STRATEGIC PLATFORM FOR INNOVATION AND RESEARCH IN INTELLIGENT POWER [IPOWER]

SMART METER CASE STUDY

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2 SUMMARY

As part of the iPower project, different solutions for activating demand response were investigated, developed and demonstrated. Demand response in residential houses is mainly related to Work Package 1 (WP1), where different research and innovation tasks have been carried out. One of the innovation tasks (WP1 T1.I.4) was the Smart Meter case study with the objective of developing a control concept based on cheap units for the control of heat pumps via Smart Meters.

The concept consisted of off-the-shelf components from Develco Products. A Smart Meter gateway from Develco Products was the key component of the concept. The gateway may either be a plug-in card in the main electricity meter of the house or a stand-alone gateway connected to the internet. The gateway had only intelligence for facilitating the Zigbee protocols for communication with and between devices in the house and the internet. A relay with Zigbee communication was connected to the heat pump in order to control the heat pump. Control signals could be send to a relay on the heat pump via the Smart Meter gateway and measurements from a number of electricity and heat meters (Kamstrup) could be returned to a server.

The concept has been tested in the EnergyFlexHouse at Danish Technological Institute and in a private house in Jutland – both houses were occupied by a family of four persons. Moreover, both houses are low energy buildings with underfloor heating and the thermal mass of the constructions of the buildings was utilized as heat storage. The houses are heated by a ground source heat pump (Nilan) with an integrated controller (Lodam), which was control enabled by implementing a relay with Zigbee interface. An interface to the gateway in the houses and a server backend were developed in order to transfer the measured data and to be able to control the heat pumps. The backend was also connected to a load forecast web service (ENFOR).

The results demonstrated that it was possible to switch off the heat pump for a relatively long period with only a minor decrease in the indoor temperature in low energy houses - mainly due to the large time constant of such buildings. However, the feedback from the family in the EnergyFlexHouse showed that people can be sensitive to even small temperature fluctuations – especially if the room temperature is very precisely displayed. However, the family did not complain during periods where the heat pump was on/off controlled with similar fluctuations of the indoor temperature as during a period where the heat pump was not controlled.

The investigations revealed that it is necessary to have local intelligence in the house – especially in case of lost connection to the internet and in order to obtain the full flexibility of the house. For this reason and together with other results from iPower, Develco Products has developed a new gateway with intelligence.

To obtain the full potential of the flexibility of the house, it is necessary to be able to not only switch off the heat pump, but also to excess heat the house prior to switching off the heating system. Excess heating can only be obtained if the thermostats of the heat emitting system can be controlled as well. However, the thermostats in Danish houses are mainly manually controlled with a fixed temperature set point. Thus, the above-mentioned local intelligence is important for obtaining the full flexibility, which heat pump systems may provide to the grid, but it requires that manual thermostats are replaced with electronical thermostats with communication.

To decrease the energy demand of the heat pump and to reduce the increased power demand (kickback effect), when the heat pump is switched on again after an off period, it is important that the capacity of the heat pump is sufficiently large so

that the heat pump can restore the indoor temperatures after an off period and without any backup from a resistance heating element.

It turned out that hourly forecast of the energy demand of low energy houses is difficult to obtain due to the large time constants of this type of houses. However, the houses may instead be controlled based on a forecast of the daily heat demand of the houses, as it due to the large time constant is not so important at which time during the day, the heat is injected to the house.

A method for calculating the heat production from a heat pump based on a cheap measurement setup has been developed and tested using data from the EnergyFlexLab and the private house. The method uses measurements of the power to the heat pump together with the temperature of the brine to the heat pump as well as the forward temperature to the heat emitting system.

3 INTRODUCTION

Smart Grid technology has demonstrated the ability to generate business cases by transforming the electrical grid from coal plants to distributed renewable generations by enabling consumer power savings and providing cost efficient operation of electrical grids.

iPower [www.ipower-net.dk] is a strategic platform where knowledge institutions and industrial partners consolidates innovation and research activities with the purpose of developing intelligent control of decentralized power consumption. The iPower platform develops and matures Smart Grid technologies for the electrical grid, industries and residential applications. The iPower platform links research, innovation and demonstration to actual product development by specifying technologies, requirements and methods for Smart Grid products.

In the iPower project, several different cases of domestic demand response were defined. One of these cases, the "Smart Meter" case study, was intended for controlling home appliances via Smart Meters. The report describes the findings from a Smart Meter case study on demand response in two single-family houses - task T1.I.4 of Work Package 1 of iPower – using equipment from Develco Products.

3.1 OBJECTIVE

The general objective of the case study was to test a cheap concept for control of a heat pump via Smart Meters using off-the-shelf devices. The concept has formerly been tested in the EnergyFlexHouse at Danish Technological Institutes (Christiansen, Jørgensen and Huet, 2013). The objective of the present work was to test the concept in a real inhabited house.

3.2 SMART METERS

Smart Meters are often defined as meters with remote reading. Another possible feature of Smart Meters is that they may function as a gateway to the building to communicate (obtaining measurements and sending control signals) with devices in the building. Typically, the gateway will only have intelligence to facilitate the communication.

In the presented investigations, a Smart Meter gateway from Develco Products has been utilized. This gateway may either be a plug-in card in the main meter of the house or a stand-alone gateway connected to the internet. The gateway only has intelligence to facilitate the Zigbee protocols for communicating with and between devices in the house and the internet.

3.3 COMFORT

In this report, the basic idea of using a heat pump to obtain flexibility in order to provide services to the grid is, that heat can be stored in e.g. the constructions of a building. When the heating system is switched off, the room temperature will slowly decrease. How slowly it increases depends on several things: the amount of heat that can be stored in the constructions, the speed of which heat can be stored and discharged, the amount of heat loss of the buildings, and the weather conditions (a high ambient temperature and solar radiation slow down the decrease in indoor air temperature, while wind may speed up it up due to enhanced ventilation of the house) as well the sensitivity of the people in the building to fluctuating temperatures.

Furthermore, if the building is pre-excess heated before switching off the heating system, the period when the building can be without heat may be much longer compared to when the heating system only can be switched off.

When using the constructions of a building as heat storage, it should be remembered that people have a temperature band in which they feel comfortable. However, the comfort band differs from person to person. The activity level and the level of clothing also define the preferred room temperature. The standard (EN 15251, 2007) gives comfort classes for the operative temperature, which is a combination of the air temperature and the temperature of the surrounding surfaces. In low energy houses, the operative temperature is close to the air temperature due to the high level of insulation in the external walls, windows, ceiling and floor. Table 3.1 shows the thermal comfort classes for the winter situation for persons with clothing that is typical for winter indoor activities (= 1 clo[1]) and mainly sedentary activities (= 1.2 met[2]). The tabel shows the temperature levels together with the PPD (Predicted Percentage of Dissatisfied), which is the percentages of persons that will not be satisfied with the temperature band of a comfort class.

Comfort class	Operative temperature range Winter [°C]	PPD [%]
I	21-23	<6
II	20-24	<10
III	19-25	<15
IV	<19->25	>15

Table 3.1: Example criteria for the operative temperature and PPD for typical spaces with sedentary activity during the winter (EN15251, 2007).

The comfort classes are defined as:

- class I: High level of expectation and recommended for spaces occupied by very sensitive and fragile persons with special requirements such as handicapped, sick, very young children and elderly persons
- class II: Normal level of expectation, it should be used for new buildings and renovations
- class III: An acceptable, moderate level of expectation, it may be used for existing buildings
- class IV: Values outside the criteria of the above categories. This category should only be accepted for a limited part of the year

According to table 3.1 less than 10 % will be unsatisfied with a temperature fluctuation of ±2 K around 22°C in comfort class II, which is recommended for normal use of a building. However, a too sudden drop within the temperature band of 20-24°C may still lead to discomfort.

[11] Clo is a unit for the level of clothing
[2] met is a unit for metabolism

3.4 THE REPORT

The test set up and tests in the EnergyFlexehouse are summarized in the beginning of the report in that the applied equipment is very similar in the two cases (EnergyFlexFamily and the private house) and because the tests in EnergyFlexFamily have been elaborated more than reported in (Christiansen, Jørgensen and Huet, 2013). Next, the test setup and the results from tests in the private house are described followed by a description of a method for the determination of the heat production from a heat pump without measuring this value. Finally, common conclusions from the two test cases are reported.

4 TEST IN ENERGYFLEXHOUSE

The EnergyFlexHouse consists of two low energy buildings, which were put into operation during the autumn of 2009 [www.energyflexhouse.dk] – see figure 4.1. The two EnergyFlexHouses are both two-story, single-family houses – each with a total heated gross area of 216 m^2. One of the buildings (EnergyFlexFamily) is furnished as a living lab and occupied by typical families, who test the energy services. The other building (EnergyFlexLab) is an unoccupied laboratory facility. The EnergyFlexFamily was used for the Smart Meter case study. However, data from the EnergyFlexLab is also utilized in chapter 6.

Figure 4.1: The EnergyFlexFamily (forefront) and the EnergyFlexLab (background).

Both houses were each provided with a heat pump, which was connected to either a low temperature floor heating system or radiators. Both systems are able to service all rooms. There is an advanced control system with individual room thermostats and room temperature set-back. The set-back function was turned off during the test period.

The houses are 'net zero energy buildings', which means that the houses produce as much energy as they consumes on an annual basis including electricity for household use and transport with an electrical vehicle. This is possible because of the 60 m^2 Photo Voltaics (PV) system on the roof. The electrical vehicle was, however, not used during the test period.

The test in the EnergyFlexFamily was conducted in the second half of 2012 and the first quarter of 2013. A family was living in the house during the period: September 28, 2012 – January 27, 2013. The family (during the test period) consisted of two parents and two boys of age 5 and 9. They had no pets.

4.1 HEATING AND VENTILATION SYSTEM IN ENERGYFLEXFAMILY

An integrated heating and ventilation system was installed in the EnergyFlexFamily consisting of:

- Nilan JVP3 ground source heat pump:
  - Rated heat output: 3 kW
  - Inverter for variable speed of the compressor

  A supplement electric resistance heater with a heat output of 2 kW was turned off during the test. The heat pump in the private house (and in the EnergyFlexLab) was the larger Compact P Geo 6 also from Nilan – see chapter 5 and 6.
- Lodam control (SMC 200) with additional relay functionalities to control on-off operation. In this case, the power to the heat pump was simply switched on and off by a relay
  - Only space heating (JVP3) was controllable
- Domestic hot water (not controlled in this test) was produced by a separate ventilation air heat pump with a backup electric heating element and a storage tank of 180 liters. All the equipment (including JVP3) was built together, placed within the same casing and sold, on the market as Nilan VP18 Compact JVP

4.2 OTHER ELECTRIC EQUIPMENT

The house was equipped with electric household appliances and lighting corresponding to the needs of a typical family, which included A-labelled fridge-freezer, dishwasher, washing machine, dryer, oven, microwave oven, television and radio.

4.3 SMART METER, SENSORS AND GATEWAY IN ENERGYFLEXFAMILY

The EnergyFlexFamily already had a large number of meters and sensors as well as a comprehensive data acquisition system. However, as the objective was to develop and test equipment, several new sensors and meters were installed. These sensors and meters came from the companies Develco Products and Kamstrup. A sketch with the sensors and meters is seen in figure 4.2.

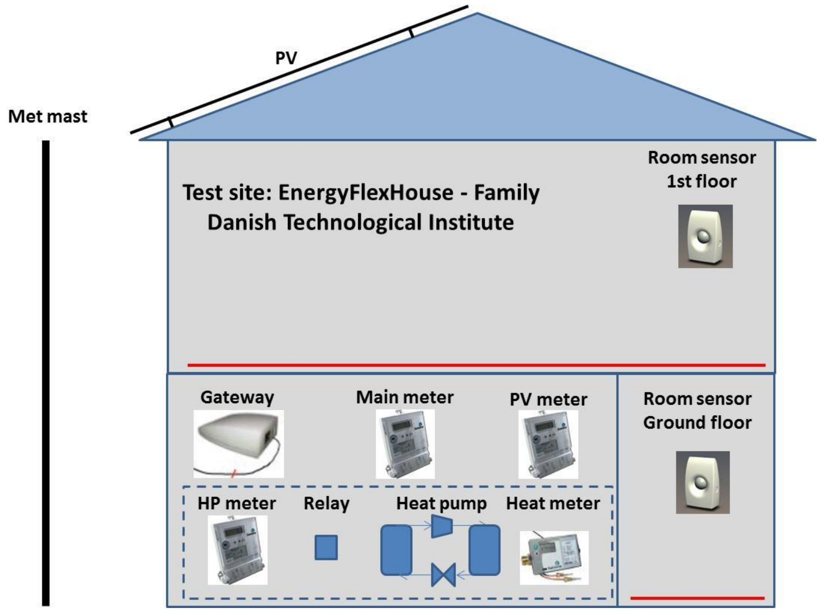


Figure 4.2: Sensors and meters applied in EnergyFlexFamily.

All the equipment in figure 4.2 had Zigbee interfaces for wireless communication using either the Home Automation or the Smart Energy protocols.

4.3.1 ZIGBEE EQUIPMENT

The installed Zigbee enabled equipment was:

- SE Ethernet Gateway
- HA PIR & Room temperature sensor, ground floor
- HA PIR & Room temperature sensor, 1st floor
- SE Kamstrup 382, main electricity meter
- SE Kamstrup 382, PV electricity meter
- SE Kamstrup 382, heat pump electricity meter
- SE Kamstrup Multical 602, heat meter on the space heating side of the heat pump
- HA on/off relay for control of the heat pump

HA (Home Automation) and SE (Smart Energy) refer to the differenrt Zigbee protocols applied for the sensors and meters.

4.4 INTERFACE, BACKEND AND FORECASTING

To be able to communicate with the equipment installed in the EnergyFlexFamily, a server and a SQL database were established. In addition, software was developed to handle the data processing and exchange of data with the SQL database as well as the external forecasting web service ENFOR PRESS [www.enfor.dk]. The data flow is seen in figure 4.3.

The structure of the setup and data flow is as follows (for numbers in bold please refer to figure 4.3):

Several sensors measuring the power consumption, temperatures, etc. were located in the house. Temperatures were collected every 2 minutes (due to standard settings), whereas all the power consumptions were collected every 5 minutes.

The sensors communicated wireless, using the Zigbee protocol, to a gateway (**1**), which was connected to the Internet. The gateway was configured to send telegrams through the Internet to a SMARTamm server located at Danish Technological Institute. 'SMARTamm server' is a trade name of Develco Products ('amm' = automatic meter management). Develco Products did the server setup.

Telegram is the name of the messages between the gateway and the SMARTamm server. A computer at Danish Technological Institute was running an application as a SMARTamm server (**2**). This server was listening for incoming telegrams from the gateway and it saved all the telegrams in a database (Microsoft SQL server) for further processing. The SMARTamm server is written in Java.

Every minute, a Windows program (**3**) read and processed the telegrams in the database to extract the measured values from the different sensors. Subsequently, the resulting data were saved in the database for further operations.

Every 15 minutes, a Windows program (**4**) looked for the saved data in the database and sent the temperatures and the total electrical consumption of the house to ENFOR's PRESS web service. ENFOR used these values to calculate a forecast for the power consumption – see section 4.6.1.

Every hour, a Windows program (**5**) called ENFOR's PRESS web service to get a 24 hour power consumption forecast for the next day. The forecast was saved in the database as well.

A Windows program (**6**) was applied to switch the heat pump on/off during predefined time intervals.

All the Windows programs have been developed with the Microsoft .NET framework.

4.5 SWITCH OFF, OF THE HEAT PUMP

Due to a number of incidents in the building service systems, including a break down of the main supply cable to the building and required heat pump service just before Christmas and other unexpected events, the actual test of switching off the heat pump for three hours each afternoon between 15:00 and 18:00 was only conducted during a short period of the family's stay in the house: January 14 to January 27, 2013.

After the family had left the house, testing of the cooling down and heating up of the house were carried out.

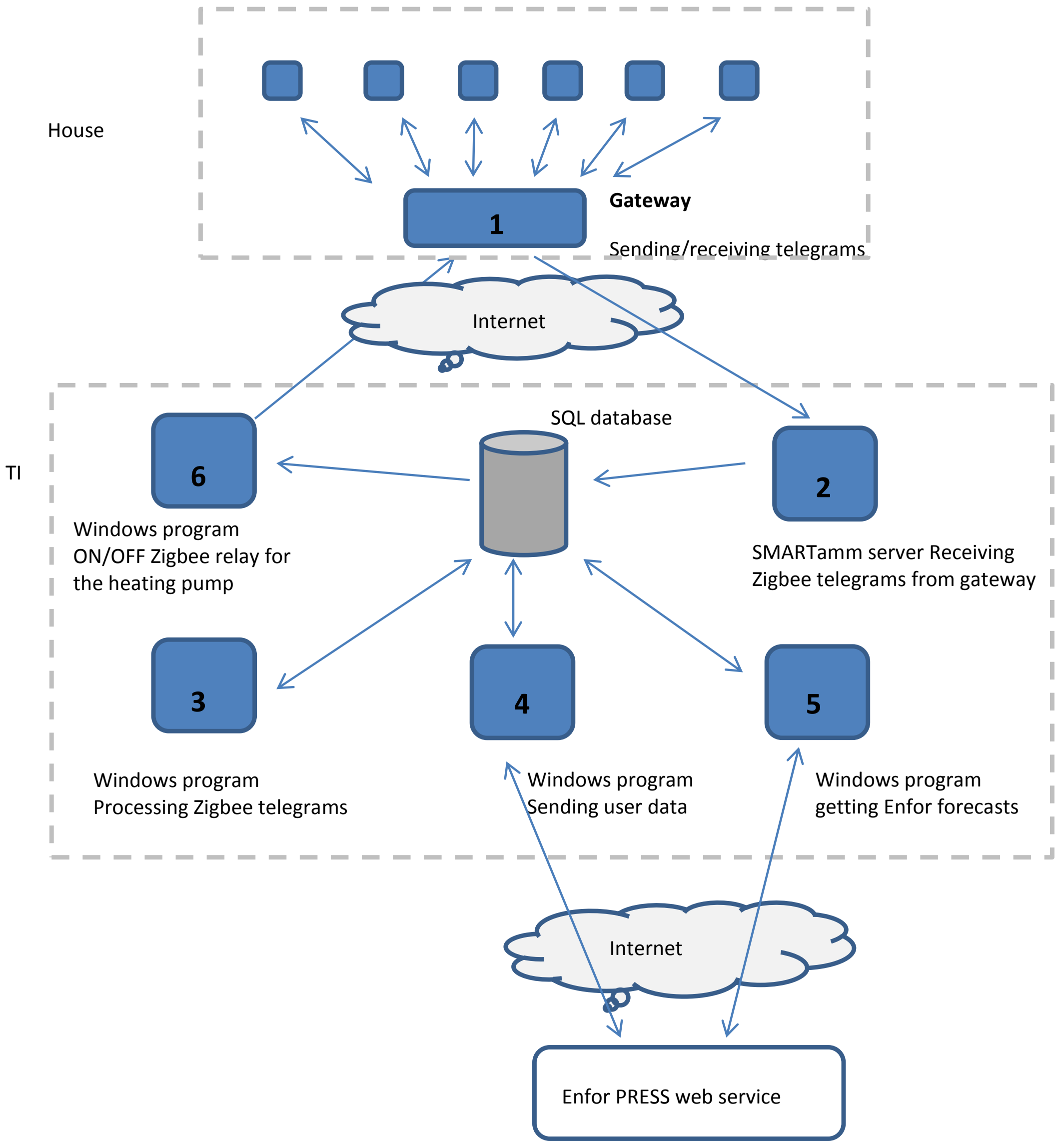


Figure 4.3: Sketch of the data flow for the test, TI = Danish Technological Institute.

4.6 RESULTS FROM THE TESTS IN ENERGYFLEXFAMILY

Based on preliminary tests, a simple control strategy was implemented from 14th until 27th of January where the system was stopped three hours each day during the period 15:00 pm to 18:00 pm. Figure 4.4 shows the room temperature and the space heat demand as hourly mean values of one day, 16th of January, which was a very cold but sunny day as seen in figure 4.5. Because the electrical resistance heater was turned off, the heat pump was not able to deliver the desired comfort temperature of 22°C in the morning. This was expected as the heat pump was not dimensioned to deliver the required heat without the resistance heater at the very low ambient temperatures, which were reached during the night between January 15 and 16. However, due to solar irradiation, comfort was reached before the heat pump was turned off. However, it seems that the heat pump only just complies with the Danish requirements of being able to maintain a room temperature of 20°C at an ambient temperature of -12°C. The room temperature did hardly decrease during the period, where the heat pump was switched off, which is supposed to be partly due to solar radiation and partly the fact that the family switched on the appliances when coming home in the afternoon.

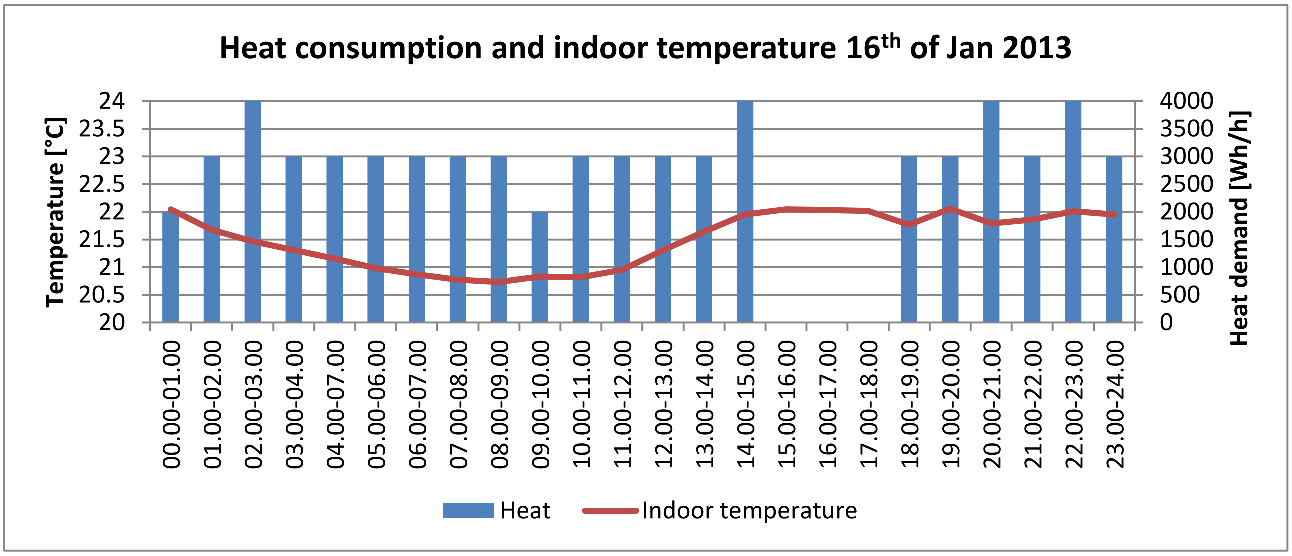


Figure 4.4: Hourly heat consumption and indoor temperature during the test period - 16th January 2013. The pump was turned off at 3 pm (UTC).

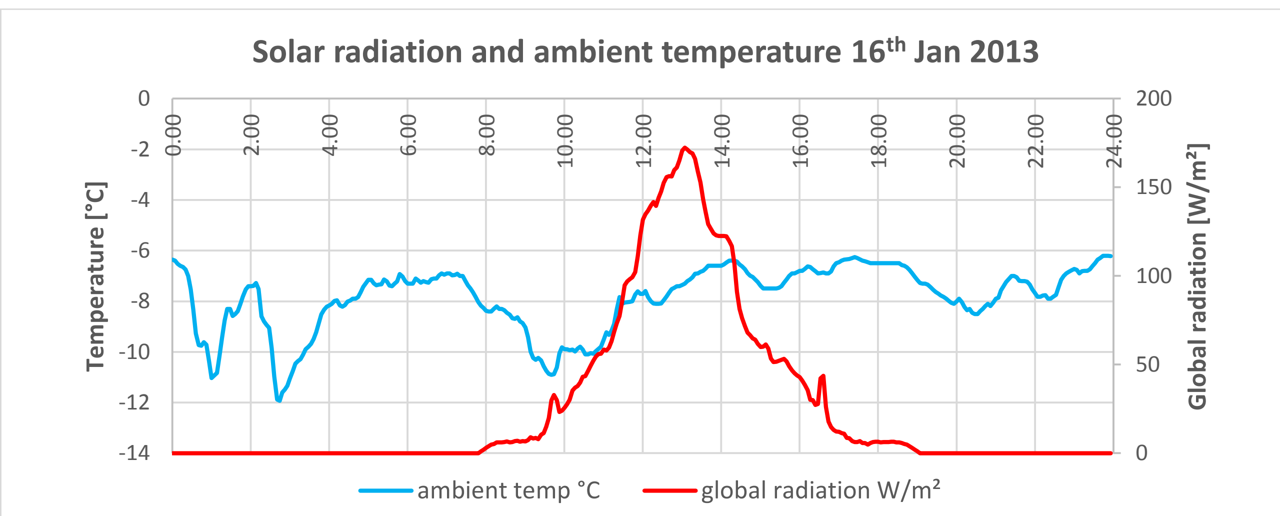


Figure 4.5: Global solar radiation and ambient temperature during the test period - 16th January 2013.

After the family moved out, a test without heating for 6.5 hours was carried out. The result is seen in figure 4.6. The room temperature only dropped 0.6 K during the switch off period. This period was also sunny, but much warmer than January 16 as seen in figure 4.7. Due to the higher ambient temperature, the heat pump had sufficient capacity to maintain the room temperature in the morning - the heat pump switched between a heat production of 2 and 3 kW (the resolution of the heat meter was 1 kWh). The larger drop compared to January 16 may possibly be explained by the absence of the family and thereby the lack of heat from the appliances.

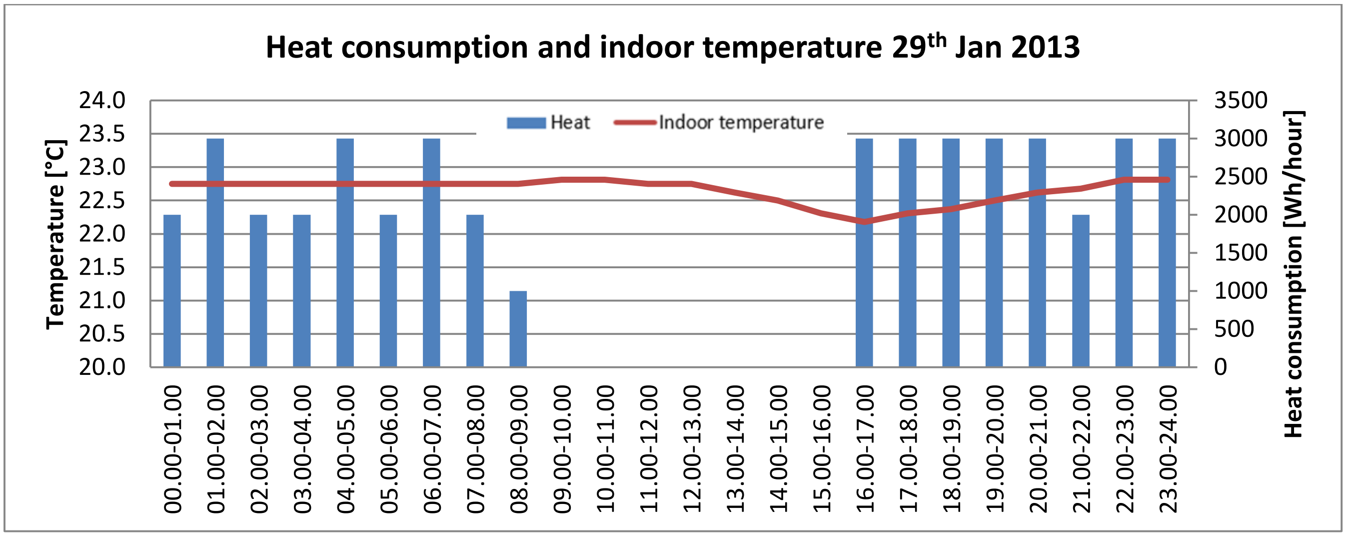


Figure 4.6: Hourly heat consumption and indoor temperature - 29th January 2013 – empty house.

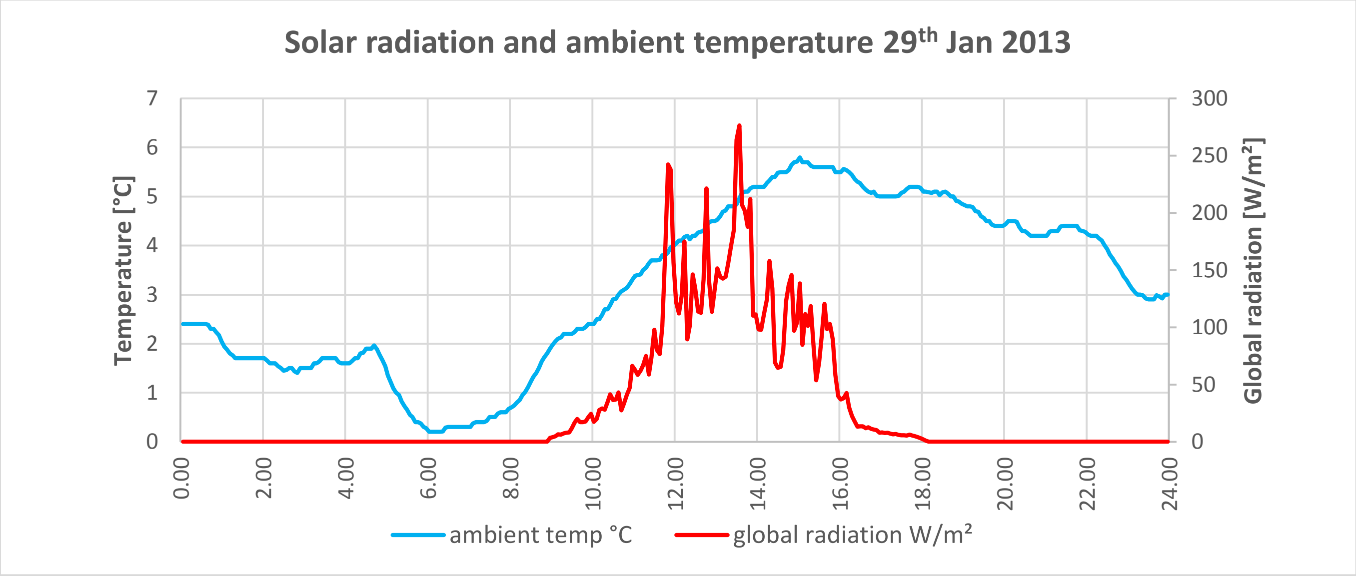


Figure 4.7: Global solar radiation and ambient temperature during the test period - 29th January 2013.

The tests and the different operation patterns of figures 4.4-4.7 demonstrate the fact that the flexibility was strongly reduced when the outdoor temperature was very low – close to the design capacity of the heat pump. The time to heat up the building again after a drop in the room temperature was long, which must be taking into account in connection with the control strategies as well as the design of the building service systems and the heat pump. On the other hand, when the outdoor temperature is higher (which is the case most of the year), good opportunities for flexible operation are available.

Before the test, where the heat pump was with switched off, the family was much focused on the room temperature being exactly 22°C – the temperatures in the different rooms were displayed on the thermostats in the rooms. However, the family did not take notice when the indoor temperature fluctuated during the period where the heat pump was turned on/off. In this period, the family was not bothered with low temperatures or fluctuations. In fact, they sometimes felt that it was too hot, even though the mean temperature was 0.3 degrees lower during this period compared to the earlier period without the heat pump being switched off (23.1°C -> 22.8°C). From time to time, the windows and doors were even opened by the family to bring down the temperature.

In other investigations of the EnergyFlexHouse, the time constant has been estimated to about 40 hours. This results in a relatively slow cooling down and heating up of the house, which can be seen in figure 4.6. In figure 4.8 the heat pump was stopped on January 30 at 9:00 in the morning. During the next five days, the temperature on the 1st floor (living room and kitchen) dropped about 5.5 degrees or in mean only 1.1 K/day. However, the temperature dropped faster the first night due to the exponentially decay of the temperature difference between the rooms and the ambient. The first night (between January 30 and 31), the temperature on the 1st floor dropped 1.8 K between 18:00 pm and 9:00 am (15 hours).

In this respect, low energy houses have a large potential in terms of flexibility, but because of the relatively low heat demand, the absolute amount of flexibility is low. It is important to observe the relatively large heating up time as well, as seen in figure 4.9, where the heat pump is restarted on February 4 at 10:00 am. During 2½ day, the temperature on the 1st floor increased with 5.2 degrees or in mean 2.1 K/day. Thus, the house seems faster to heat up than to cool down. However, the ambient temperature and the solar radiation need to be examined to understand this.

The ambient temperature is shown in figures 4.8-9. The ambient temperature is rather similar during the two shown periods, so this cannot explain the difference in the cooling down and heating up time. Figure 4.10 show the global solar radiation during the two periods. Global solar radiation is the total radiation on a horizontal plane. Unfortunately, there are data outages on February 3-4. Figures 4.8-9 show the temperature increases during the afternoon, especially for the ground floor. This can only be caused by the solar radiation as there were no family coming home and no switching on of the electrical appliances. Figure 4.10 shows a larger amount of solar radiation during the period shown in figure 4.9 than during the period shown in figure 4.8. On the one hand, the solar radiation slows down the cooling down of the house, while it on the other hand increases the heating up of the house after a period where the heat pump was switched off. Use of the electrical appliances will have the same effect on the room temperature as solar radiation. Without solar radiation (or use of appliances), the cooling down of the house will be faster and the heating up will be slower. However, the latter has not been investigated via tests in the EnergyFlexFamily.

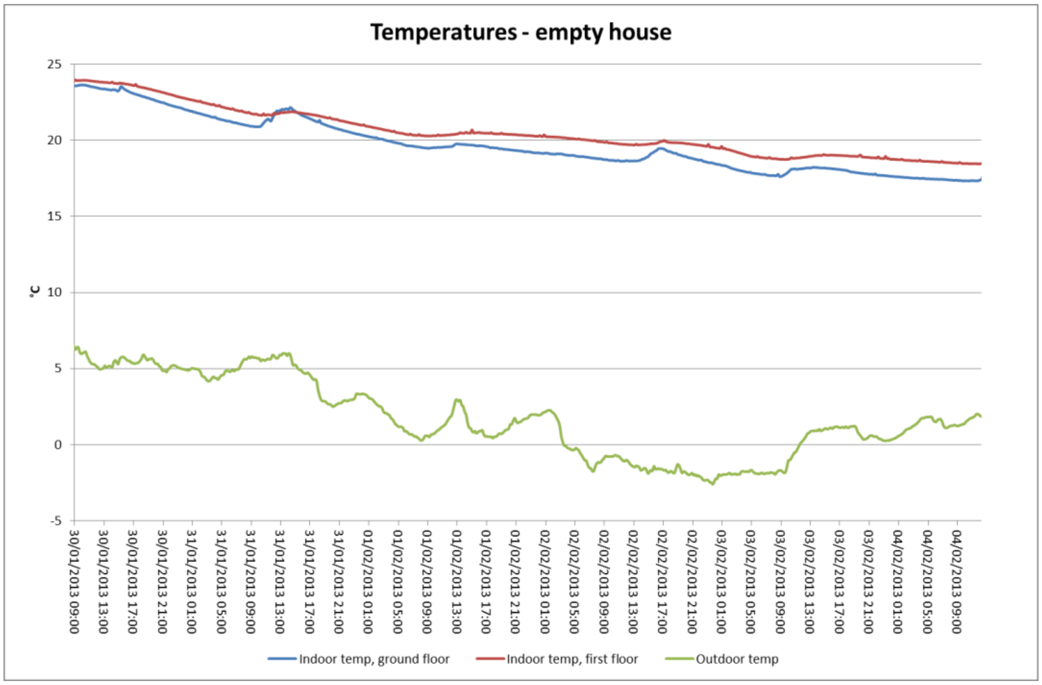


Figure 4.8: Indoor temperature, 30th January to 4th February. Heat was turned off 30th January at 9 o'clock.

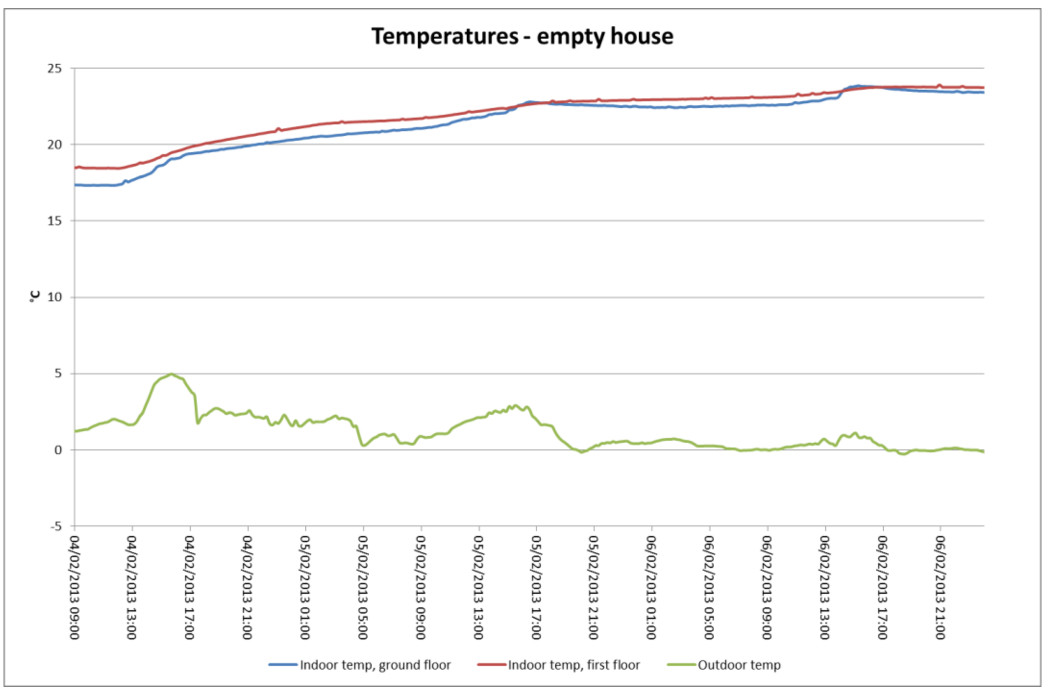


Figure 4.9: Indoor temperature, 4th to 6th February 2013. Heat was turned on 4th February at 10 o'clock.

If the first night between January 30 and 31 is used as a reference and the exponential decay is found based on the measurements from this period, the room temperature would have dropped to 13.1°C on the first floor on February 4 at 9:00 am without solar radiation instead of only dropping to 18.5°C as seen in figure 4.8.

Thus, to make forecast of the progress of the room temperature after a switch off and a turn on of the heating system is rather complex, especially in low energy houses, where free gains from solar radiation and appliances have a large influence on the resulting room temperature.

During the tests, it was only made possible to switch off the heat pump. It was not possible to excess preheat the building as the valves of the heat emitting system were not controlled. Heating up the house before a switch off – within the comfort band – would increase the period, where the heat pump may be switched off and thereby increase the possible flexibility of the house.

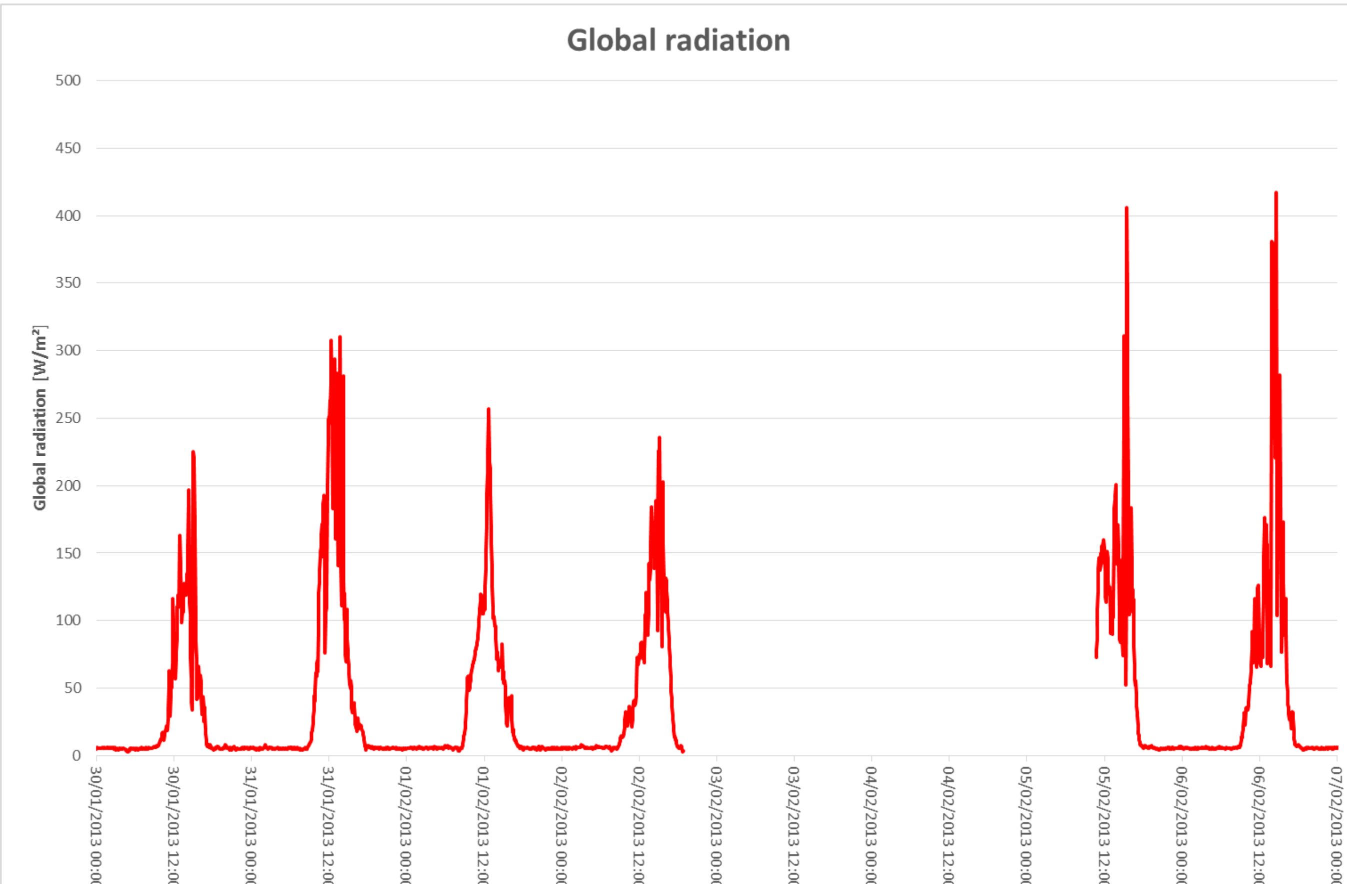


Figure 4.10: Global radiation 30st January to 7th February 2013. Unfortunately, there are data outages for 3rd and 4th February.

4.6.1 LOAD FORECASTING

The test case aimed at investigating Smart Meter control of a heat pump. In the tests in the EnergyFlexFamily several sensors and meters were applied, which made the setup very expensive – too expensive for application in real houses. For that reason, it was investigated if it was possible to perform forecasting of the hourly heat demand of the house, which was only based on readings from the main electricity meter of the house. This makes sense as figures 4.4 and 4.6 indicate that the electricity demand of appliances may have a large influence of the cooling down of the house when the heat pump is switched off - at least in low energy houses. As explained in chapter 4.4, the applied forecast service was the web-based forecast service PRESS developed by ENFOR (ENFOR, 2016). PRESS utilizes model-based prediction. Based on historical data, a model of the system (here electrical use in the house) is calibrated to give the best possible fit to the historical date. Based on the model, PRESS generates 24-48 hours of forecast – in this case – of the electricity use of the house. However, as the applied model is based on historical data there is a need for a certain learning period of a couple of months without major disturbances. This was not possible to obtain due to the incidents explained in chapter 4.5, e.g. the break-down of the main electricity supply and the stop of the heat pump just before Christmas.

Therefore, it is not really useful to compare the forecast with the actual measurements during the tests in the EnergyFlexFamily, as the learning period was too short. Furthermore, ENFOR's PRESS is made for heat load forecasting, where the input load in the tests in the EnergyFlexFamily was electrical power from the main meter, which also included the appliances. However, figure 4.11 gives an overall picture of how it might look like for a forecasted electric power of the house. In general, it should be discussed how to use load forecasting, how to convert heat load into electric power (or vice versa as discussed in chapter 6) and in which context the load forecasting can be used – see also section 5.3.4.

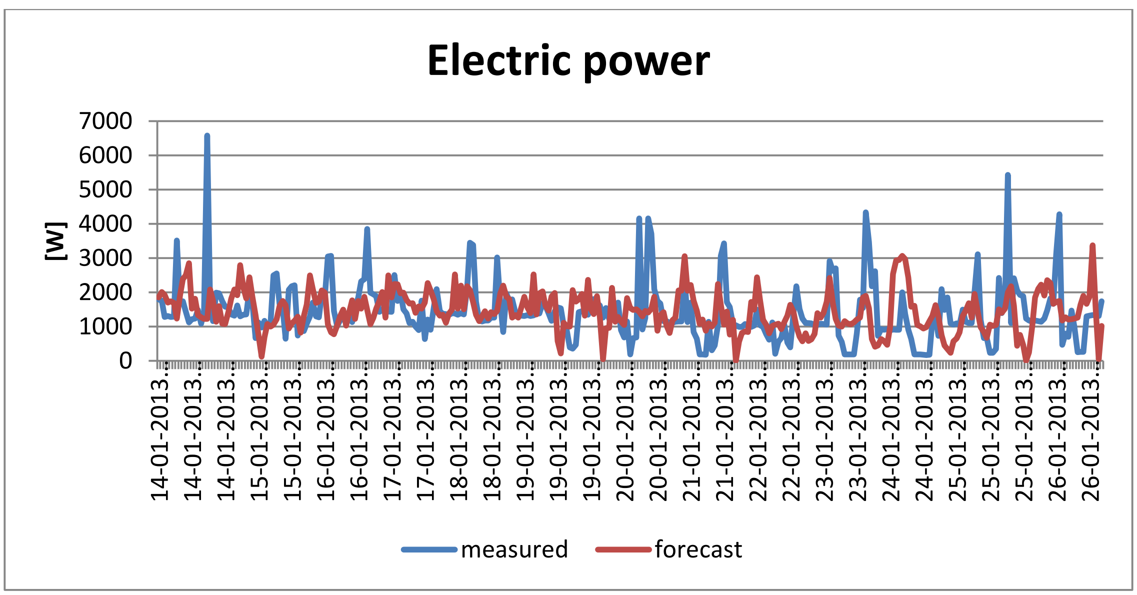


Figure 4.11: Electric power – forecast and measured – 14th to 27th January.

4.7 CONCLUSIONS FROM THE TESTS IN ENERGYFLEXFAMILY

The purpose of the tests in the EnergyFlexFamily was:

- to obtain experience with the chosen concept
- gain knowledge on how to install the equipment
- develop a communication platform between the equipment in the house and an entity, which utilizes the concept to control the heat pump in order to gain flexibility
- test how the house will react when switching off the heat pump
- obtain a first impression on how people will react when their heating system is remotely controlled by others

This was to be obtained before the concept was installed in a real house.

As often when testing new concepts for the first time, there were some commissioning problems. When these were solved there was only little time to test the concept with a family still living in the house. However, and despite this, valuable knowledge was obtained.

- the concept worked as intended: it was possible to transfer measured date to a database and it was possible to switch the heat pump on and off at desired periods.
- the EnergyFlexFamily has a large time constant, which means that the heat pump can be switched off during several hours without loss of comfort. This makes low energy houses very energy flexible, but due to the low energy demand the absolute amount of flexibility is low
- the control of the heat pump was rather harsh as the power to the heat pump was simply cut. Therefore, this type of control may lead to loss of warranty
- the family living in the EnergyFlexHouse complained about the fluctuation in room temperature before the switch off test of the heat pump. During the test, the family did not complain. A too accurate display of the room temperature to the users may lead to more complains compared to the situation with no information about the actual room temperature
- due to difference incidences, it was not possible to obtain sufficiently long learning periods for the forecast service to be able to compare measurements with forecast. However, important information about how to exchange data with ENFOR's forecast service PRESS was obtained
- it seems that the heat pump without the resistance-heating element of 2 kW (see section 4.1) had just or nearly sufficient capacity to maintain a room temperature of 20°C at an ambient temperature close to the Danish design requirement of -12°C. The capacity of the heat pump was, however, not sufficient to maintain the preferred (general in Denmark) room temperature of 22°C. Without the help of solar radiation and the use of appliances, the heat pump would not have been able to restore the room temperature to 22°C after a switch off period at an ambient temperature of -12°C. With the resistance-heating element, it would be possible to restore the room temperature, but the kick back effect would be large. If the heat pump had a COP of e.g. 3.5, it would need 0.86 kW electrical power to produce 3 kW heat, but the electrical power to the resistance-heating element is 2 kW in order to produce 2 kW of heat. This leads to a total electrical power demand of 2.86 kW in order to produce 5 kW heat. If the heat pump had a capacity of 5 kW, this would lead to an electrical power demand of 1.43 kW or only half the power demand for

the smaller heat pump with a resistance-heating element. The conclusion is that a heat pump needs to have sufficient nominal power to make the resistance-heating element unnecessary. The current, common design rules, i.e. that the resistance-heating element should cover 5 % of the annual heat demand, lead to the fact that heat pumps cannot deliver flexibility during cold weather conditions. If heat pumps should be able to deliver flexibility all year round, the heat pumps need to have an overcapacity compared to cold weather conditions.

- only “half” the flexibility of the house was investigated at it was only possible to switch off the heating system. It would be possible to have longer off periods if the house was excess preheated (within the comfort band) before switching off the heating system. However, excess heating of a house is not possible when only controlling the heat pump. It is necessary to control the thermostats of the heat emitting system as well. If the set point of the valves of the heat emitting system is not increased, the heat pump cannot deliver excess heat to the house.

5 PRIVATE HOUSE

The private test house chosen for the investigation is situated in Djursland in Jutland. The house is a 194 m² low energy house from 2013 (actually, the house complies with today's standards according to the Danish Buildings Code from 2015). Figure 5.1 shows a picture of the house, while figure 5.2 shows a floor plan of the house.

Figure 5.1: Picture of the test house seen from South-West.

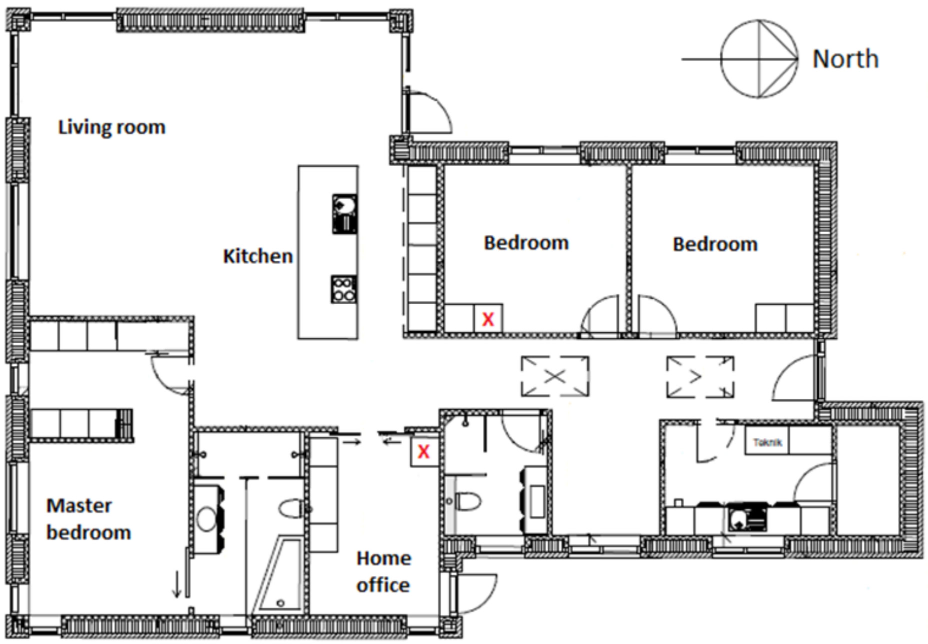


Figure 5.2: Floor plan of the test house. The red crosses indicates where the two temperature and moisture sensors were located in the house.

A family of four persons inhabits the house: two adults and two children.

The house is built according to the specifications of a Low energy 2015 residential house in the Danish Buildings Regulations from 2010 (BR10).

The thermal envelope of the house consists of:

- external walls: outside brick wall, 245 mm insulation and 100 light weight concrete
- windows: 3-pane low energy glazing
- ceiling: 495 mm insulation
- ground floor slab, from the ground: 370 mm insulation with 120-150 mm concrete above with integrated under floor heating tubes.

The heating and ventilations system is a (older version of) Compact P GEO 6 heat pump/ventilation system from Nilan. Compact P GEO 6 consists of a ground source heat pump with a nominal heat production of 2-6 kW (on/off controlled in the area of 0-2 kW and inverter controlled in the area of 2-6 kW), The heat pump is connected to the underfloor heating of the house. An air-to-air/water heat pump extracts heat from the exhaust air from the building and heats the domestic hot water and the fresh air to the buildings. Figure 5.3 shows a picture of the Compact P Geo 6 heat pump.

Figure 5.3: Photo of Compact P GEO 6.

The mandatory Energy labeling report states that the annual energy demand of the house is 35.1 kWh/m² primary energy, which with a primary energy factor of 2.5 for electricity leads to an annual electricity demand for heating, ventilation, domestic hot water and building related electricity demand of 17,6 kWh/m² or in total 3,400 kWh. In the Energy labeling report the annual electricity for heating is stated to be 2,235 kWh (Poulsen, 2014). For 2015, the total electricity consumption of the houses incl. appliances was measured to be 6,970 kWh, while the electricity demand of the heat pump for space heating was 2,126 kWh.

The house is very airtight. A pressurization test showed an air change of 0.25 l/m²s at both an over and under pressure of 50 Pa (Warming, 2014). The requirement of the Building Regulation was 1 l/m²s for this type of house. The related small infiltration of the house is included in the above calculated annual energy demand of the house.

5.1 VISUALIZATION OF THE ENERGY CONSUMPTION AND INDOOR CLIMATE

The family was given the opportunity to follow their energy consumption and indoor climate on an online visualization platform, eButler (Kamstrup, 2016). The data are visualized on an hourly basis in order for the family to be able to gain insight into their energy pattern.

Figures 5.4 and 5.5 show screen dumps from eButler - from the mobile app and the user interface on a computer, respectively. The eButler system was used to engage the family in participating in the test, but it was not used as part of the test itself. Therefore, this is not elaborated further in this report.

Figure 5.4: Example of a screen dump from the visualization tool, eButler, on a smartphone.

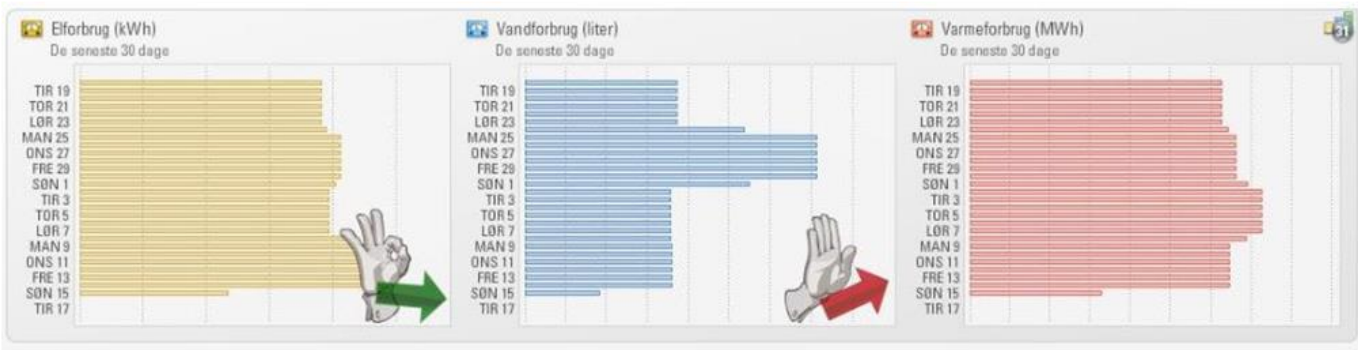


Figure 5.5: Example of a screen dump from the visualization tool, eButler, on a computer.

5.2 TEST SETUP IN THE PRIVATE HOUSE

The test setup in the private house was very similar to the test set up in the EnergyFlexFamily as seen when comparing figure 5.6 with figure 4.2. The only differences from the test setup in the EnergyFlexFamily are:

- there is a heat meter on the brine side of the heat pump
- the two room sensors do not include a PIR sensor
- the relay does not switch the electricity to the heat pump on and off. Instead, the set point and the measured forward temperature from the heat pump are manipulated. If the set point of the forward temperature is raised, the heat pump will start, while a raise of the "measured" forward temperature will make the heat pump stop. In this way, it is the heat pump's own controller that switches the heat pump on and off. There will, thus, be no warranty problem
- the SMARTamm server was not situated at DTI, but it was hosted in a server hotel

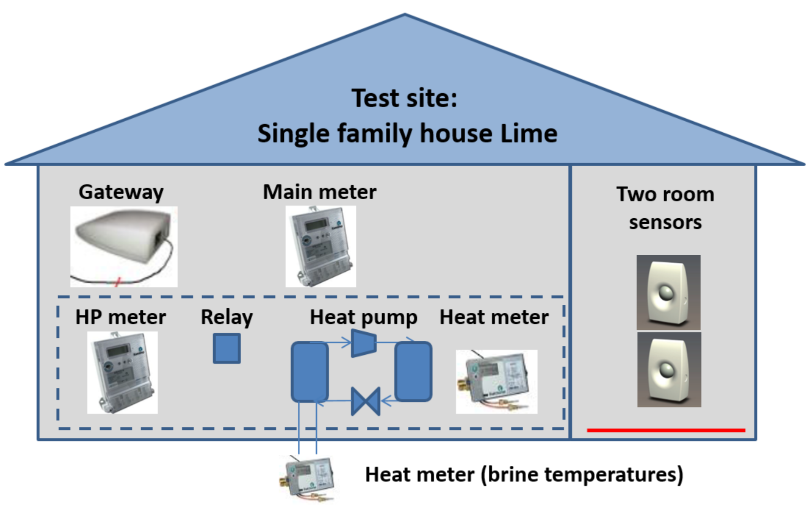


Figure 5.6: Sensors and meters applied in the private house.

The two room temperature sensors were, as seen in figure 5.2, located in a bedroom and in the home office. A temperature sensor was not located in the living room due to the large windows causing the sensor to be hit directly by solar radiation, which from time to time led to too high measured temperatures. The door between the living room and the home office is mainly open. It is further known that the internal heat exchange in low energy houses is much higher that the heat exchange to the ambient, which leads to rather similar air temperatures in the different rooms of the house.

One more temperature sensor was located where it was exposed to the ambient, i.e. at a carport to the north of the house. The sensor was shielded by the roof of the carport, but from time to time it was hit by solar radiation during the winter.

5.3 RESULTS FROM TESTS IN THE PRIVATE HOUSE

The measuring campaign in the private house lasted from February 2014 until March 2016. In the following and in chapter 6, the results from the measurements in the private house will be described using measurements from both 2014 and 2015.

5.3.1 RELIABILITY OF THE INSTALLED EQUIPMENT

Figure 5.7 shows the measured indoor temperatures. First of all, it is noticed that the house has problems with overheating during the summer – i.e. temperatures above 28°C. This is unfortunately often seen in low energy houses where measures to prevent this have not been considered. Furthermore, it is seen that the room temperature during the heating season fluctuates around 22°C with a fluctuation of ±2 K as in comfort class II shown in table 3.1. This is without external control of the heat pump, which means that the family would not notice a Smart Grid control of the room temperature of 22°C ±2 K.

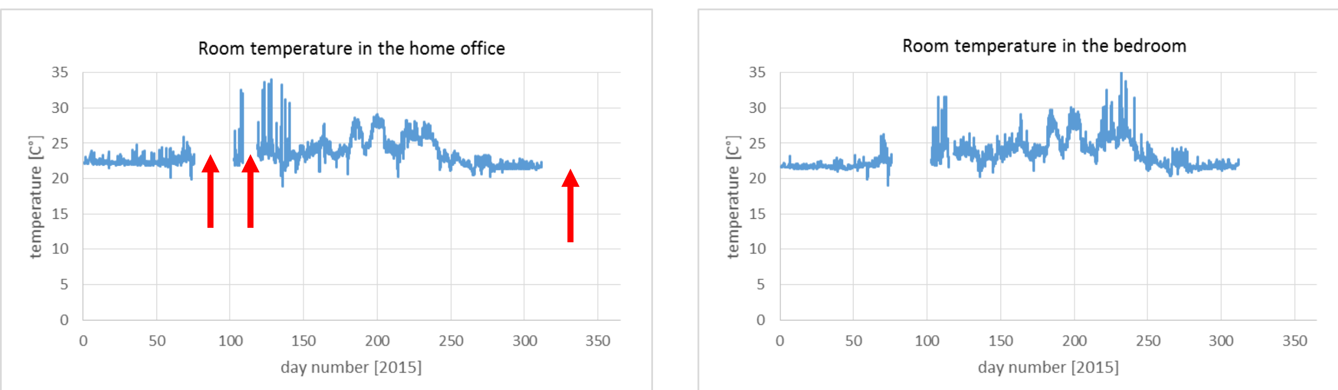


Figure 5.7: Measured room temperatures in the private house during 2015.

Figure 5.7 shows three gabs in the measurements pointed out by the red arrows. The first and the last gap are due to lost contact to the gateway. The gateway had to be restarted in order to regain access to the equipment in the house. The second gab is of different lengths in the two graphs shown in figure 5.7, and since this gab is not seen for the ambient temperature, the loss of data is not due to a loss of contact to the gateway. Moreover, the two gaps start at different times, but stops at the same time. The second gap occurred due to flat batteries in the two indoor temperature sensors.

During 2014, the gateway had to be restarted twice.

Loss of contact to the gateway means loss of contact to the heat pump.

- if the contact is lost when the control of the heat pump is set to “on”, the heat pump will continues to run until the control of the heating system stops it. After this, the heat pump will run normally just fulfilling the demand of the house. However, flexibility will be lost.
- if the contact is lost when the control of the heat pump is set to “off”, the users of the house will soon discover this during the winter (if the heating system is not able to switch the heat pump on again, e.g. if the control switches off the power to the heat pump as in the EnergyFlexHouse case in chapter 4), as the indoor air temperature will keep decreasing. This can easily be fixed by the user by restarting the gateway. However, this will be annoying for the user and it may make them lose faith in the concept so that they may decide to stop providing flexibility.

If the measured room air temperatures are used to determine if the heat pump may be switched off, i.e. when the temperatures is within the chosen comfort band, it is very important that these room temperatures are measured correctly and transferred to the gateway. In the private house the temperature sensor were located on tables. Therefore, the sensors could easily be covered making them give wrong readings. Or, if hit by the sun the control system may “think” that the house is overheating so that the heat pump may be switched off, while in fact the house may need heat. Loss of measurements from wireless devices can either be due to flat batteries or problems with the wireless communication.

Based on the above, there is a need for some intelligence in the house that can maintain a correct operation of the heat pump if the connection to the internet is lost. The intelligence should also be able to determine the state of the sensors in the system, e.g. the power level of the batteries of the wireless devices. The intelligence may also react to outliers in measurements – e.g. that a temperature sensor suddenly changes level in the readings. However, the intelligence can hardly detect if sensors are wrongly located. As described in the EnergyFlexFamily case study, intelligence in the house may be utilized for controlling the valves of the heat emitting system in order to obtain the full flexibility of the house by enabling excess preheating (within the comfort band) of the house prior to switching off the heating system.

Based on the tests in the two Smart Meter case studies, Develco decided to “develop a new and improved platform for the operation of Home Area Networks intended for energy management and smart homes”, because “The pilot test sites in iPower have together with research and the business development on the smart home market made it clear that local intelligence is needed to control heat pumps, air condition and other appliances.” (Gårdbo–Pedersen, 2016 – page 5).

5.3.2 CONTROL OF THE HEAT PUMP

The intention was to let a commercial aggregator control the heat pump in the private house in order to obtain end-to-end proof of the concept. Unfortunately, this was not succeeded as the aggregator, who was interested in trying to control the heat pump, changed the focus for their business. At the eleventh hour (at the end of the heating season 2015-2016), it was attempted to connect the private house to SYSLAB at Risø [www.powerlab.dk/facilities/syslab.aspx]. However, this was not obtained before the end of the heating season. The private house is a low energy house with a thereby short heating season.

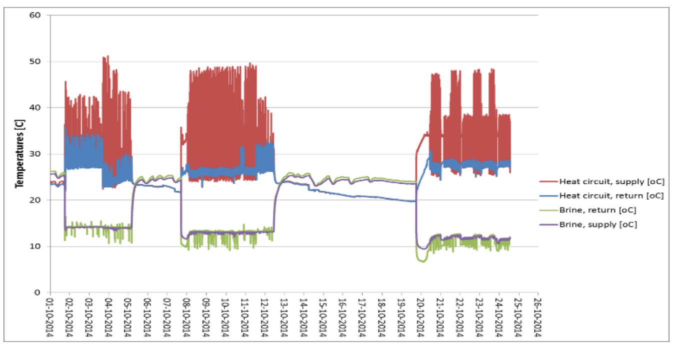
Danish Technological Institute could have carried out simple tests on controlling the heat pump, but when it was clear that this was the last possibility, the heating season was past. Moreover, controlling the heat pump carried a risk in that the contact to the gateway could be lost during the experiment as described in the former section. However, the heat pump has been stopped three times in a heating season during the measurements: in the spring of 2014 due to the installation of thermostats in the underfloor heating system and two times in October 2014. The two stops in October 2014 will be investigated in the following section.

Aggregated control of heat pumps has successfully been carried out by another team in iPower. In (Biegel et el, 2014), the result from aggregated control of 54 heat pumps is described.

5.3.3 THERMAL INERTIA OF THE PRIVATE HOUSE

Figures 5.8 shows the measured temperatures around the heat pump, in the house and the ambient during October 2014. The temperatures around the heat pump shows that the heat pump was switched off October 5-7 and October 12-19. This leads to a small drop in the indoor temperatures during the first period.

Measured temperatures around the heat pump



Measured ambient and indoor air temperatures

Figure 5.8: Measured temperatures in the private house during October 2014. The blue arrows in the right graphs indicates the switch-off periods.

The first switch-off, of the heat pump occurred in the morning on a warm and sunny day. Thus, the indoor room temperature increased instead of decreased. During the little more than two days of the first switch-off period, the indoor temperatures decreased with 1.9 K during a not very cold period. During the second switch-off period, the ambient temperature was the same as for the first period, but the indoor temperatures indicated less solar radiation. The indoor temperatures dropped here 3.9 K during a period of little more than seven days.

The indoor temperature dropped only 0.9 K during the first night of the second switch-off period with an ambient temperature below 10°C – in mean approx. 8°C during 14 hours. Thus, like the EnergyFlexHouse the private house has a large time constant, which makes it very energy flexible. However, the absolute power which may be switched on and off, is limited as seen in the following chapter 6.

5.3.4 LOAD FORECASTING

Figure 5.9 shows the temperatures around the heat pump, in the house and the ambient during November 2014, while figure 5.10 shows the power demand and heat production of the heat pump. The figures show three modes of the heat pump: off, on/off controlled, and inverter controlled. The power consumption during off mode is discussed in chapter 6. The difference between on/off and inverter controlled operation is shown in figure 6.5 in chapter 6, and discussed there. The efficiency of on/off controlled operation is lower than during inverter controlled operation due to capacity losses during the off periods in the on/off controlled operation mode.

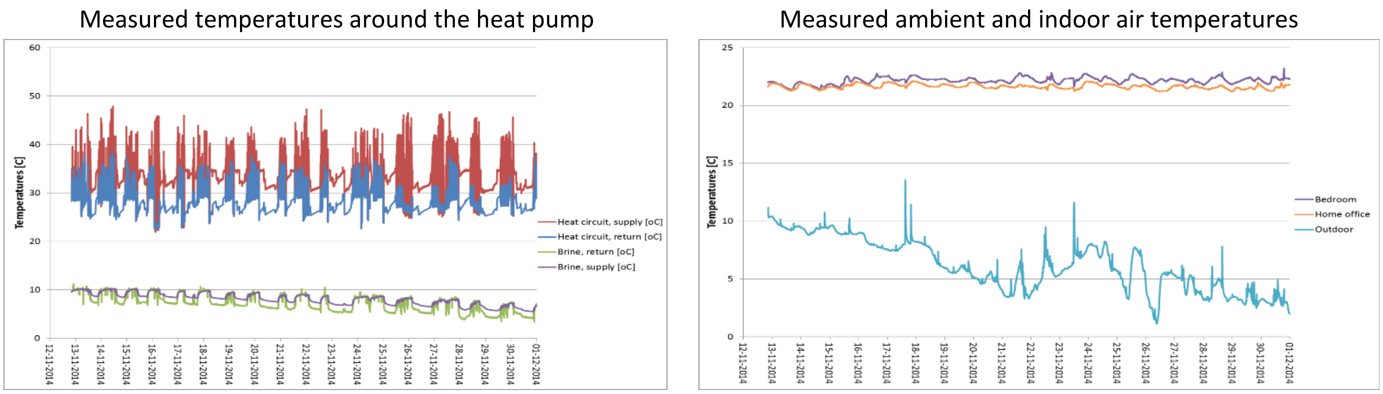


Figure 5.9: Measured temperatures in the private house during November 2014.

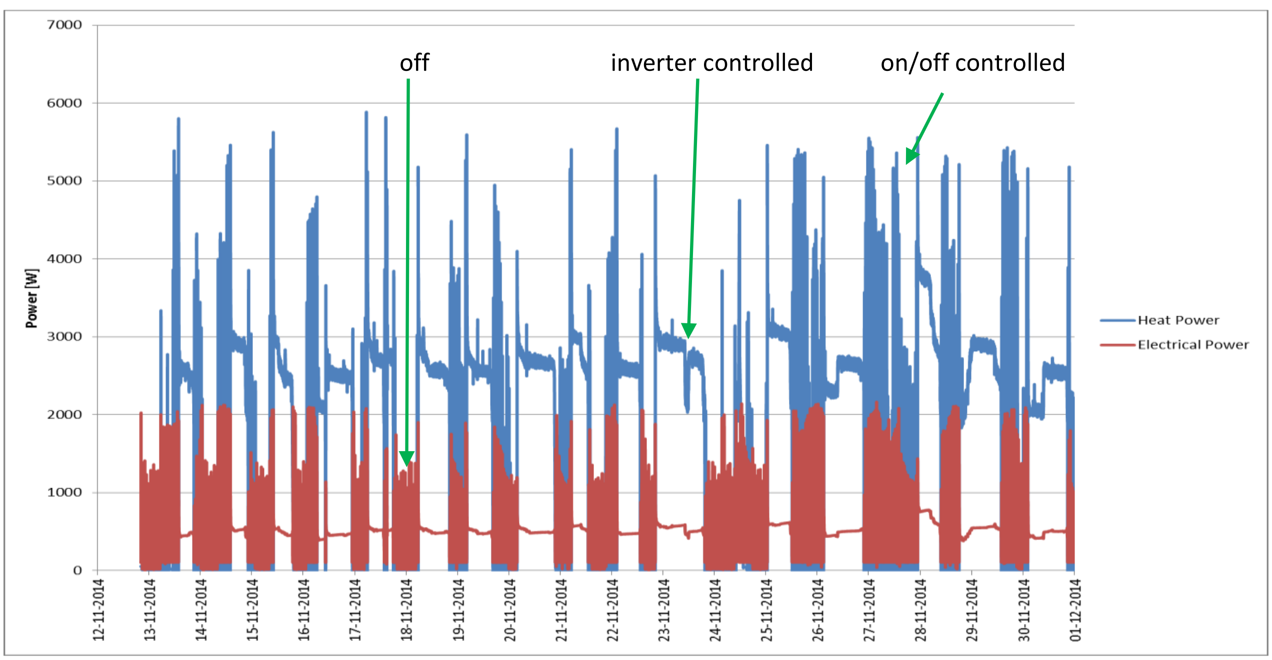


Figure 5.10: Measured power demand and heat production of the heat pump during November 2014.

Figure 5.9 shows that the heat pump cools down the ground, - the forward temperature of the brine to the heat pump is gradually decreasing. The forward temperature to the underfloor heating system is between 30 and 35°C (during inverter control) leading to a high efficiency (COP) of the heat pump. The mean COP of the heat pump was 3.3 during October, 3.9 during November and 4 during December 2014. The annual COP of the heat pump during 2015 was 3.5.

Due to the fluctuating nature of the power to the heat pump and the high thermal inertia of the house, it was not possible to develop a model in PRESS to forecast the hourly power demand of the house. The conclusion by ENFOR was that it is very difficult to develop models for forecasting the hourly energy demand of low energy houses due to the large time constant.

Forecast has successfully been utilized in another iPower WP1 case study. The investigation was carried out in an old two-family houses with a heat pump and a solar heating system where forecasts via PRESS on heat demand, solar heat production, weather and electricity prices was utilized in a local EMPC (Economic Model Predictive Controller) to optimize the electricity demand from the grid (Parvizi et al, 2016).

Although the large time constant of low energy houses makes it difficult to forecast the hourly energy demand of a house, the large time constant may in fact make it easier to control the heat production in low energy houses. In (Paulsen, 2013), it is suggested that the heat production could be based on a forecast of the necessary heat demand to the rooms instead of being controlled by temperature set points for the different rooms of a house. It is suggested that the valves of an underfloor heating systems or radiators are opened hour by hour only as long as it takes to deliver the forecasted heat. However, due to the large time constant of low energy buildings, it is really not that important when the heat is delivered to the house. The time of heat injection can more or less be chosen randomly over the day.

This means that it is not necessary to forecast the <u>hourly</u> heat demand, it is sufficient to forecast the <u>daily</u> heat demand. The daily injection of the daily heat demand can then be distributed over that day when the energy is cheapest. However, this strategy may lead to overheating during periods with large solar radiation. Therefor, the thermostats should prevent the house from getting too hot or too cold. Forecast of solar radiation could be included in the forecast of the daily heat demand.

In order to forecast the daily heat demand, there is a need for historical data of the heat demand. In a Smart Meter case, the only reading obtained comes from the main meter of the house. However, an electricity meter with data output is rather cheap. The problem is though that the relationship between electrical power and heat production of a heat pump is rather complex. The heat production is e.g. dependent on the actual brine temperature and the forward temperature from the heat pump to the heating system as seen in figure 6.1.

A proposal for obtaining the heat production from a heat pump by simple means is described in the following chapter 6.

5.4 ECONOMY

No economic considerations have been carried out in the Smart Meter case study. A thorough investigation of the economic potential of controlling a large number of Danish heat pumps (>300.000 heat pumps) has been carried out in (Stryg, 2014).

5.5 CONCLUSIONS FROM MEASUREMENTS IN THE PRIVATE HOUSE

The aim of the test in the private house was to gain experience from the real world with the test setup already tested in the EnergyFlexFamily. The main conclusions from the measurements in the private house were:

- the investigated setup proved to be somewhat unstable. Contact with the gateway was lost from time to time, and short battery life for the applied wireless devices gave loss of data. Subsequently, the wireless devices have been improved to have much longer battery life time
- there is a need for intelligence in the house to control the heat pump. This controller may also control the thermostats of the heat emitting system in order to allow for max flexibility by making it possible to excess preheat the house before switching off the heat pump. The controller may also be utilized for other purposes than obtaining flexibility, e.g. energy optimized operation of the energy service system of the house, securing the house, etc.
- a hard control by cutting of the power to the heat pump should be avoided. Instead a soft control should be applied where set points and measured values in the heat pump are manipulated in such a way that the controller of the heat pump still is in charge of starting up and switching off the compressor. In practice this strategy is to ‘prevent the heat pump from starting’ e.g. by manipulation of the measured heating system temperature in the controller. When the controller registers a measured (manipulated) heating system temperature higher than the set point, it will not start the compressor. On the other hand, to start the compressor again after a period of manipulation, the actual measured heating system temperature is starting the compressor, when this is lower than the set point temperature (which it is likely to be after a period without heating).
- remote control of the heat pump was not carried out due to the challenge of finding an aggregator. However, the measured fluctuations of the indoor temperature during the heating season indicated that the family may not have had problems with a remote control leading to fluctuating indoor temperatures of 22°C ±2 K
- Develco Products decided to develop a new platform with local intelligence in the building based on the performed Smart Meter case studies and research in iPower
- the private house has as EnergyFlexHouse a large time constant, which makes forecasting of an hourly energy demands very difficult
- low energy houses with large time constants may, however, possibly be controlled based on forecast of the daily heat demand, as it is not that important when heat is injected to the house during the day

6 DETERMINATION OF THE HEAT PRODUCTION FROM HEAT PUMPS

When utilizing heat pumps to stabilize the power grid, it is beneficial to be able to forecast the heat demand of the house. However, the precise heating demand depends on the use of the building, the ambient temperature and the solar radiation as described in the earlier chapters. When forecasting the heating demand, it is an advantage to have time series of the actual heating demand. However, it is typically rather expensive to install heat meters (in Denmark typically > €500), - an expense that is difficult to pay back based on the savings from participating in a Smart Grid market. The measuring of electricity consumption and temperatures is, on the other hand, rather cheap to carry out.

In the following, a new method for calculating the actual heat production of a heat pump is investigated. The method is based on time series of the electricity demand of a heat pump, the inlet temperature of the brine, and the forward temperature from the heat pump to the heating system (radiators or underfloor heating) as well as knowledge about the COP of a heat pump at different operation conditions. The temperature difference between the forward temperature of the heat pump and the inlet temperature of the brine is typically large (see figure 6.6 and 6.12), so a sufficient accuracy on the measured ΔT is easy to obtain. The following is the results from a preliminary investigation, which, however, are very promising.

A heat pump Compact P Geo 6 from the Danish company Nilan was installed in two different low energy houses: the EnergyFlexLab at Danish Technological Institute (the house in the background in figure 4.1) and the private house investigated in the former chapter. Geo 6 is as already mentioned a ground source heat pump that only delivers space heating with a nominal capacity of 6 kW. The heat pump is frequency controlled in the area of 2-6 kW and on/off controlled in the area of 0-2 kW. In the private house, underfloor heating was applied as the heat emitting system, whereas the heat emitting system in the EnergyFlexLab was a radiator system. Figure 5.6 shows the installed measuring equipment in the private house. EnergyFlexLab has a much larger and wired data acquisition system (Janssens, 2015).

The sampling in the private house was carried out on a minutely basis, but especially the heat meter on the warm side often lost its connection to the system. Thus, jumps in the sampling time of 2-30 minutes occurred. This is not a problem if the aim is daily, monthly, or annually integrated values. However, it is a problem when aiming at on-line calculation. In the present case, it made the data handling and preparation somewhat more difficult, but it could be overcome in this case. Thus, special awareness should be paid on securing alignment of the measurements from different sources from the start.

The sampling in EnergyFlexLab was done every fourth minutes. Here, the electricity meter sometimes skipped one sampling time, which was easy to fix, but it showed an odd pattern in the graphs showing the energy flows when not corrected.

Figure 6.1 shows the COP provided by the manufacturer. The COP is dependent on the temperature set (the brine temperature to the heat pump and the forward temperature from the heat pump) and the heat production measured according to EN 14511. However, the heat production is measured at more operation conditions than specified in EN 14511 as the standard only considers full load. Thus, figure 6.1 is more in accordance with the requirements of EN 14825.

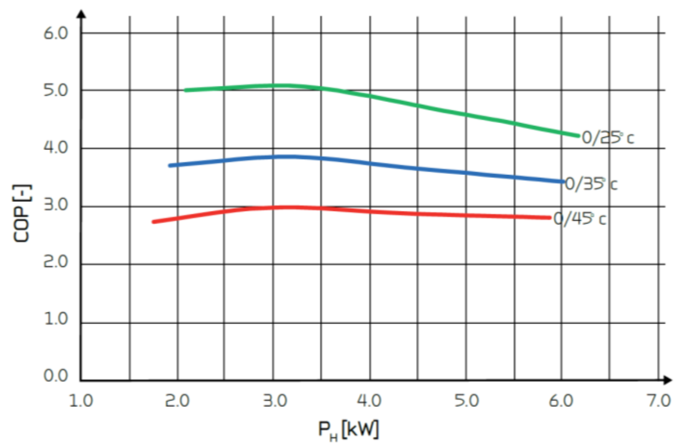


Figure 6.1: The COP of the heat pump depends on the temperature set and the heat production measured according to the test procedures stated in EN 14511. The meaning of the numbers to the right of the curves is as follows: the inlet temperature of the brine was always 0°C, while the forward temperature from the heat pump to the heating system was 25, 35 and 45°C leading to ΔTs of 25, 35 and 45 K, respectively.

The values shown in figure 6.1 were measured according to the specifications given in EN 14511. In these tests, a part of the power to the brine circulation pump and the circulation pump(s) of the heating system is included in the COP, i.e. the necessary pumping energy to overcome the pressure drop across the heat pump itself. The tests have been carried out with a constant flow on each side of the heat pump. The power added to the power of the heat pump was 24 W. When using figure 6.1, the Carnot efficiency and simple multi-regression, the following equations for the heat production based on the power to the heat pump and the ΔT may be derived:

$$\Delta T = (T_h - T_c) \quad [4]$$

$$COP_{carnot} = T_h / \Delta T \quad [5]$$

$$COP_{HP} = eta * COP_{carnot} \quad [6]$$

$$eta = -0.02623*P + 0.0010993*\Delta T + 0.4016 \quad [7]$$

$$Q_H = P * COP_{HP} \quad [8]$$

where: COP_{carnot} is the system Carnot COP based on the forward temperature from the heat pump (25, 35 and 45°C) and the brine temperature to the heat pump (0°C) in figure 6.1
- T_h: is the forward temperature from the heat pump [K]
- T_c: is the brine inlet temperature to the heat pump [K]
- COP_{HP}: is the "real" COP of the heat pump at the actual operating conditions
- eta: is the system Carnot efficiency of the heat pump
- P: is the electrical power to the heat pump [kW]
- Q_H: (P_H in figure 6.1) is the calculated heat produced by the heat pump [kW]

Figure 6.2 shows a comparison between the different COPs as they appear from figure 6.1 and values calculated using the equations [4] – [8].

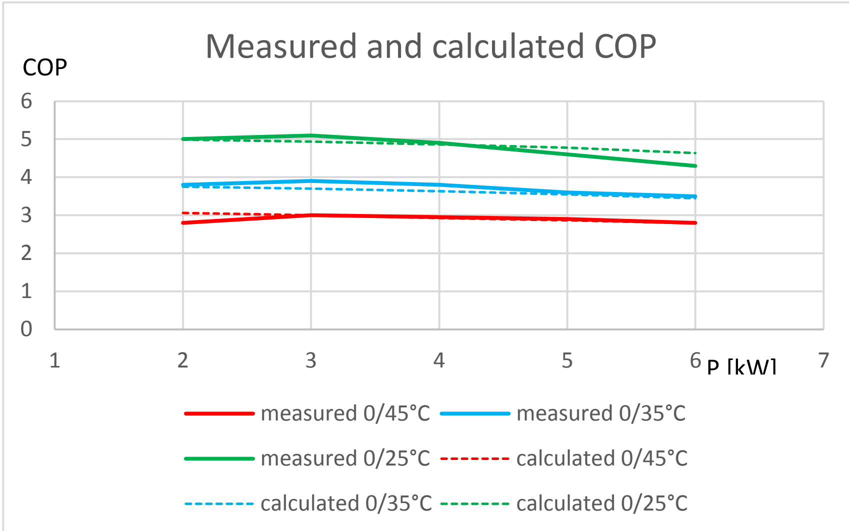


Figure 6.2: Calculated COPs compared with the curves of figure 6.1.

In the following, the model of the heat production will be compared with the measurements from the private house and EnergyFlexLab.

6.1 PRIVATE HOUSE

Measurements from November 13 to November 30 and the whole of December are investigated in the following.

Figure 6.3 shows the measured power to the heat pump and the heat production from the heat pump during 18 days in November 2014 with measurements. Please notice that the unit on the x-axis in the following figures is numerical day numbers: 1-365. It is seen that the heat pump very often changes between constant operations, on-off operation and being switched off. The used electrical power seems to be higher during switch-off than during operation. This is not really the case as shown in figure 6.4, which shows only one day. Figure 6.4 shows that the power demand is close to zero during switch-off except from regular peaks of about 1,300 W that occur at an approximately hourly basis. The duration of the peaks is less than two minutes and they constitute an energy consumption of less than 40 Wh. The peaks are believed to be caused by a bypass on the warm side of the heat pump. When the thermostats are closed in the heating system, there is still circulation through the bypass. When the temperature of the water drops below the set point temperature, the heat pump starts for a short period. This causes the water temperature to go above the set point, which then forces the heat pump to stop quickly without any real heat production. When modelling the heat production, these peaks have been avoided as they did not lead to a measured heat production. Figure 6.4 also shows measured heat production without any real power demand of the heat pump. An explanation of this phenomenon has not been searched for, and it has, therefore, been avoided in the modelling.

The above situations can be omitted if knowledge about the necessary runtime is applied when the heat pump is started and the necessary switch-off time is kept before the heat pump can be started again.

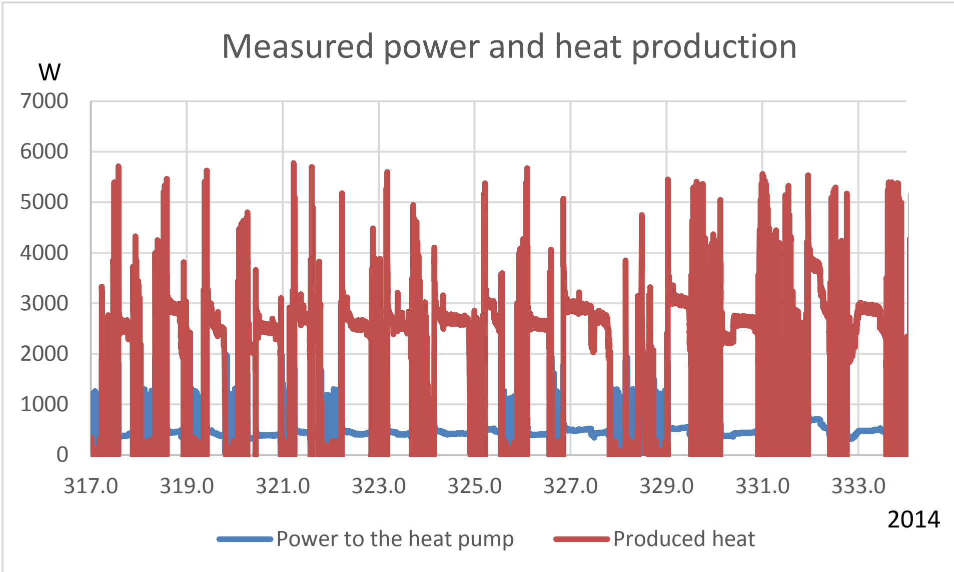


Figure 6.3: Measured power to the heat pump and heat production from the heat pump during the 18 days in November 2014.

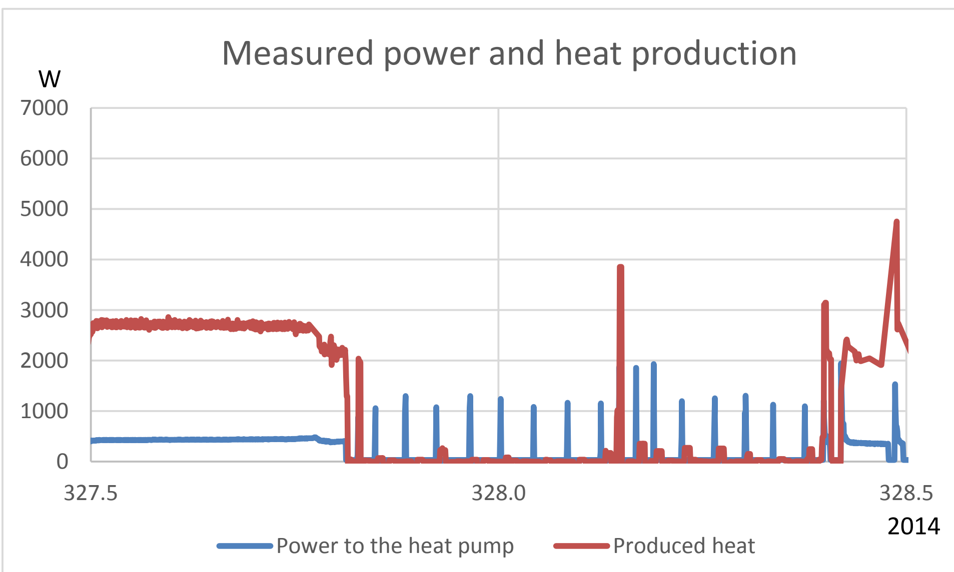


Figure 6.4: Close-up of figure 6.3 – November 23-24, 2014.

Due to the difficulties of interpreting figure 6.3, the calculated and measured heat productions are analyzed for only one day in the following with both constant and on/off operation and without alignment problems (all values are minutely). Figure 6.5 is a close up of figure 6.3 for November 25, 2014, and figure 6.6 shows the measured temperature from the heat pump to the underfloor heating system and the temperature of the brine to the heat pump for that same day. Figure 6.6 shows that the forward temperature from the heat pump to the underfloor heating system is between 32 and 34°C (during inverter control), while the temperature of the brine to the heat pump is around 7°C.

Figure 6.7 shows a comparison between the measured and the calculated heat production – the latter is calculated by using the equations [4]-[8] mentioned earlier. The figure shows that there is a rather good agreement between the measured and the calculated heat production during constant operation. However, problems occur in connection with on-off operation, where the calculated heat production often is almost double the nominal heat production of the heat pump. In figure 6.7, a barrier is inserted so that the calculated heat production cannot be higher than the nominal heat production of 6,000 W. The reason for the high calculated starting peak is a high startup current of the heat pump, as seen in figure 6.8, combined with a low start-up ΔT, which is due to the fact that the forward temperature during standby approaches the indoor room temperature, see figure 6.6.

Figure 6.9 shows that the calculated start-up heat production is still too high despite the barrier of 6,000 W during start-up. Thus, a more advanced approach could be considered. However, the maximum of 6,000 W only leads to a total overestimation of 6 % by the model for the seven on-off running periods in figure 6.9, which is quite good.

Figure 6.10 reveals that there is an offset of between one and three minutes between the measured and the calculated heat production. The same offset is seen between the measured power and the measured heat production. This offset may be cause by the clocks of the energy meters being a couple of minutes off compared to each other. Another reason may be that the heat pump needs a couple of minutes of runtime before the heat production can be measured and that the circulation pump of the heating is running constantly and uses a few minutes to cool down the system. However, the offsets are without importance because quarterly or hourly integrated values are often sufficient for control purposes, e.g. in connection with Smart Grid.

Based on the above, the total calculated heat production is 13 % lower than the heat production measured in November and 10 % lower in December with a higher heat demand. In figure 6.6, the ΔT over the heat pump (forward temperature from heat pump minus the temperature of the brine to the heat pump) was approx. 25 K during continuously operation, while the measured heat production was approx. 3 kW (see figure 6.7). At this operation condition, the model underestimates the heat production with approx. 3 %, as seen in figure 6.2. Thus, the uncertainty of the model can only partly explain the observed discrepancy. However, 10-13 % off is not bad considering the rather simple model of the heat pump. More importantly, the dynamics of the measured heat production is well represented by the model, as seen in figures 6.7 and 6.9. Therefore, it is believed that it may be possible to fine-tune the model in order to obtain even better agreement with the measurements. An alternative approach would be if a reliable flow rate could be extracted from the pump of the heating system. However, this means that one more value has to be logged and more precise temperature measurements are needed due to a smaller temperature difference.

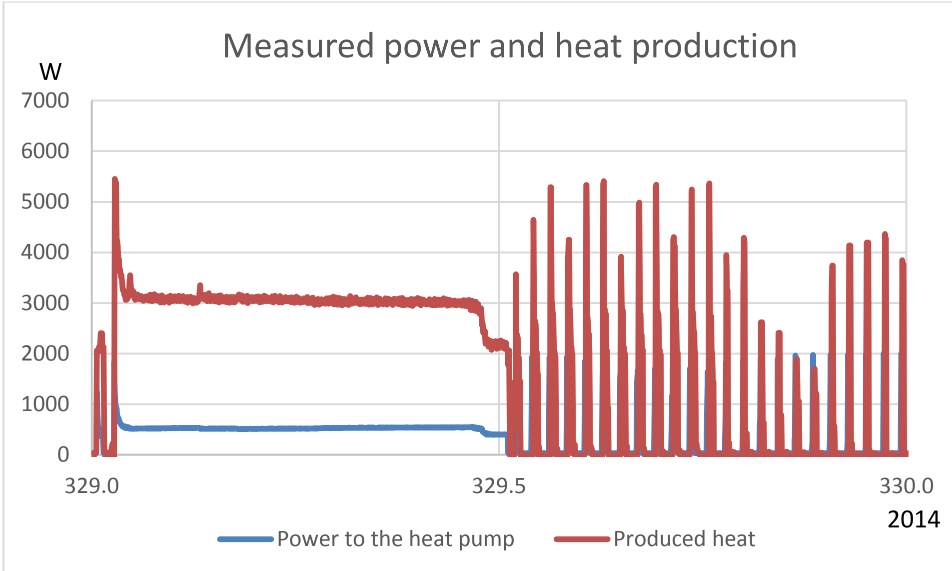


Figure 6.5: Close up of figure 6.3 – November 25, 2014.

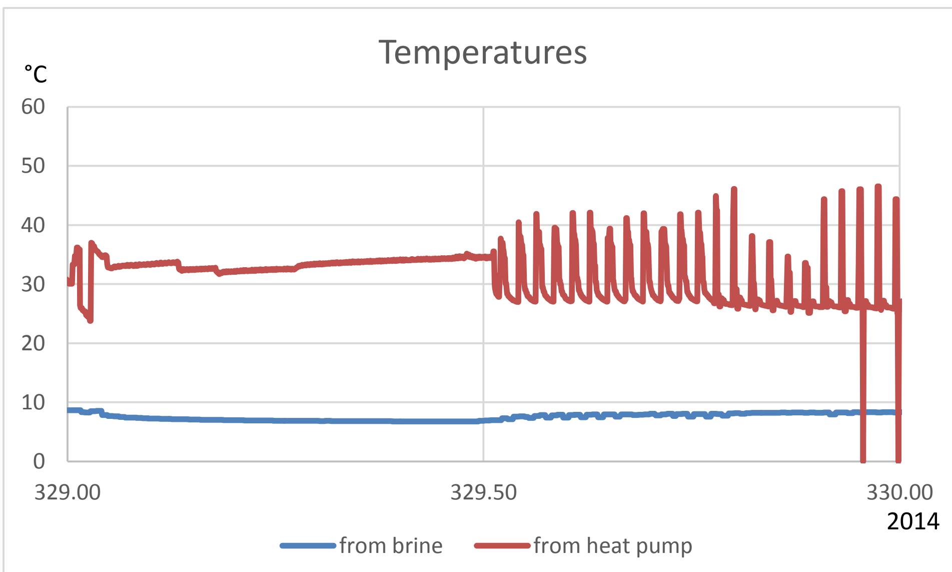


Figure 6.6: Measured temperature from the heat pump to the underfloor heating system and the temperature of the brine to the heat pump – November 25, 2014.

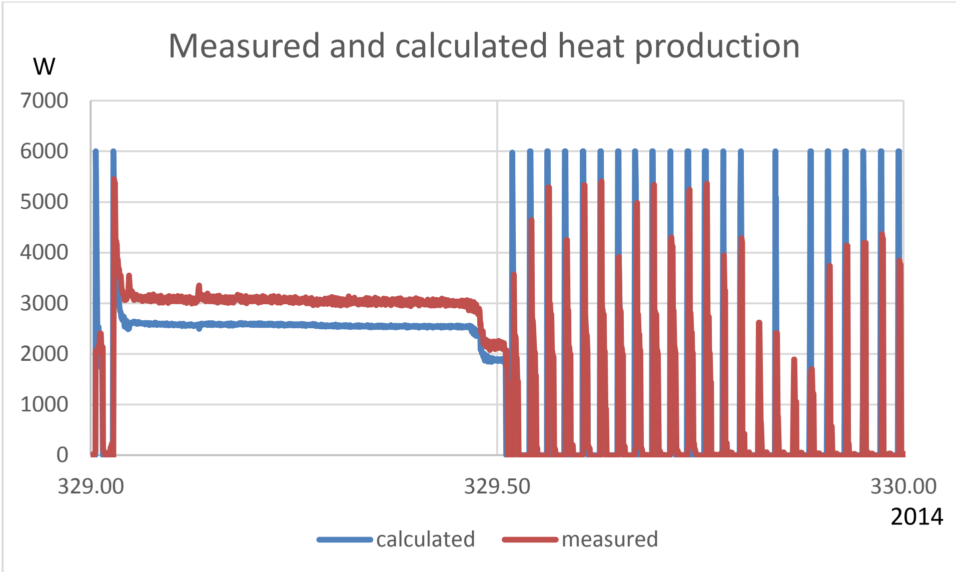


Figure 6.7: Measured and calculated heat production – November 25, 2014.

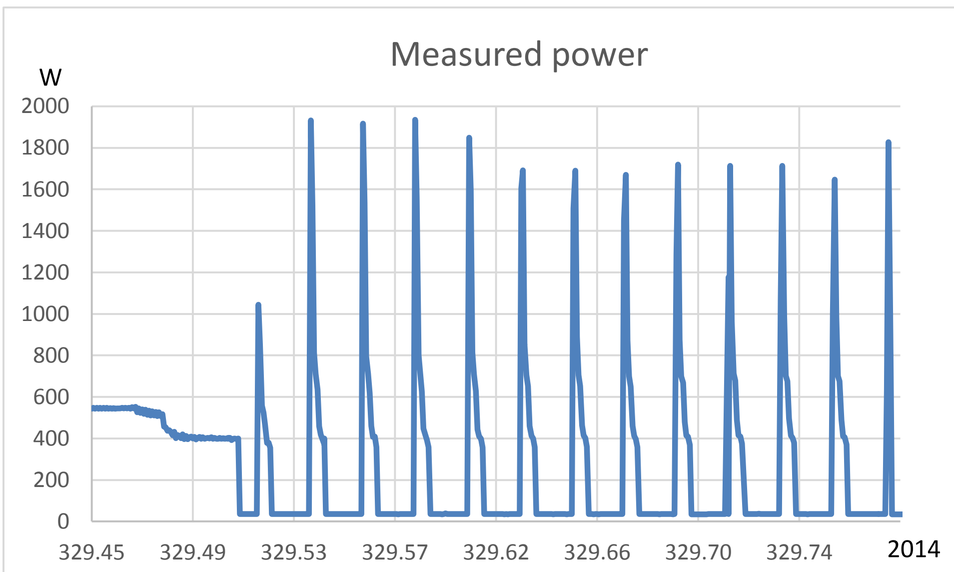


Figure 6.8: Measured power to the heat pump – eight hours during November 25, 2014.

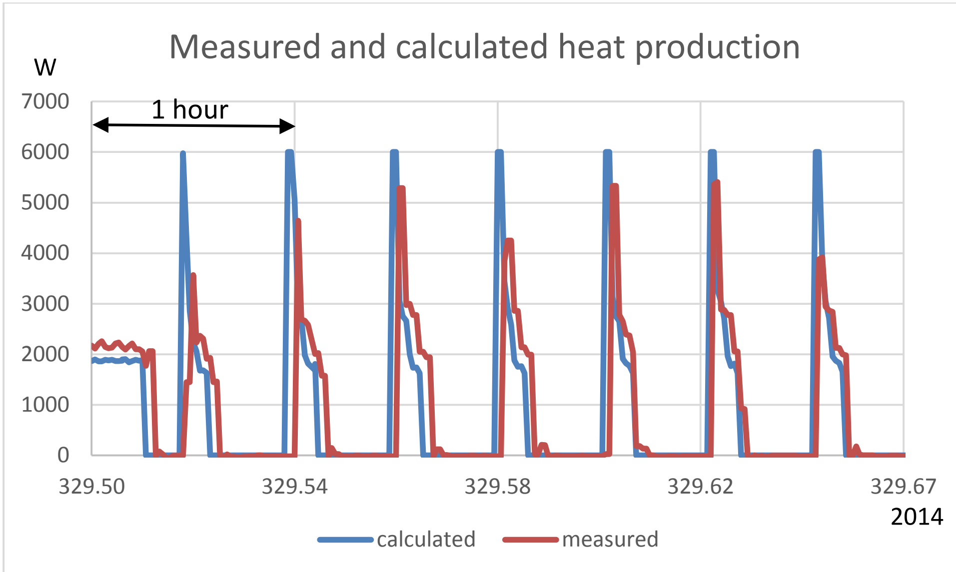


Figure 6.9: Extract from figure 6.7, measured and calculated heat production from noon to 5 pm on November 25, 2014.

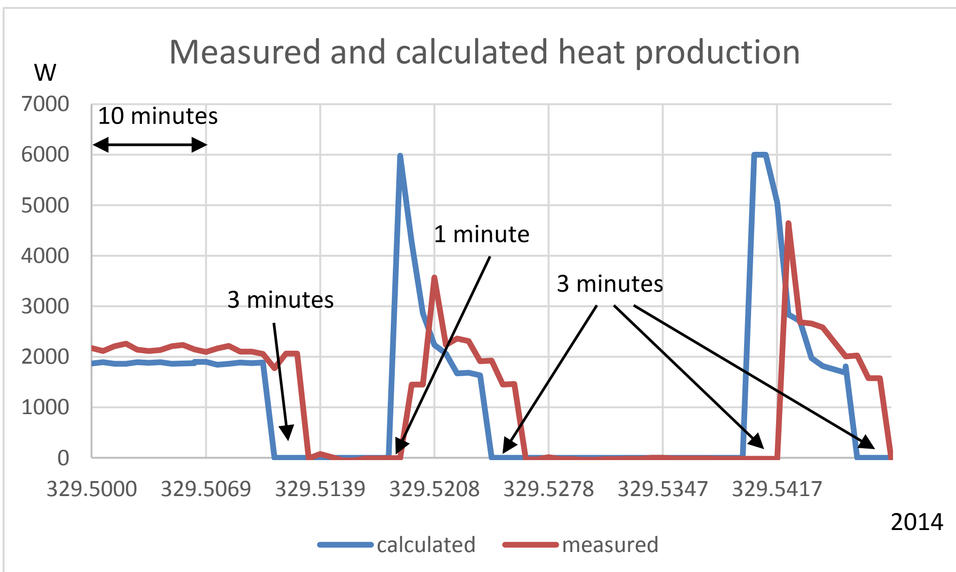


Figure 6.10: Extract from figure 6.7, measured and calculated heat production 70 minutes after noon on November 25, 2014.

6.2 ENERGYFLEXLAB

The investigated measurements are from another project (Christiansen, 2014). The purpose of this experiment was to investigate the decrease in room temperature that occured, when the heat pump was switched off for 12 hours each day, between 9 am and 9 pm. The experiment lasted for one week during December 2013.

Figure 6.11 shows the measured power to the heat pump and the heat production from the heat pump. Figure 6.12 shows the temperature from the heat pump to the radiators and the temperature of the brine to the heat pump.

The temperature from the heat pump to the radiators was stable around 48°C when the heat pump was running and the brine temperature was stable around 2°C. There are some unexplained dips in the power to the heat pumps, which of course also appear in figure 6.13 showing the measured and calculated heat production. Figure 6.14 shows a close up of a little more than a day of the seven-day period.

Figures 6.13-14 show that the model of the heat production catches the dynamic of the heat production quite well, except for:

1) a few measured fast peaks in the heat production during an otherwise stable operation. This has not yet been investigated.

2) a few calculated fast dips in the heat production due to measured fast dips in the electricity consumption. This may be a measuring error by the electricity meter or some phenomena in the operation of the heat pump. As the dips in power lasted for only one scan interval, their influence on the electricity consumption is insignificant. Furthermore, the dips are too fast to influence the measured heat output from the heat pump.

3) high peaks (heat production) measured at the start-up. Figures 6.13-14 show that the measured start-up peak of the heat production of the heat pump in the EnergyFlexLab is above the nominal power of the heat pump and higher than calculated. The measurements in the private house (figure 6.9) showed the opposite - and a more logical situation, i.e. that the calculated start-up peaks were higher than the measured start-up peaks.

When comparing the total heat production over the week, it is seen that the measured heat production was 310 kWh, whereas the calculated heat production was 272 kWh. Thus, the model underestimates the heat production with around 12 %, which is the same order of magnitude as for the private house. In figure 6.12, the ΔT over the heat pump was approx. 46 K during continuous operation, and the measured heat production was around 3.5 kW in average (figure 6.11). At this operation condition, the model predicts a COP identical to the tests seen in figure 6.2. Hence, this is not the cause of the discrepancy. Again, a discrepancy of 12 % is not bad considering the rather simple model of the heat pump, and more importantly, the dynamics of the measured heat production is also well represented by the model, as seen in figures 6.13 and 6.14. Therefore, it is believed, that it may be possible to fine-tune the model in order to obtain an even better agreement with the measurements.

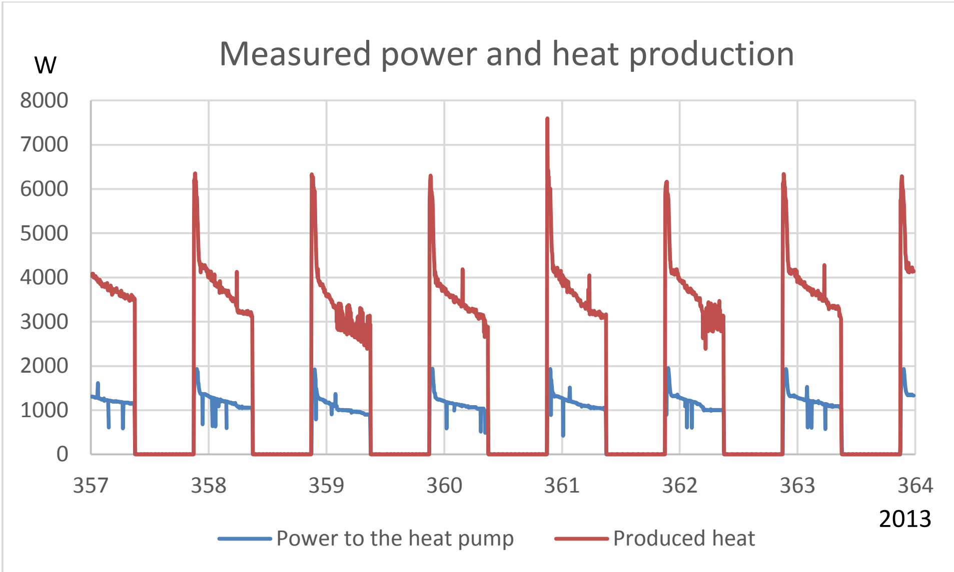


Figure 6.11: Measured power to the heat pump and heat production from the heat pump.

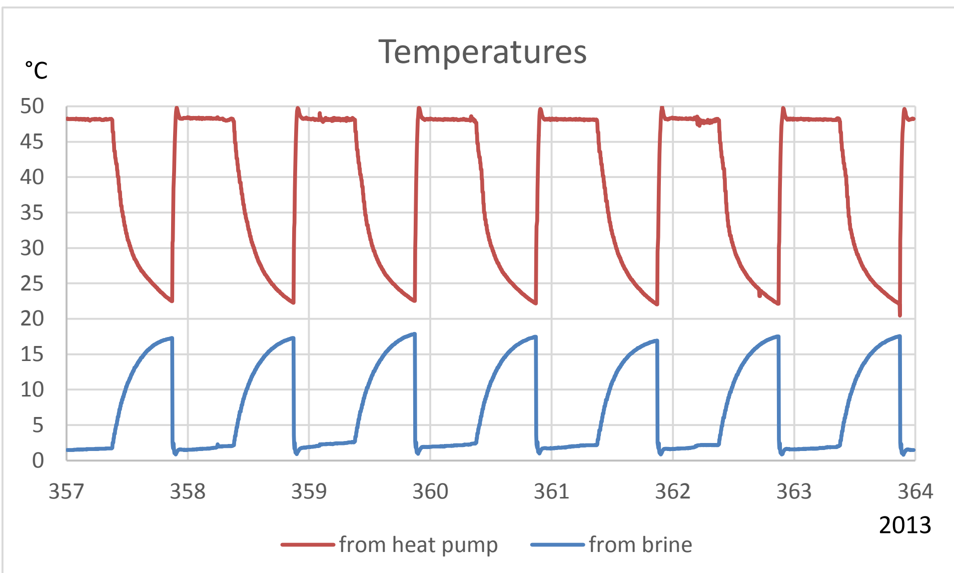


Figure 6.12: Measured temperature from the heat pump to the radiators and the temperature of the brine to the heat pump.

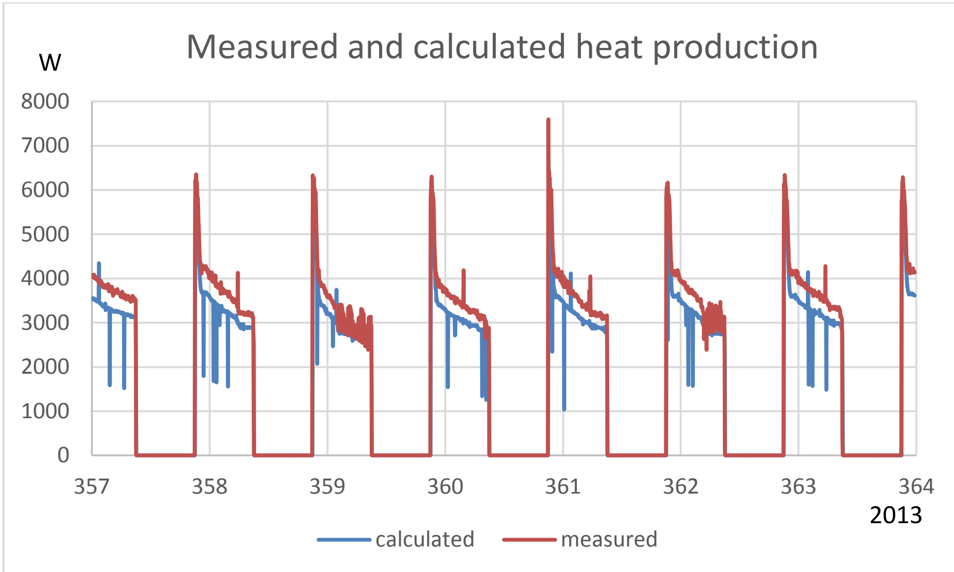


Figure 6.13: Measured and calculated heat production.

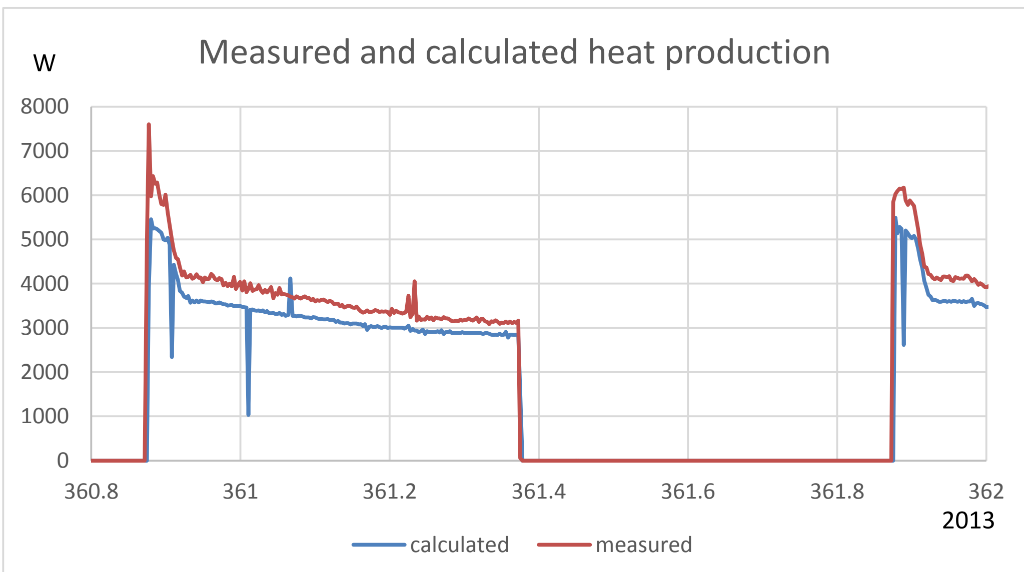


Figure 6.14: Close-up of figure 6.13.

6.3 CONCLUSIONS ON CALCULATIONS OF THE HEAT PRODUCTION FROM HEAT PUMPS

Even if the absolute discrepancy between the measured and the calculated heat production is slightly high, the difference is mainly systematic. Due to the good agreement between the measured and the calculated dynamical behavior of the heat production, it should be possible to develop rules for calibrating the model of the heat production in order to make a very good fit with the actual heat production. A better model for the start-up of the heat pump could also be considered.

The above investigation shows that it is possible to obtain a rather good agreement between the measured and the calculated heat production from a heat pump based on knowledge about the COP of the heat pump and time series of the power to the heat pump as well as the temperatures around the heat pump. This was shown for two different levels of forward temperatures from the heat pump i.e. 32-34°C and 48°C, for a space heating heat pump only. However, the good agreement at the high temperature level gives rise to believe that a good agreement may also be achieved for DHW production. Thus, heat production including DHW may also be calculated.

The investigation shows that is it not easy to obtain high quality data sets in real buildings. The quality of the actual measured data was good, but there were some difficulties with the connection to the measuring equipment, and the alignment between measurements was often poor. Even in the highly controlled EnergyFlexLab, some alignment problems occurred. Therefore, for a future deployment of online calculation of the heat production from heat pumps based on measurements in real houses, there is a need for a strong focus on the quality of the measuring equipment.

The COPs in figure 6.1 are derived using only the power to the heat pump and 24 W for the brine and circulation pumps to overcome the hydraulic pressure of the heat pump itself. Thus, when calculating the heat production of a heat pump using the measured electrical power to the heat pump, care should be taken that the measured power is comparable with the power from tests producing values like those in figure 6.1.

It was the intention to test the developed method with time series from other houses with heat pumps. However, it was not possible to find time series with all the necessary measurements: power to the heat pump, heat production from the heat pump, brine temperature and forward temperature to the heating system with scan intervals of approximately every five minutes.

The method is, however, not only valuable for forecasting of heat demand in connection with Smart Grid. It may also be used for verification of the COP of installed heat pumps and thereby ease fault detection, which leads to more efficient installed heat pumps.

7 CONCLUSIONS

The aim of the Smart Meter case study was to investigate a cheap concept for control of a heat pump using off-the-shelf devices. The aim of controlling heat pumps is to obtain energy flexibility, which may support the distribution grids when a large amount of uncontrollable renewable energy sources is introduced in the Danish power grid. The concept was tested in two houses: the EnergyFlexFamily at Danish Technological Institute and in a private house in Jutland. Both houses were inhabited by a family of four during the tests.

Furthermore the aim was to let the heat pump in the private house be controlled by a commercial aggregator which controlled a fleet of private heat pumps. Even though this was not obtained, valuable results were obtained from the measurements in the two houses:

- there is a need for intelligence in the house. The originally design was a remote control signal that should switch on and off the heat pump. However, if the internet connection is lost, there is a need for local intelligence to secure a proper operation of the heat pump. This local intelligence may also be used for other services such as optimization of the operation of the energy service systems in the house, security in the house, better comfort, etc. This bundling of services may improve the business case of introducing remote control of heat pumps in order to obtain energy flexibility
- based on the above, Develco Products decided to develop a new gateway with local intelligence
- when controlling the heat pump, set points and measured values should be manipulated, which allow the internal control of the heat pump to control the heat pump instead of hard cut of the power to the heat pump. The former leads to less wear on the heat pump and allows for more sophisticated control of the heat pump
- when only controlling the heat pump, only “half” of the possible flexibility is obtainable. The switch-off time of the heat pump can be extended if the house is excess preheated (within the comfort band of the room temperature) before a switch-off, of the heating system. In order to be able to excess heat the house, it is necessary to be able to control the thermostats of the heat emitting system - to increase the set point of the thermostats. The control of the thermostats may be carried out by the above mentioned local intelligence
- low energy houses, as the two houses investigated in the case study, have large time constants. This gives high flexibility, but the absolute amount of flexibility may be low due to the low heating demand of the houses. Due to the large time constants low energy houses may be controlled based on forecasts of the daily heat demand rather than forecasts of the hourly heat demand
- the capacity of the heat pump (including DHW production in case of combined heat pumps) should be sufficiently large to be able to regain the indoor temperatures after a switch-off. A back-up resistance heating element will increase the energy demand of the system and create large kickback effects when the heat pump is switched on after an off period
- the two families seemed to accept the temperature fluctuations when the heat pumps were switched off. However, from the EnergyFlexFamily tests it seemed that a too precise information about the room temperature may lead to complaints, because the eye (on a display) more easily detects fluctuations in the room temperature than the body – especially if the fluctuations are not too fast or too large

- a method for calculating the heat production from a heat pump based on cheap measuring of the power to the heat pump together with the temperature of the brine to the heat pump and the forward temperature to the heat emitting system has been developed and tested using data from the EnergyFlexLab and the private house.

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