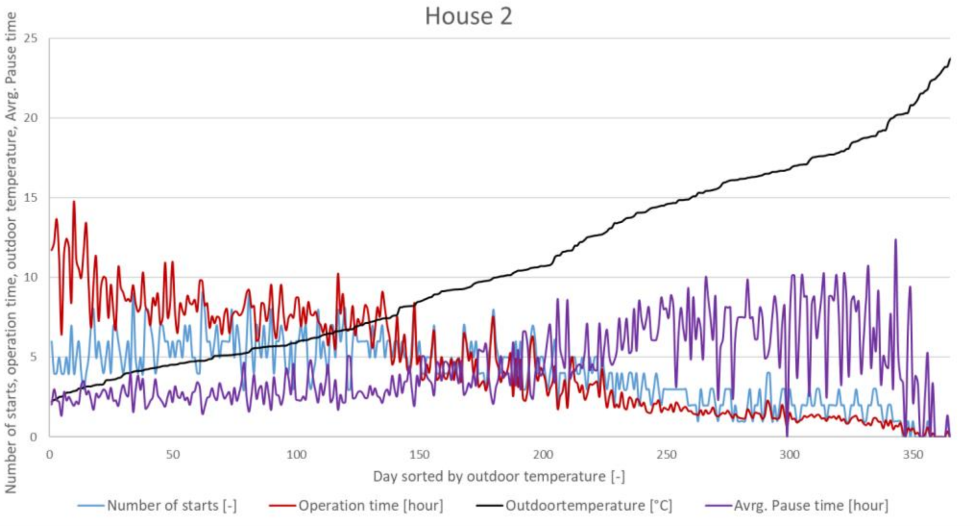

Figure 2.2-6 Performance of the system installed at House 2.

2.3 House 3

House 3 located close to the airport in the southern part of Lolland, see Figure 2.3-1. The house is a brick house from 1997 with 190 m² living area. It is heated with floor heating. It is occupied with two adults and one child. The house is different from the other two houses, in regards to the domestic hot water. The house has a circulation pipe for the domestic hot water ensuring hot water as soon as the hot tap is turned on.

Figure 2.3-1 Location of House 3 and a picture of the house.

The previous energy system for the house was an oil burner with a yearly consumption of 1800 liters oil. The system installed in this house is again a Suntherm system with a slightly bigger heat pump of 9 kW and a 400 liters storage tank with water and PCM. The configuration of the system is the same as House 1 and House 2. The measurements are available from 1/12-2019.

In Table 2.3-1 key figures for House 3 are given.

Table 2.3-1 Key figures for House 3 and the system installed.

House 3		
Building area	190	[m²]
Year of build	1997	[-]
*Building heat loss**	0.157	[kW/K]
Building time constant	146	[hour]
Building heat capacity	22.8	[kWh/K]
Size heat pump	9	[kW]
Size buffer storage (water/PCM)	400	[liters]
Measurements from	1/12-2019	[dd/mm-yyyy]

** the building heat loss is determined based on measurements of the delivered space heating during periods with a constant indoor temperature.*

Space heating

The yearly consumption for space heating is approx. 11 MWh, see Table 2.3-2, which is much like the consumption for House 2. The consumption corresponds with when the house is built and demand for insulation resulting in a low heat loos coefficient for the house.

Table 2.3-2 Energy for space heating House 3 from the 1/12-2019 to 1/6-2021.

House 3 – Space heating	*2019* *1/12 – 31/12*	*2020* *1/1 – 31/12*	*2021* *1/1 – 1/6*
Degree days [-]	376	2372	1777
Energy Space heating [MWh]	1.79	10.39	7.68

The space heating delivered to House 3 is shown on Figure 2.3-2 over the course of a year. Again, the outdoor temperature is given with the colour scale, where the higher consumption of space heating occurs when the outdoor temperature is low.

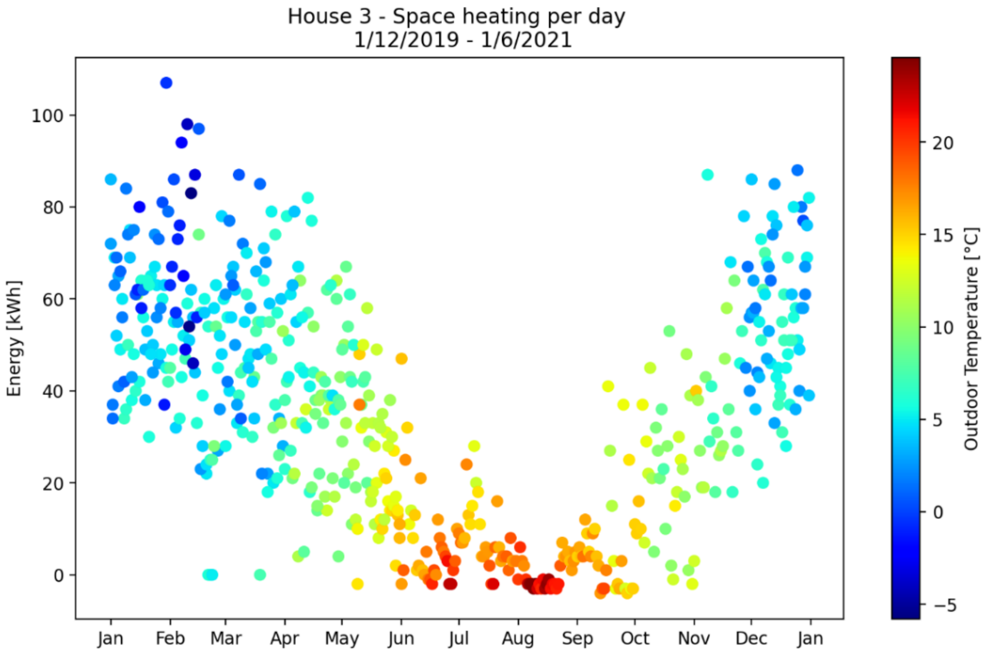

Figure 2.3-2 The need for space heating for house 3 as a function of the time of the year, with the colour indicating the outdoor temperature.

Domestic hot water

There is, as mentioned earlier, a circulation pipe for the domestic hot water, which appear in the yearly consumption measured in the house of approx. 10 MWh, see Table 2.3-3. The consumption here consists of the losses from the pipes and the domestic hot water consumption. Also because of the circulation the daily consumption of hot water in liters is not given, but the liters flowing through the energy meter incl. the circulation.

Table 2.3-3 Energy for domestic hot water for House 3 from the 1/12-2019 to 1/6-2021.

House 3 – Domestic hot water	*2019* *1/12 – 31/12*	*2020* *1/1 – 31/12*	*2021* *1/1 – 1/6*
Energy domestic hot water [MWh]	0.86	9.47	4.16
Average flow through the energy meter per day [liters]	3580	4149	2987

On Figure 2.3-3 the average hourly consumption is shown with the black dotted curved. Because of the circulation it is difficult to detect an actual profile, only an evening peak around hour 17 to 20 can be seen.

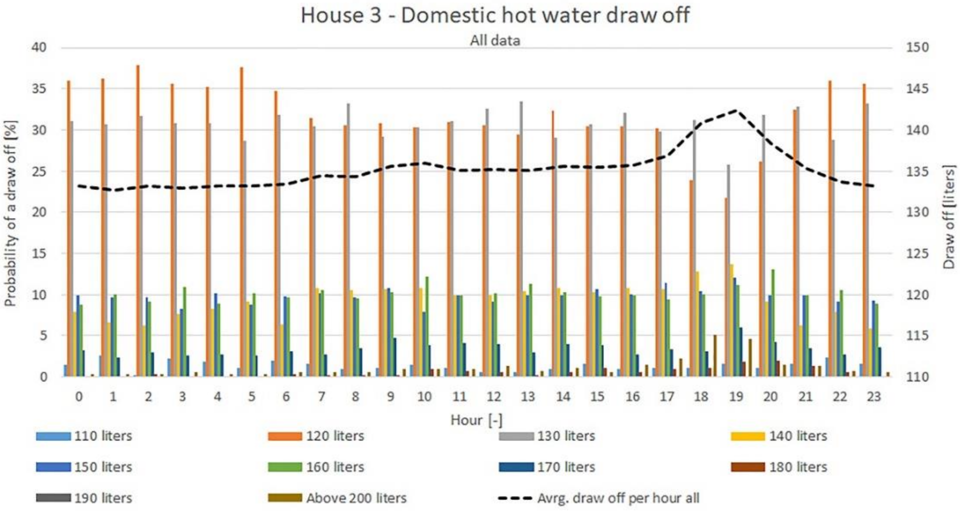

Figure 2.3-3 The effects of circulation on the probability for House 3 and the average draw off based on all data.

The same difficulties to detect profiles is also seen in Figure 2.3-4 where weekday profile is compared with weekend profile.

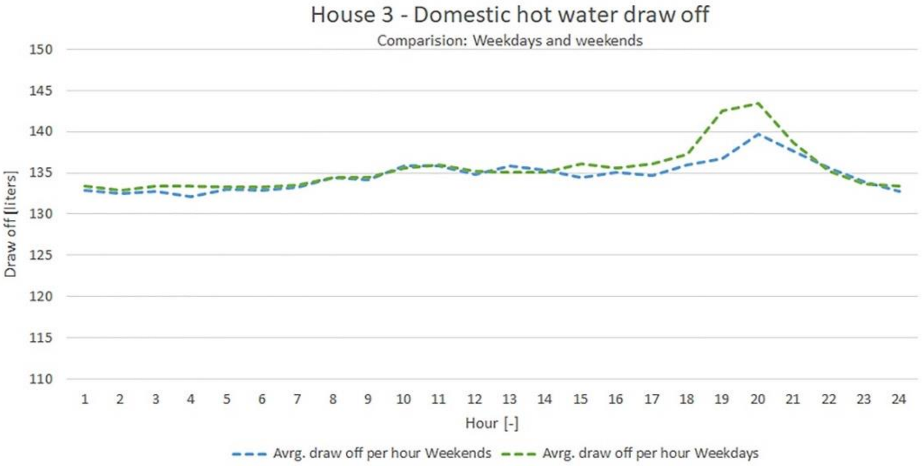

Figure 2.3-4 Comparison between weekdays and weekend profiles for House 3.

Performance

The system performance of House 3 is shown on Figure 2.3-5. Here it can be seen that the daily system COP is more or less constant around 3.5.

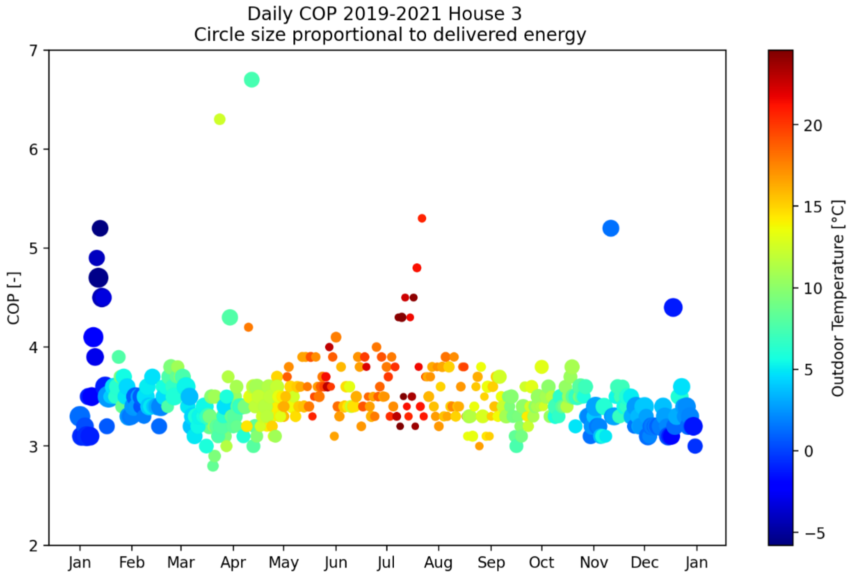

Figure 2.3-5 System COP for the heat pump system installed at House 3.

The size of the circles corresponds to the amount of energy delivered by the heat pump. Because of the circulation on the domestic hot water, the operation of the heat pump is higher during the summer months compared with the other two-family houses.

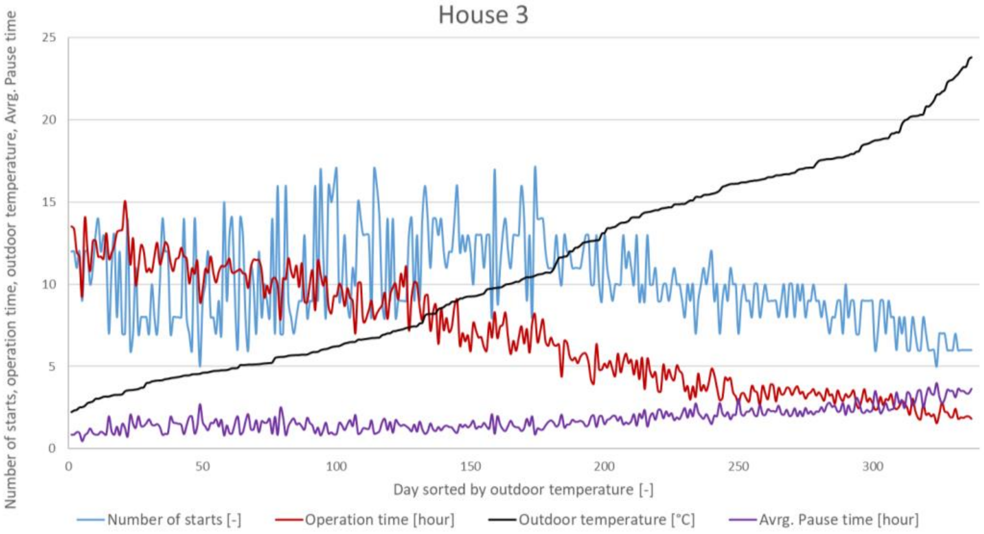

Figure 2.3-6 Performance of the system installed at House 3.

The overall performance for the system installed in House 3 is given in Figure 2.3-6. On the figure it can be seen the average duration of periods without heat pump operation and the number of starts is more or less constant over the course of a year. The operation time over the course of a day ranges from 13 hours to 2 hours.

3. Storage capacity and potential

Thermal energy storage is an important component in energy systems, especially when there is a wish to shift between when energy is produced and when energy is used. Having an energy storage will allow for an increase in utilization of sustainable energy.

Three typical types of storage for energy system are: Sensible heat storage, heat of fusion storage and chemical storage. A sensible heat storage is utilizing a temperature increase in a heat storage material, usually water. Heat of fusion storage is where a phase change is utilized in order to increase the energy content per volume compared with e.g. water. In chemical storage a chemical reaction is utilized in the storage. The chemical storages are not included in this project, and are therefore not described further.

3.1 Water storage

Water storages are the most common sensible heat storage and are usually cylindrical tanks made of steel or stainless steel with water inside. The freezing point for water is 0°C and the boiling point is 100°C, making the operating temperature vary from 0°C to 100°C, which corresponds well with demands for many energy systems.
For the Bosch system installed in the airport the operating temperature of the storage is between 30°C to 45°C with a water volume of 300 liters. The theoretical energy content in the storage is 5.2 kWh. The measured discharge power from the storage is between 1.5-2.0 kW. The total energy discharged from the tank during a shutdown period is approx. 4.5-5 kWh over the course of 2-2.5 hours.

3.2 PCM storage

In a phase change storage, a large part of the heat is stored during the phase change of the heat storage material. The most promising change is from solid to liquid phase since many materials have a melting point between 25°C to 70°C, see Table 3.2-1.

Table 3.2-1 Different salt hydrates which can be used as heat storage material.

	Formula	Melting point, °C	Heat of fusion, kJ/kg salt hydrate
Sodium carbonate decahydrate	$Na_2CO_3{\cdot}10H_2O$	33	247
Sodium thiosultfate pentahydrate	$Na_2S_2CO_3{\cdot}5H_2O$	48	209
Sodium acetate trihydrate	$NaCH_3COO{\cdot}3H_2O$	58	265

The PCM material used by Suntherm has a melting point of 48°C. A comparison between the theoretical heat content of 100 l stores with water, PCM with a melting point of 48°C and PCM with a melting point of 58°C is given in Figure 3.2-1

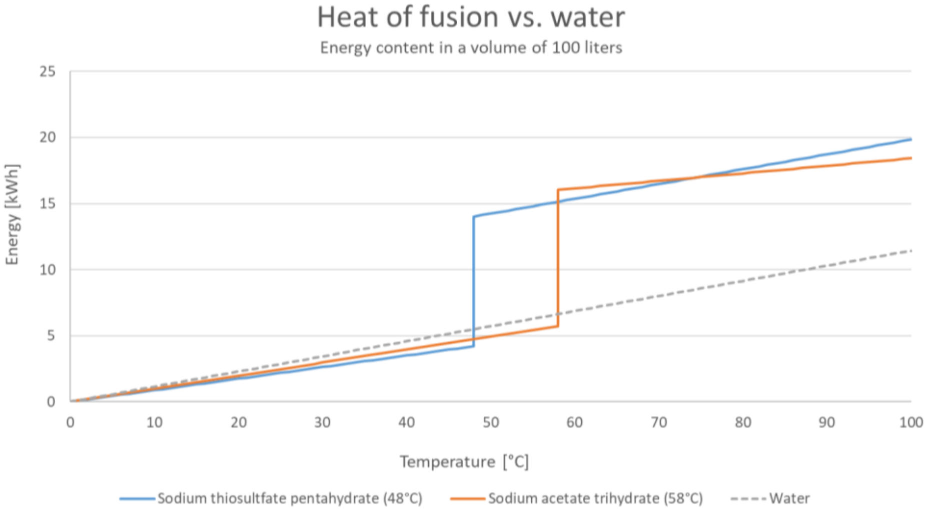

Figure 3.2-1 Heat content of 100 l stores with water and PCMs.

The blue curve shows the heat content in a 100 liters volume of PCM with a melting point of 48°C. Up until the melting point the increase in energy more or less follows the increase in the 100 liters water volume. When the melting point is reached, the temperature remains at 48°C while the heat content increases and the PCM changes from solid to liquid. When all PCM is melted, the temperature increases again during charge of the heat storage. The orange curve shows the same pattern for a PCM with a melting point of 58°C. The dotted curve shows heat content of the water storage.

Overall, it can be observed that there is a great potential in utilizing the latent heat content in the PCM compared with sensible heat content in water. The PCM allows for larger heat storage capacities without increasing the volume.

The Suntherm storages installed in this project all have a volume of 400 liters. Of the 400 liters 30 % is PCM material, 66 % is water and 4 % is the plastic encapsulating the PCM. The operating temperatures in the storages are from 47°C to 58°C.

The maximum theoretical heat content in the Suntherm storages is 11.4 kWh, where the water accounts for 3.6 kWh and the PCM for 7.8 kWh. A water storage with a heat content of 11.4 kWh in the same temperature interval 47°C-58°C would have a volume of 893 l. That is, the water storage volume would be 2.2 times larger than the PCM heat storage used by Suntherm.

In this project, the measured discharge power from the Suntherm storages is approx. 2.5 kW depending on the control settings in the storage tank. In total the energy discharge from the tank during a shutdown period is between 4.0 – 5.0 kWh of the course of 1.5 – 2 hours.

One of the obstacles making it difficult to utilize more of the energy in the PCM is the plastic encapsulating the PCM. It hinders a high heat transfer from the PCM to the water and vice versa. Also, the theoretical energy content calculated for the PCM is based on very small quantities determined by T-history method. Investigations have shown difficulties in upscaling the volume of PCM and obtaining the same latent heat content because of phase separation problems in the PCM.

4. Optimised control of heat pumps

4.1 Introduction

Some of the heat pumps in the FUTURE project has been connected to Neogrid server and optimised control has been applied. In this chapter the optimised control is explained and the results from the analysis and tests are shown.

4.2 Heat pump survey and control access

Heat pumps can be separated into 3 categories with regard to their “Smart Grid Readiness”.

In order to make a heat pump useful for optimised control basic data must be logged and sent to Neogrid’s server. Then analysis take place and an operation schedule for the heat pump is calculated and sent back to the heat pump. This can be implemented in different ways dependant on the type of heat pump.

Table 4.2-1 Heat pump types and add-on equipment for optimized control

Heat pump type		Necessary equipment for optimized control[1]
1	Standard heat pump with relay input	● Gateway with relay control ● Room temperature sensor ● PT-1000 outdoor temperature sensor emulator
2	Bigger heat pumps and heat pumps with Modbus (RS-485) interface	● Gateway with RS-485 interface ● Room temperature sensor
3	Cloud connected heat pump with API for logging of data and control	● Nothing

The table above shows three types of heat pumps and the required retrofit in order to make the heat pump ideal for optimised control. Older and/or simpler heat pumps (cat 1) requires a gateway to get it online and to collect all sensor and meter data. Control is established via the heat pumps relay input or by manipulating the outdoor temperature sensor. Other heat pumps (cat 2) have a communication interface where much more data and control capabilities are available. Newer heat pumps (cat. 3) are “born” online and have the possibility to collect data from external sensors and meters. The heat pump manufacture typically operates a cloud where all data are collected and available for a third-party actor like Neogrid via an API.

Heat pumps used by Suntherm in the FUTURE project belong to cat 3, with full online access to all data and control setup. The Bosch heat pump in the airport is cat 1 type.

4.3 Flexibility

For a given installation the flexibility is the heat pumps capability to postpone or put forward its operation and still deliver the agreed comfort. Many parameters in the installation determine the flexibility, some typical are listed in the table below:

---

[1] Energy and electricity meter data is assumed to be available

Table 4.3-1 Parameters determine flexibility

Parameters which determine flexibility
↑ Big storage tank ↑ Big domestic hot water tank ↑ Big heat pump ↑ Frequency controlled heat pump vs on/off type ↑ Ground water heat pump vs air water type
↑ Large heat capacity of building ↑ High time constant of the building ↑ Low temperature for the heat pump ↑ No limiting thermostats inside building ↑ Use of floor heating
↑ Relaxed comfort requirements inside building ↑ Use of wood burner ↑ Use of short showering

For a typical building a simple model to describe the dynamics are:

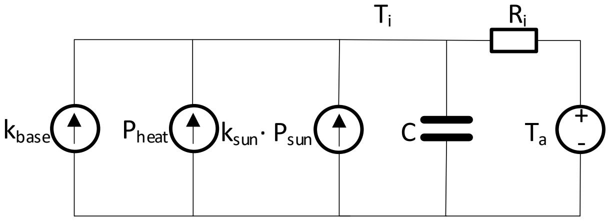

Figure 4.3-1 Building model for a standard house

where

Pheat	Power delivered to the house [kW]
Ti, Ta	In- and outdoor temperature [˚C]
Ri	Heat resistance from indoor to outdoor [˚C/kW]
ksun	Transfer function between out- and indoor sun power [$1/m^2$]
C	Heat capacity of the house [kWh/˚C]
kbase	User behaviour generated power to the house [kW]

For “house 2” of the Suntherm installations (the newer wooden house) the key figures: Ri, ksun, C and kbase are determined. It’s also tested that one degree of variation on the indoor temperature is acceptable and then it is possible to determine the daily amount of flexibility in hours. This is plotted in Figure 4.3-2.

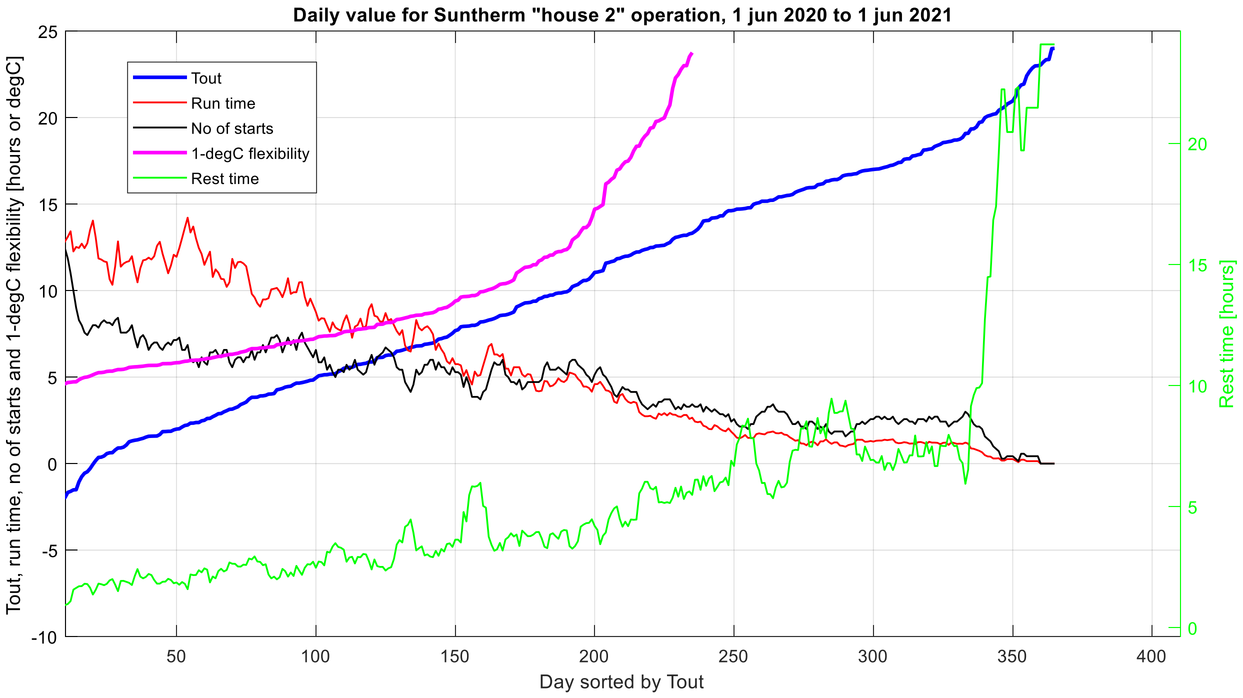

Figure 4.3-2 Daily operation characteristics for a Suntherm operated building during a year

In the above figure daily key values like "No of starts", "run time", "rest time" and "1-degC flexibility" are sorted based on ascending Tout and plotted. "1-degC flexibility" is the duration it takes for the indoor temperature to drop one degree based on the specific weather. It can be seen that this house has minimum 5 hours of flexibility even on the coldest day. This means that this house in best case can handle 5 hours with no added heat if the indoor temperature is at maximum comfort always and thus avoid operation on these hours. It should however be noticed that hot water storage capabilities and demand also has an impact on the available flexibility.

4.4 Value proposition

Table 4.4-1 Heat pump service list

	Type	Heat pump owner Value proposition
1	Operation optimisation and monitoring	● Online access to key data from heat pump ● Low operation cost ● Improved comfort
2	Services against ● DSO ● Electricity Markets	● Lower energy bill ● Reduced CO_2 footprint
3	Aggregator services ● Electricity Markets	

In Table 4.4-1 the value propositions from a heat pump running optimized control are separated into three categories. The first category are services available as soon as data is collected from the heat pump and connected meters. Then calculation of key performance indicators is possible like daily COP and can be delivered by a company like Neogrid or a third-party actor. If external control is activated extra services like MPC[2] control can secure a lower operation cost of the heat pump. This category "only" requires a bilateral agreement with the heat pump owner and a cloud connected operator.

In category 2 variable prices, tariffs and services to the DSO are taken into account. Variable prices and tariffs are rolled out over most of Denmark, but DSOs flexibility demand to cope with bottlenecks is still limited in Denmark.

In category 3 specialized services to the electricity markets are delivered. This might be regulating power and frequency reserves. Those services require separate settlement of the electricity to the heat pump and an aggregator is required to pool a number of heat pumps. Settlement is a little more complicated as this goes via the aggregator, who gets paid from the aggregated service delivered. How this is then shared between the different actors might depend on several factors like: flexibility size, numbers of activation etc.

4.5 Optimized control

There exist two main types of control: Price signal-based control or direct control. With price signal-based control, a price signal is broadcasted and some local AI determines a schedule for the heat pump. This is useful for Smart Home devices reacting on variable electricity prices etc. For this project direct cloud-based control is applied as the heat pump is a bigger device and full knowledge of the heat pumps operation is required to deliver some of the wanted services. The optimised control is mainly tested on the Suntherm installations using the block diagram shown below.

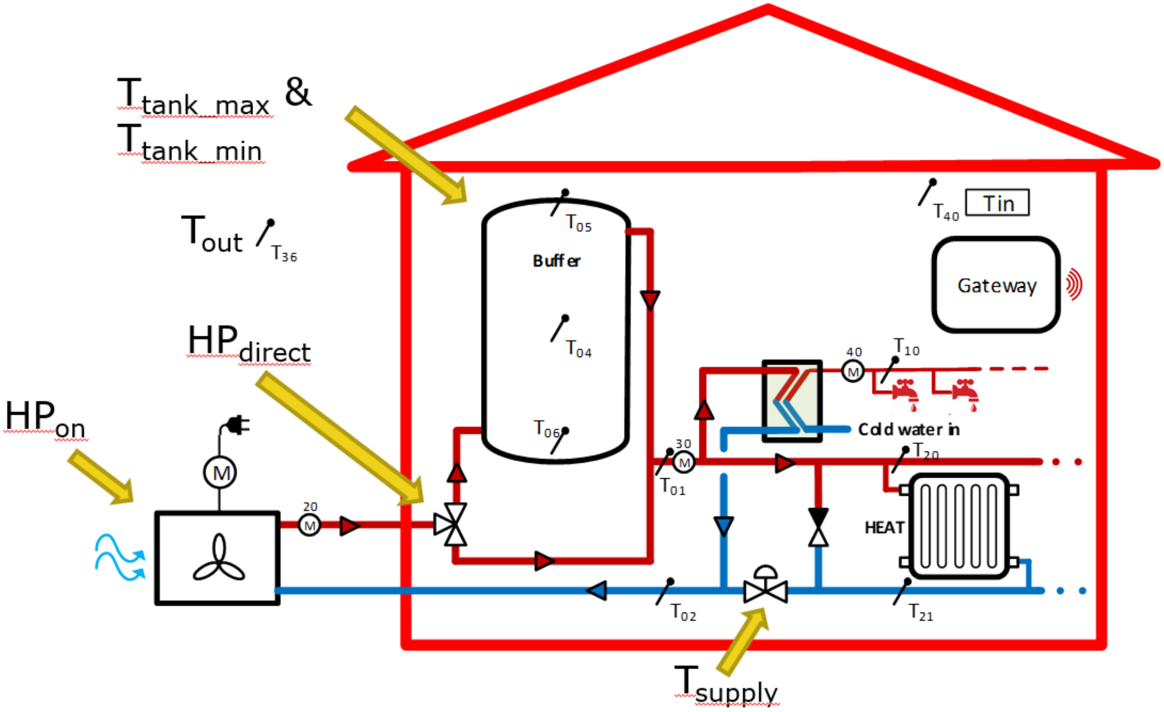

Figure 4.5-1 Suntherm heat pump block diagram showing control input

The main structure of the optimised control is like:

---

[2] MPC – Model Predictive Control, could be cloud based model and weather prognosis-based control

Table 4.5-1 Heat pump optimised control algorithm

Area	Details
Inputs	- Variable net tariffs plan - Variable electricity prices plan - CO_2 content forecast - Weather prognosis - Heat pump COP vs T_{out} - Heat pump COP v s T_{supply} - Heat pump defrosting demand vs T_{out}
Constraints	- Storage tank temperature - Heat pump run-/rest time - T_i comfort window (maybe time dependent)
Output schedule: Control variable	- T_{tank} max and T_{tank} min - HP_{on} - HP_{direct} heat pump delivering to tank or house - T_{supply} supply temperature for room heating

The above table leas to the following mixed integer problem formulation:

minimize

$$\sum_{n=1}^{N} \alpha_n \left(T_{in_n} - T_{set_n}\right)^+ + \beta_n \left(T_{in_n} - T_{set_n}\right)^- + \gamma_n \cdot HP_{on_n} \cdot C_n$$

subject to

$$HP_{on_n} \in \{0,1\} \text{ (mixed integer)}$$

$$T_{tank\_min} \leq T_{tank_n} \leq T_{tank\_max}$$

$$COP = f\left(T_{out}, T_{supply}\right)$$

$$T_{tank_{n+1}} = T_{tank_n} + \frac{dt}{Vol \cdot c}\left[HP_{on_n} \cdot P_{hp} \cdot COP_n - P_{water_n} - P_{heat_n}\right]$$

$$T_{in_{n+1}} = \mathbb{A}_n \cdot T_{in_n} + \mathbb{B}_{\boldsymbol{n}} \cdot \begin{bmatrix} T_{out_n} \\ P_{sun_n} \\ P_{heat_n} \end{bmatrix}$$

definition

n : n^{th} timeslot
T_{in} : Indoor temperature [°C]
T_{out} : Outdoor temperature [°C]
T_{set} : Setpoint indoor temperature [°C]
α, β, γ : Weight factors
HP_{on} : Heat pump on/off
P_{hp} : Electricity consumption heat pump [W]
C : Cost function
COP : Heat pump COP
P_{water} : Power domestic hot water [W]
P_{heat} : Power room heating [W]
P_{sun} : Sun power vertical [W/m²]
P_{max} : Max heat pump power [W]
T_{tank} : Temperature in storage tank [°C]
dt : Time step size [h]
Vol : Storage tank volume [l]
c : Storage tank heat capacity [Wh/°C/l]
$\mathbb{A}, \mathbb{B}$: Matrices for state space model

It should be noted in the problem formulation, that the solver is capable of handling parameters, that are time varying.

4.6 Results and perspectives

Relay test on the Bosch heat pump at the airport has been carried out in the above sections. This section explains the optimized tests made on 3 Suntherm heat pump installations. Then the results are listed and discussed. The tests have mainly been carried out on 2 houses and not 3 as one house owner decided not to join the tests.

First step in optimized control is to select some variable inputs. The analysis here are done with the variable DK1 spot prices[3]. Variable tariffs are included from N1 a major DSO[4], where peak hour prices are 0.54 dkk/kWh from 5 to 8 PM and 0.17 dkk/kWh outside this period.

Second step is choosing a cost function, in general here lowest price is selected. Other cost functions like lowest energy, minimum indoor temperature variation or lowest CO_2 content could have been selected.

Third step is setting up constraints for the optimisation. This is mainly about indoor comfort and domestic hot water temperature. Indoor temperature variation on 1 °C in total is selected as this was not really noticeable by the participants. Tank temperature limits were set to 47 °C as low and 53/58 °C as high. Boosting tank temperatures means higher capacity for hot water production but also a reduced COP. The low tank temperature still secured hot water for a shower.

Fourth step is to select control inputs. Here 4 are available HP_{on}, T_{tank}, T_{supply} and HP_{direct}. T_{tank} is settled as described above and HP_{direct} is chosen for simplicity to be off so heat is delivered to the tank. The advantage with HP_{direct} is to be able to send heat directly to the house and not to the tank.

Operation period feb 5th 2021 to jun 1st 2021.

The main dashboard for monitoring and visualisation of the operation is shown on Figure 4.6-1

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[3] DK1 spot prices from Nordpool https://www.nordpoolgroup.com/Market-data1/Dayahead/Area-Prices/ALL1/Hourly

[4] N1 DSO variable tariff https://n1.dk/priser-og-vilkaar/timetariffer

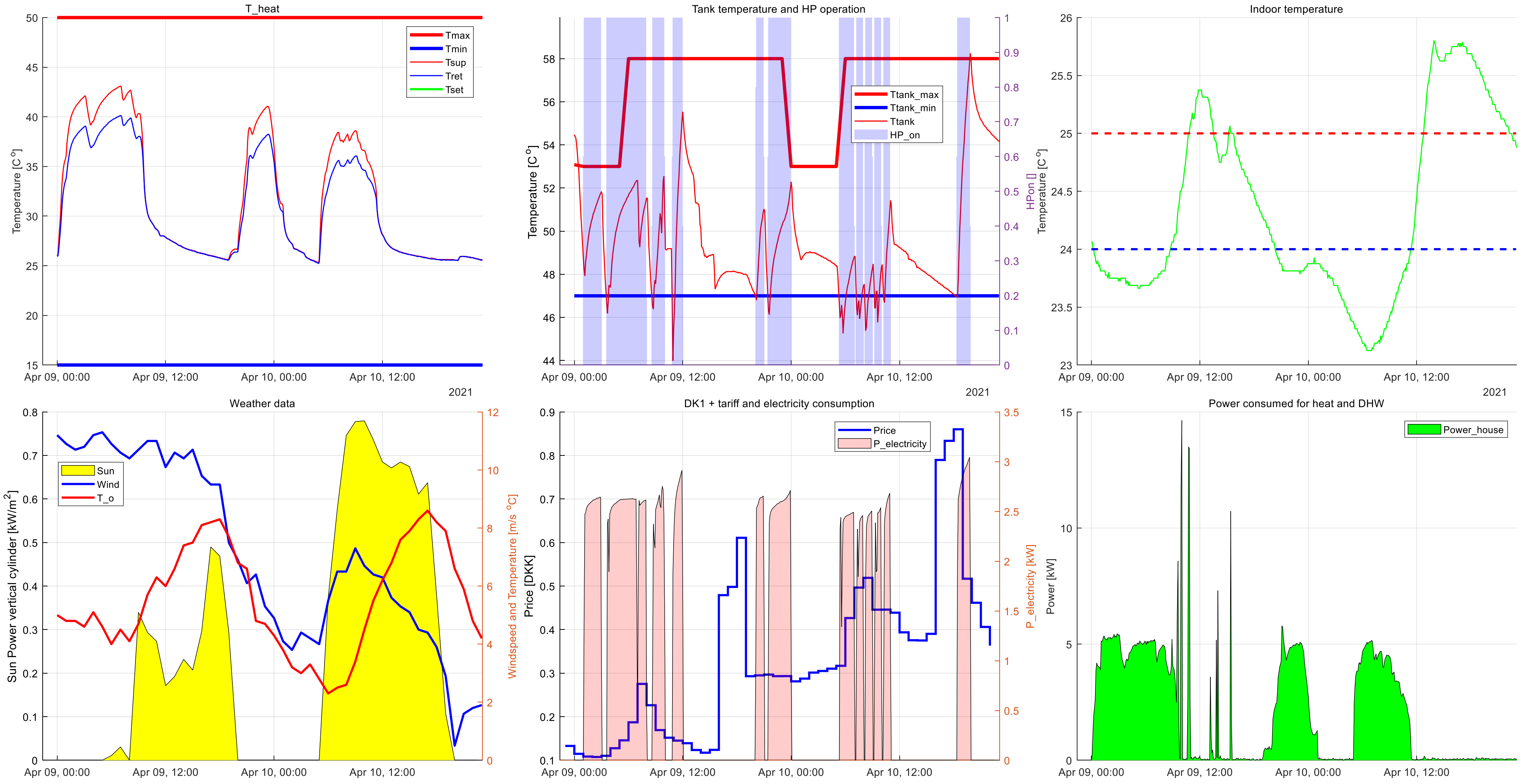

Figure 4.6-1 Dashboard picture from April 9th 2021

The above dashboard shows some of the typical results from optimised control and will be explained in the following.

In the bottom left weather inputs are shown. This is a typical winter day in Denmark with temperature around 5 °C, light wind and clear sky with sun.

In the top left figure is shown the heating temperatures like supply and return temperature and max/min setting of the supply temperature. It can be seen that the heat pump is running in 3 cycles and forward temperature is within the limits.

Bottom right figure shows the energy delivered to the house via room heating and hot water consumption and it's measured on the dedicated energy meters. The energy fits with the pulses of the supply temperature and the peaks represent the periods with hot water consumption.

Top right figure shows the measured indoor temperature during control and the associated min/max requirements. It can be seen that the temperature is fluctuating during the day, determined partly by the supply temperature control and partly by user interactions.

Bottom mid figure shows the electricity consumption of the heat pump, i.e. heat pump operation cycle and the combined price signal used as cost signal. It can be seen that the heat pump is operated outside the two expensive periods. Unforeseen user behaviour like timing of showering and ventilation creates "noise" in the deterministic behaviour and can create unforeseen consumption from the tank and thereby potential unforeseen operation of the heat pump, but this is still handled so the heat pump avoids the expensive periods. Similarly, the defrosting operation of the heat pump is difficult to predict and begins around 5 °C. It is not seen in the above figure tank temperature is always raising when the heat pump is running.

Top mid figure shows the tank temperature and its limits. It can be seen that the two showers from April 9th 12 AM can roughly drain the tank and it can also be seen there is some increased flexibility due to the extended limits of the tank temperature.

Tests on the other installation show similar behaviour but the dimensioning temperature of the heat pump is here much closer to 0 degrees, which means there is much less flexibility left when reaching this temperature.

Applying optimised control of the heat pump changes its operation schedule and it is important that it does not have a negative impact on the COP. A simple method to check this is displaying the daily COP for some periods before and after the control.

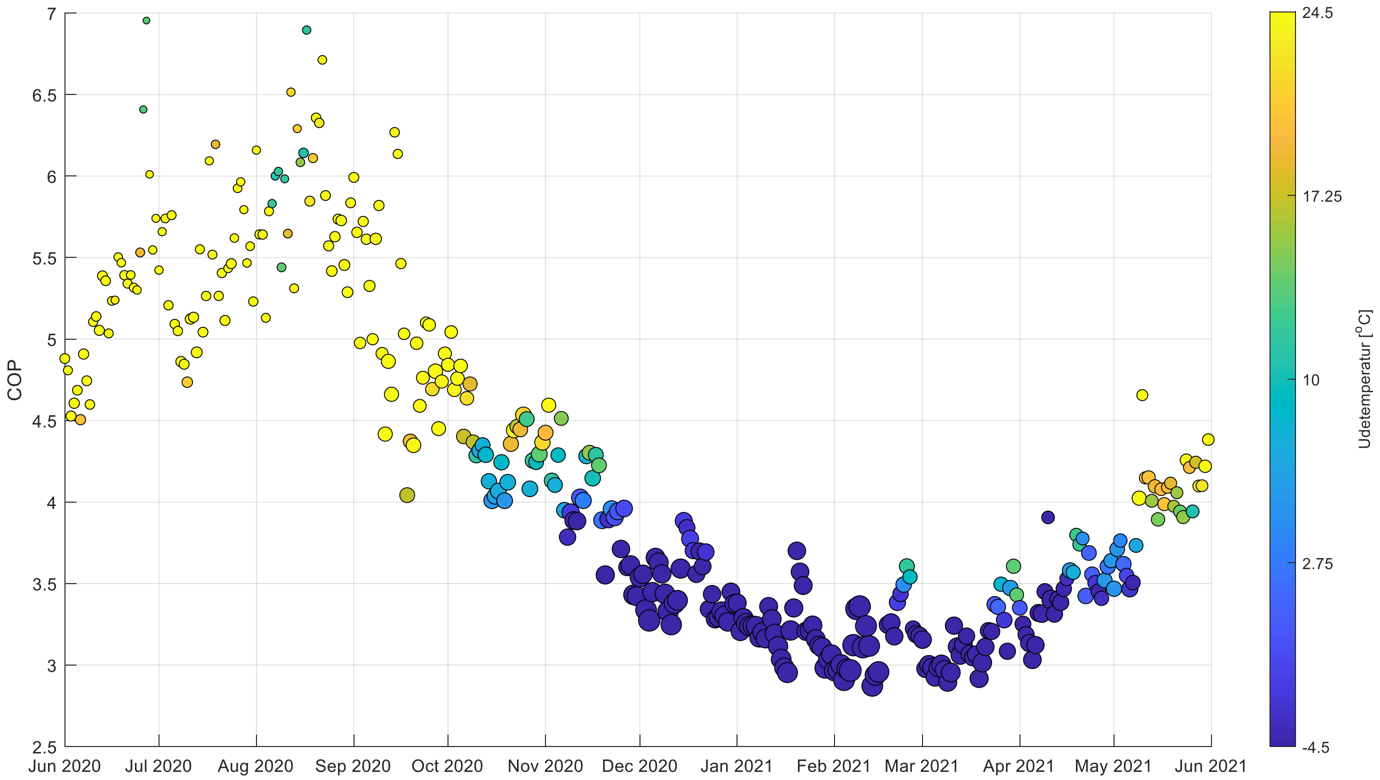

Figure 4.6-2 Daily COP before and after optimised control

In Figure 4.6-2 the daily COP vs date is plotted. Colours on the circles indicate the outdoor temperature and circle size represent the amount of energy produced by the heat pump that day. It can be seen that there is no unforeseen change of COP due to the optimised control.

5. Conclusion

In the Future project case #1 two types of heat pumps have been analysed and tested with their capability to offer flexibility to the local grid and electricity system. The first type is relay controlled (Lolland airport) and the second one is full cloud connected and API controllable.

The major key findings for case #1 are:

- Flexibility in operation of the heat pump is available from two sources in the Suntherm heat pumps: storage tank and building
- The 400 liters salt storage will roughly double the flexibility and will be fully usable when hot water production is separated from the salt storage.
- Large variation in available flexibility from the houses where dominating factors are:
    - Dimensioning temperature of the building
    - Building structure (heavy or light)
    - Building heat loss
    - User comfort requirements inside the house
- Existing relay-controlled heat pumps can be retrofitted to support flexibility
- Extra services, beside delivering electricity system/power grid services, like reduced energy consumption, better comfort and monitoring the heat pump performance can be bundled with the service to deliver flexibility in order to improve the business case.
- Optimised control requires
    - interface to control actual operation of the heat pump
    - and best if heat supply temperature control exists
    - online measurement of “important” indoor temperature and storage tank temperature
- Beginning at 0 degrees, available flexibility from a typical house without a storage tank is enough to avoid the 5 most expensive hours per day.
- Flexibility services to electricity system like balancing power can be delivered when connected to an aggregator.

Appendix A

One way to identify or feature the hot water consumption patterns of families is to use the K-means clustering technique. Generally, K-means clustering is a method to find groups that have similar members, which are more related to each other than to members in other groups. In the hot water consumption case, the members in groups are time series hourly data. Both the peak patterns and intensities of hot water consumption can be reflected in different clusters.

Typical K-means clustering uses the Euclidean distance as the criteria to group members but is not accurate for time series data. Therefore, the Dynamic Time Warping (DTW) distance is used internally instead of Euclidean distance in the K-means algorithm. DTW calculates the smallest distance between all points in time series data. Thus, it has the advantage over Euclidean method if we would like to identify its shape.

A drawback of K-means clustering is that we have to assign the number of clusters. However, it is typically not intuitive to know the optimal number of clusters in the real world, like the hot water consumption case. The elbow method can be used as a graphical tool to identify the best number of clusters - k. Typically, the best k is at the inertia start decreasing linearly. Below figure shows the elbow method case in house 1.

We collected all the hot water consumption data of the location since it was put into use from September 2019 until June 2021. There are in total 547 days of effective data. It can be seen from the figure that the curve starts decreasing linearly from k = 4.

Therefore, the optimal number of clusters is 4.

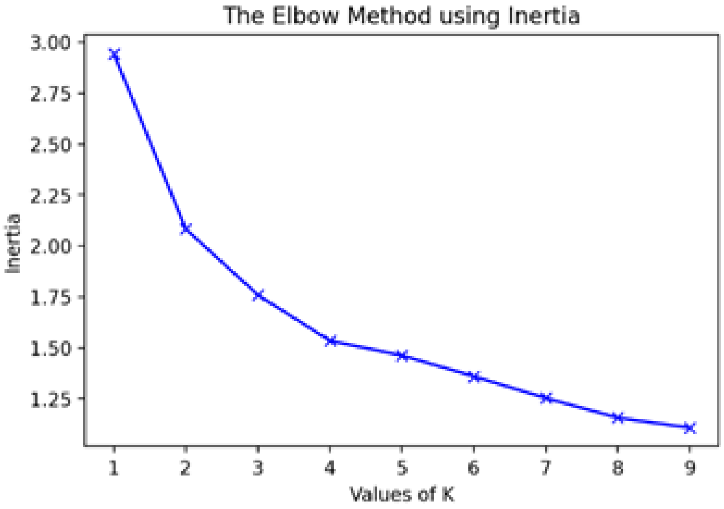

Figure A-1 The Elbow method using inertia.

Then the K-means clustering with DTW distance was carried out for all the data. The four cluster centroids are shown in Figure A-2. It can be seen that the four clusters are identified according to their peak patterns and the energy consumption intensity.

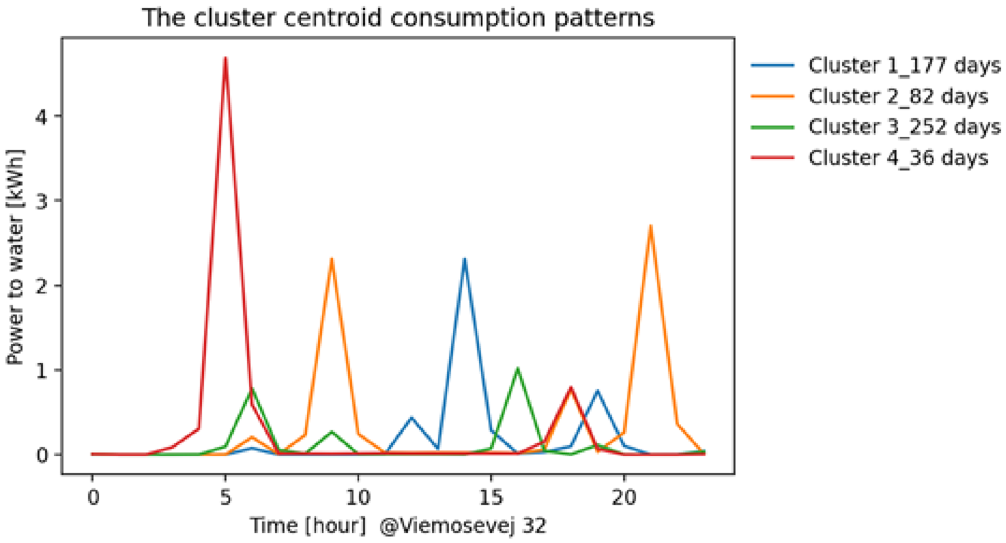

Figure A-2 The cluster centroid consumption patterns.

The daily curves in each cluster are plotted in below figure. A cluster distribution map is shown in Figure A-4.6-1. It shows how the house's daily hot water consumption profile changes cluster throughout the period. The Nan days indicates the days that the hot water consumption was not correctly recorded and they were removed from the clustering calculations.

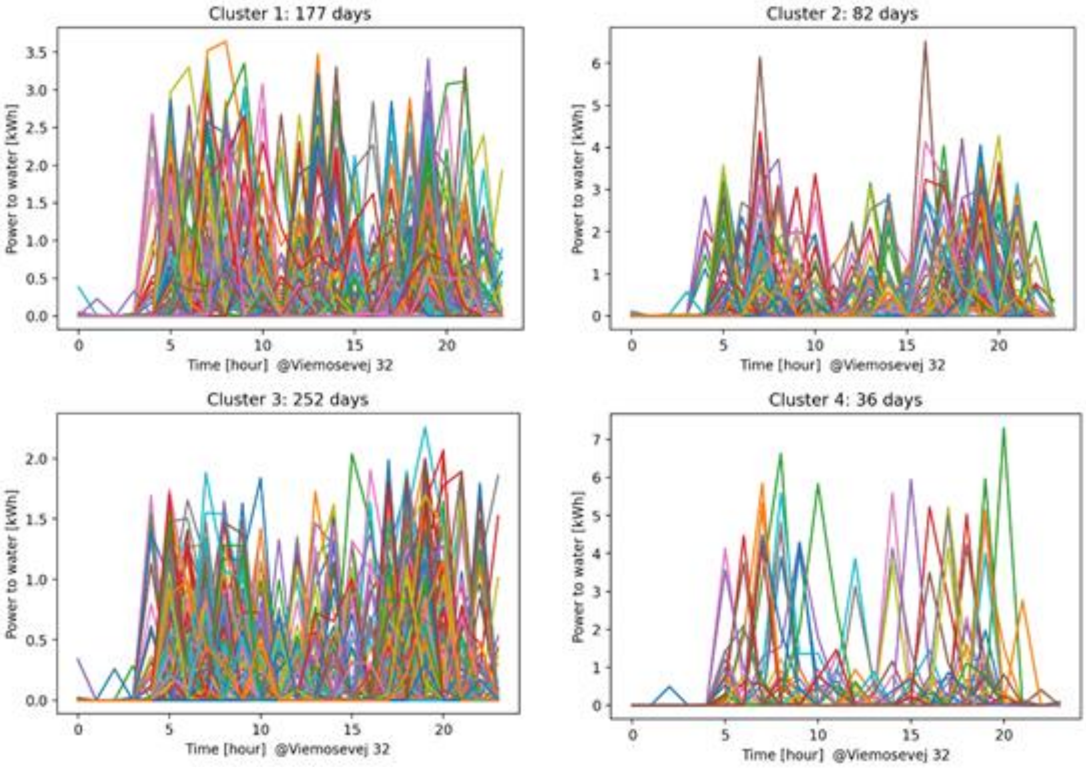

Figure A-3 Cluster 1-4.

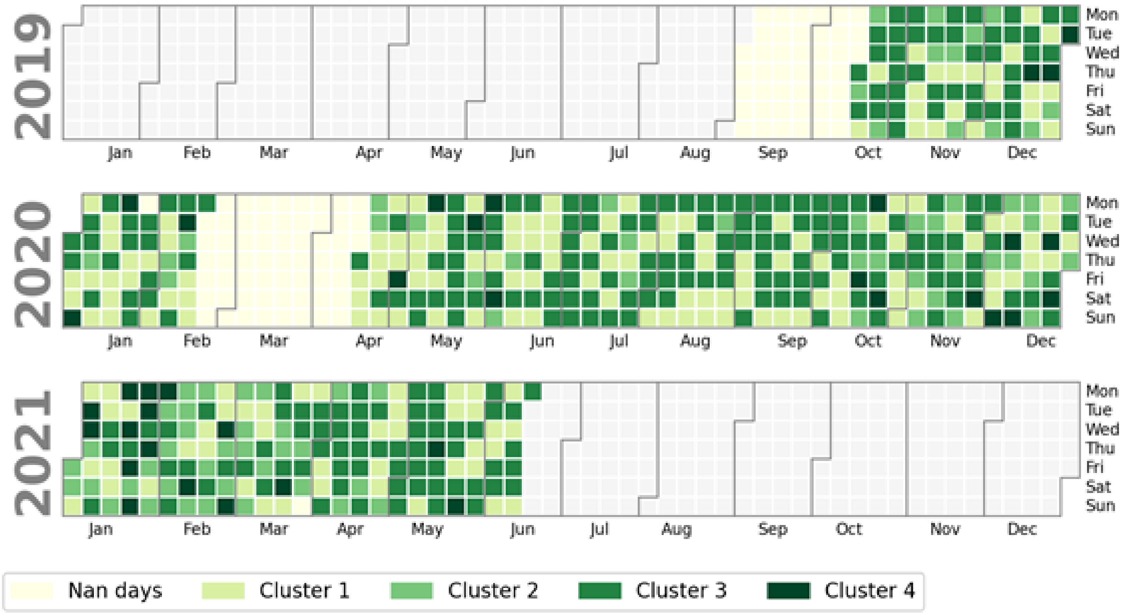

Figure A-4.6-1 Cluster distribution map based on the measurements from House 1.


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