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Universitet/högskola/företag RISE Research Institutes of Sweden	Avdelning/institution Energi och Resurser
Adress Box 857, 501 15 Borås	
Namn på projektledare Markus Lindahl	
Namn på ev övriga projektdeltagare Tommy Walfridson, Claes Sandels, Niclas Ericson, Marco Tiloca, Rikard Höglund	
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1 Preface

This project has been financed by the Swedish Energy Agency through the research program “Digitalisering möjliggör energi- och klimatomställningen”.

RISE Research Institutes of Sweden has been the project leader and main executor of the project. A group of companies is also connected to the project, as representing four large heat pump manufacturers in Sweden, an interest organization, a trade organizations and two energy companies. An important part of the project has consisted of discussions and interviews with the companies involved in the project together with other stakeholders. The companies are:

1	Bosch Thermoteknik	Heat pump manufacturer
2	Enertech	Heat pump manufacturer
3	Nibe	Heat pump manufacturer
4	Thermia	Heat pump manufacturer
5	Power Circle	Interest organization
6	Svenska Kyl & Värmepumpföreningen	Trade organization
7	Tekniska verken i Linköping	Energy company
8	Vattenfall	Energy company

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3 Sammanfattning

I ett elsystem med stor andel intermittent elproduktion från vind och sol kommer behovet av flexibilitet för att balansera variationer i elproduktionen att öka. Efterfrågeflexibilitet kan bidra till att minska problem med flaskhalsar och brist på kapacitet i elnätet samt undvika nedreglering av förnybara energikällor. Det här projektet har undersökt möjligheter och begränsningar för ett koncept där villavärmepumpar aggregeras och styrs via tillverkarnas molntjänster för att hjälpa till att stödja elsystemet med efterfrågeflexibilitet. Fokus har legat på att leverera efterfrågeflexibilitet till tre typer av tjänster, Svenska kraftnäts balanstjänster, lokala flexibilitetsmarknader eller bilaterala avtal. Projektet har tittat på flera aspekter, såsom värmepumpars tekniska begränsningar, hinder kopplat till elmarknaden och elnätet, cybersäkerhetsfrågor samt informationskedjan med fokus på lämpliga kommunikationsprotokoll. Projektets resultat bygger på såväl expertintervjuer som litteraturstudier och fälttester.

Resultaten från projektet visar att det finns flera hinder på elmarknaden som försvårar för värmepumpar att erbjuda efterfrågeflexibilitet. Ett hinder är krav på minsta budstorlek för medverkan på Svenska kraftnäts balanstjänster eller de lokala flexibilitetsmarknaderna, vilket medför att ett flertal värmepumpar behöver aggregeras. Ett annat hinder är behovet av att ha samma balansansvarig för alla medverkande i ett bud, samtidigt som det finns en mängd balansansvariga i Sverige. Ett tredje hinder är kravet på realtidsmätning av flexibilitetsresurser. Detta är ett potentiellt problem eftersom dagens värmepumpar saknar elmätare, vilket riskerar att minska noggrannheten i mätningen av efterfrågeflexibilitet.

Inom projektet intervjuades tekniska experter från värmepumptillverkarna. De har en gemensam syn på hur snabbt deras värmepumpar kan styras för att minska eller öka effektförbrukningen. Tillsatsvärmaren kan ändra sin effekt på sekunden, men den kan behöva ny programvara anpassade för att leverera flexibilitet. On/off-kompressorer kan också stängas av på sekundbasis, men behöver lite mer tid för att starta igen. Värmepumpar med varvtalsstyrda kompressorer justerar sin effekt betydligt långsammare. De kan ta minuter att starta, stoppa, eller reglera varvtalet på.

Projektet har undersökt olika sätt att kommunicera mellan aggregator, molntjänst och värmepump. Sju olika kommunikationsstandarder har utvärderats, främst så kallade kommunikations-middleware. OpenADR och IEEE 2030.5 är två USA-baserade standarder som bedöms har stor potential för att möjliggöra efterfrågeflexibilitet från värmepumpar. En potentiell nackdel är att de fortfarande inte är så vanliga i Europa. Intressanta europeiska alternativ är EEBus och EFI/S2. Alla dessa fyra standarder är gratis eller kan köpas för en mindre kostnad. De är inte rangordnade här och mer arbete behövs för att rekommendera någon av dem.

Värmepumpar måste styras via internet för att kunna bidra till flexibilitet på ett effektivt sätt. Detta kan, liksom för alla internetanslutna enheter, göra dem sårbara för cyberattacker. Hotet från cyberattacker måste tas på allvar, hackade värmepumpar kan orsaka stora problem inte bara för de enskilda värmepumpsägarna utan också vara en risk för elsystemet som helhet.

4 Summary

In a power system with a large share of intermittent sources, such as wind and solar, the need for flexibility to balance variations in electricity production will increase. Flexibility, or demand response, can help reducing problems due to bottlenecks and shortage of capacity in the electricity grids, as well as avoiding curtailment of renewable energy sources. This project has investigated possibilities and constrains for a concept where residential heat pumps are aggregated and controlled via the manufacturers cloud service to support the power system with flexibility with focus on Svenska kraftnäts ancillary services, local flexibility markets or bilateral agreements. The project covers several aspects, such as technical constraints of heat pumps, electricity market and power grid barriers, cybersecurity issues and the information chain with focus on suitable communication protocols. The project results are based on expert interviews, literature review and field tests.

Results from the project shows that the electricity market has several barriers that hinder heat pumps from offering demand response. One barrier is the minimum bid size for the balancing markets, which requires aggregating many heat pumps. Another barrier is the need to have the same balance responsible party (BRP) for all customers in a bid, but there are several BRPs in Sweden. A third barrier is the demand of real-time measurement of flexibility resources by the balancing service provider. This is a potential problem since today's heat pumps lack electricity meters, which risk to lower the accuracy of demand response measurements.

Within the project technical experts from the heat pump manufacturers were interviewed. They have a common ground in how fast their heat pumps can be controlled to decrease or increase power consumption. The auxiliary heater can change power in a second, but it may need new software adapted for flexibility. On/off compressors can also be turned off in a second, but they need some time to restart. Variable speed heat pumps are much slower to change power. It can take minutes to start or stop them or control their speed when they are already running.

The project has investigated different ways to communicate between the aggregator, the cloud services and the heat pumps. Seven different communication standards were evaluated, mainly higher-level protocols, also referred to as communication middleware. OpenADR and IEEE 2030.5 are two US-based standards that have great potential for enabling demand response from heat pumps. A potential drawback is that they are not that common in Europe today. Interesting European alternatives are EEBus and EFI/S2. All these four standards are free to use or can be bought at limited costs. They are not ranked here as further work is needed to recommend any of them before the others.

Heat pumps need to be controlled over the Internet to effectively contribute to flexibility. This can, as for all internet-connected devices, make them vulnerable to cyberattacks. The threat from cyber-attacks has to be taken seriously as hacked heat pumps could, at least in the future, cause severe problems not only for the heat pump owner but also to the national power system.

5 Introduction

There is a clear trend of intermittent electricity production increasing in Sweden as well as globally. In a power system with an increased share of electricity from intermittent renewable sources such as wind and solar, a more flexible electricity consumption is most likely necessary. Flexibility, also called demand response, can help reducing problems due to bottlenecks and shortage of capacity in the electricity grids, as well as avoiding curtailment of renewable energy sources. Today, there is ongoing work to find affordable solutions to increase the robustness and flexibility of the power system. This project investigates the possibilities to use residential heat pumps to deliver demand response. The heat pumps manufacturers' cloud solutions and application programming interface (API) are investigated as to their possible use for communicating demand response between an aggregator and individual heat pumps, in order to deliver flexibility in the power system.

5.1 Goal and scope

This study investigates demand response based on load control of residential heat pumps from different aspects. The study focuses on the concept of using the heat pump manufacturers' cloud solutions and application programming interface (API) to communicate demand response between an aggregator and individual heat pumps.

The overall project goal is to show that it is possible to control heat pumps on a large scale, in order to support the electricity grid with demand response based on the heat pump manufacturers already existing hardware and cloud solutions. To do that, the project will look into several areas and identified barriers and possibilities related to technical constrains in heat pumps, barriers related to the electricity market and power grid, as well as issues related to cybersecurity. The project will also look into the "information chain" between the aggregator and the individual heat pump, and into potential communication protocols suitable for demand response from heat pumps.

One aim within the project is to make functional tests with remote control, to show that it is possible to control a heat pump with sufficient precision to fulfil the requirements for one of Svenska Kraftnät's existing ancillary services.

5.1.1 Limitations

- The focus is mainly on conditions and available flexibility products for the Swedish power system.
- The evaluated solution is valid for residential heat pumps with hydronic heating systems, meaning ground source, air-to-water and exhaust air heat pumps, which are connected to a manufacturer's cloud service. Air-to-air heat pumps or industrial heat pumps are out of the scope of the study.
- The project has a main focus on the technical aspects and requirements for demand response. Other issues like comfort, or the end user's willingness to participate and provide their heat pump for load control or suitable business models are only roughly investigated.

5.2 Concept

To enable a rapid deployment of heat pumps as a flexibility resource, the project studies the possibilities to communicate the load control to the individual heat pumps via the manufacturers' already existing cloud and application programming interface (API) solutions. The thesis of the project is that using the manufacturers' cloud and API solutions requires no hardware changes to get an initial flexibility solution up and running. Thereby the investment cost to use heat pumps as a flexibility resource, and in the next step reach economical breakeven, is lower compared to solutions where new hardware needs to be installed. Other studies, e.g. [1], have shown that one barrier to attain flexibility from heat pumps is to find a beneficial business model for all the involved parties.

The manufacturers' cloud and API solutions have been in use for approximately ten years, which means that many installed heat pumps are ready to be used for flexibility purposes once the communication is in place. In Sweden, all the major manufacturers of hydronic heat pumps provide users with functionalities for controlling and monitoring their heat pumps via an app, by connecting the heat pump to the manufacturer's cloud infrastructure. This means that many heat pump models can be controlled externally. For example, the heating curve can be altered by the owner via the app, but there is also automatic planning of the heat- and domestic hot water production based on the hourly price of electricity for some heat pump models [2][3]. From a control point of view, there are still missing functionalities for enabling the delivery of flexibility to the power system via these cloud services, but as the hardware is in place since several years, the potential amount of heat pumps with the hardware already installed is assessed as large. Figure 1 show a schematic overview of the proposed communication flow to deliver flexibility from heat pumps to the power system.

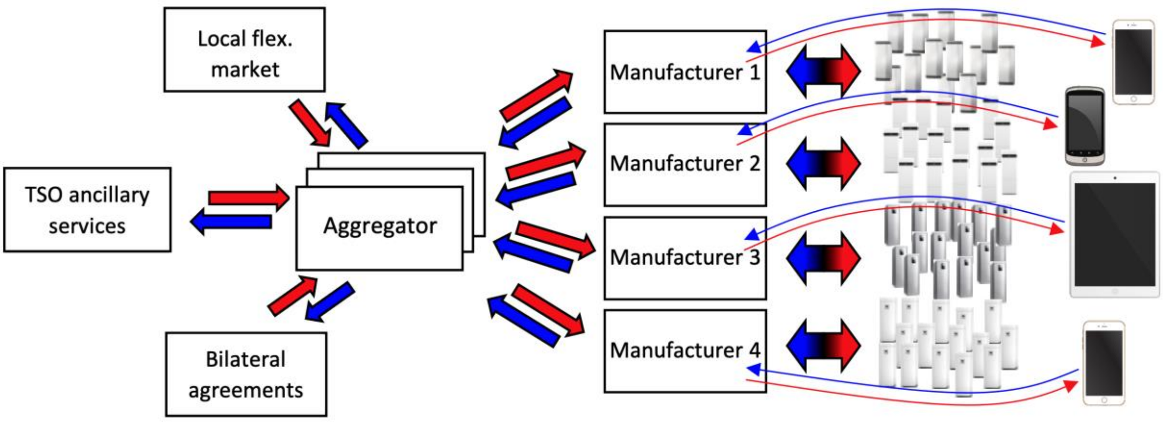

Figure 1. Overview of the communication flow for demand response from heat pumps using the manufacturers cloud solution.

According to the concept investigated in this study, the aggregator is active on one or several of the available flexibility markets and uses the manufacturers cloud solution to communicate with the individual heat pumps. Depending on how the communication is done and to what extent the heat pump manufacturer wants to be in the control, the manufacturer can either more or less forward the control signals to the individual heat pumps or “translate” the signals for each heat pump model to ensure that the heat pump reacts in a desired way. In the latter case, each individual heat pump can then react to demand response with less risk for decreased comfort to the end user, as the manufacturers have the deepest knowledge about their products and how to control them, which means that they have the best possibilities to make the heat pump react in the desired way. Furthermore, this approach adds an additional layer to mitigate cybersecurity risks as the manufacturer can ensure that control signals are reasonable.

5.3 Definition of flexibility

In this study, we focus on demand response from aggregated heat pumps delivering explicit flexibility to the power grid having 1) a bilateral agreement with a grid owner, 2) participates at Svenska kraftnäts ancillary services or 3) is active at a local flexibility market. The main focus in the project has been on Svenska kraftnäts ancillary services, since the flexibility market is well established and the demands for the flexibility resources to fulfill are well described, even though the criteria are not defined for heat pumps and other aggregated products in first place. More information about flexibility and potential flexibility markets can be found in Background, see chapter 6.4 and 6.5.

6 Background

There is a clear ongoing trend that electricity production from intermittent sources is increasing both in Sweden and on a global level, see Figure 2 and Figure 3 below. As more electricity is being generated from weather-dependent intermittent sources, larger variations in electricity production will occur. In a power system with a large share of intermittent sources, the need for flexibility to balance variations in electricity production will increase. Flexibility can also help to reduce problems with bottlenecks and shortage of capacity in the electricity grids.

Sweden has set a political goal to have 100% fossil-free electricity by 2040 [5][6]. At the same time, there is an ongoing electrification of the whole society. Several roadmaps from “Fossilfritt Sverige”, an initiative to reduce global warming from different industrial sectors, suggest increased electrification as a way to reduce the climate impact of each industry [7]. To support this transition, the former Swedish government published an electrification strategy [8]. The strategy highlights flexible use of electricity as an important part and specifically mentions increased flexibility related to electrical heating. All this indicates that Sweden’s electricity grid will experience a higher demand in the future and a significant portion of this demand will be met by intermittent sources.

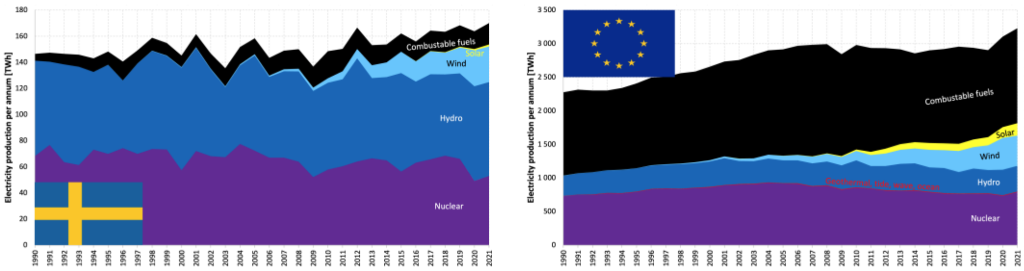

Figure 2. Sources for electricity production in Sweden (left) and EU 28 (right). For better readability, UK is included in 2020 despite Brexit. Data come from Eurostat [9] and the Swedish Energy Agency [10], while some data for UK are extrapolated in 2020.

The global trend regarding an increasing share of electricity from renewable sources is similar, see Figure 3.

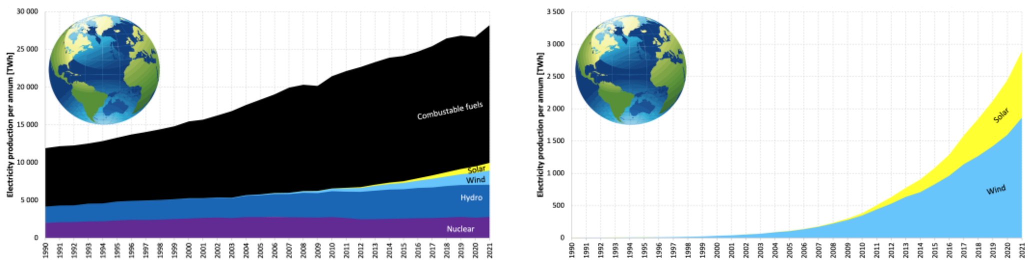

Figure 3.Sources for electricity production of the World (left) and zoom in on wind and solar to see the growth rate (right) [11].

The EU's Renewable Energy Directive for 2030 [12] sets a binding target for at least 32% of final energy consumption to come from renewable sources. However, there are ongoing discussions to increase this target to 40% as part of the European Green Deal [13]. Child *et al.* has made a scientific forecast that shows how the EU should be able to have an almost completely renewable electricity production by 2050. According to the forecast, weather-dependent sources would need to account for 60% of the EU's electricity production on an annual basis already by 2030 [14].

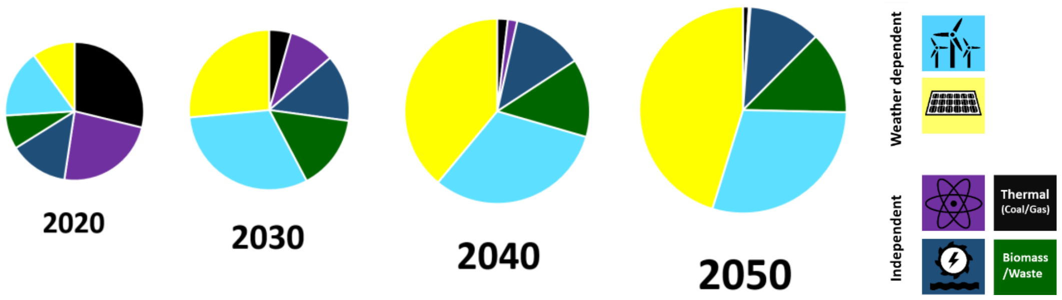

Figure 4. Forecast by Child et al. [14] on reaching a renewable electricity production up to 2050 within EU. The diameter of the diagram is proportional to the forecasted electricity produced each year. Note that 2020 is also a forecast here, in reality wind + solar was 20% in 2020, see Figure 2 above.

6.1 Earlier projects in the area

There are several other finalized or ongoing projects where the possibilities to use heat pumps for demand response is investigated from different aspects, where some of them also include large scale demonstrations of demand response from heat pumps. The main difference between many of them and this project is how communications with the heat pumps occur, but also what grid services the heat pumps are intended to deliver.

6.1.1 Klokel and Växel

One the most well-known Swedish projects focusing on demand response from heat pumps is Klokel [15], led by Sustainable Innovation in cooperation with Ngenic, Upplands Energi and Enertech (2014 to 2018). The follow up project, Växel, [16] running from 2017-2020 together with the partners Ngenic, Ferroamp C-TEK, Stuns Energi and Upplands Energi focused more on making demand response from different sources available, heat pumps being one of them.

In the Klokel project, control of the customers hydronic heating systems, including various types of heat pumps and electric boilers, were installed. The aim was to reduce the power consumption of the heating system when the power grid was strained. It was proved that by controlling 250 systems (heat pumps and electric boilers), it was possible to decrease power consumption of 1.5 MW. The test was done with very cold weather and the results are thus not generally applicable.

The results from the project showed that the indoor climate and comfort of customers were not affected by the control. In fact, the indoor climate became more stable. The new control also helps regulate the indoor temperature using three devices that measure indoor and outdoor temperatures as well as solar radiation.

This has led to energy savings of up to 10% for the heat pump. The main reason is that solar radiation is utilized more efficiently in combination with weather forecasts, resulting in a more consistent temperature.

An important difference between the Klokel project and this project is the way the communication with the heat pump is done. In Klokel the Swedish company Ngenics solution is used, where the heat pumps outdoor temperature sensor is replaced with their control equipment. This makes it possible to send an adjusted outdoor temperature to the heat pump, thus overriding the control system and control the heat pumps heat production.

Within Växel, a technical solution was developed where an operator, e.g., an aggregator, can use a common open standard, based on the OpenADR framework (see chapter 10.3.5), to control all resources regardless of which flexibility assets the resource consists of. In the project, solar PV, charging stations for EV, batteries and heat pumps were controlled. The operator in charge of control must be able to combine all these resources and to optimize their operation and performance, considering both the individual customer's needs and the overall system perspective. The project focused on providing flexibility services to the local electricity grid. The flexibility that was made available through the project was used to participate in the local flexibility market Coordinet during the final phase of the project.

In the project, a review of candidate open standards for load control was made, and OpenADR was seen as the best alternative to adopt and use. The project also proposed that relevant Swedish authorities conduct a larger investigation to see if they can recommend the Swedish industry to adopt OpenADR as a communication protocol for demand response.

6.1.2 EcoGrid EU and EcoGrid 2.0

Another early project in the area of flexibility from heat pumps was the EU project EcoGrid EU (2011-2015) [17] followed by EcoGrid 2.0 (2016-2019) [18].

The purpose with the EcoGrid projects was to demonstrate the operation of a power system with high share of renewable and variable energy resources on the Bornholm island in Denmark. More than 50% of the electricity consumption on Bornholm is covered locally by renewable energy production. In the follow-up project, EcoGrid2.0, 1000 heat pumps and electric radiators were remotely controlled via an aggregator in order to optimize their power consumption, consistently with the amount of power available in the power system at any given time.

The demonstration has shown that there is significant potential for demand response from homes heated by heat pump with automatic control systems. The project also showed that a real-time price signal can be used for load control of the heat pumps and that the response can be forecasted.

Two different tools for remote control of heat pumps were developed in the project, called "IBM control" and "PowerMatcher control". Both had the possibility to send an off signal to the heat pump for a certain duration. In chapter 10.3.6 the potential of PowerMatcher control is further evaluated.

6.1.3 Flexible Heat and Power

Flexible Heat and Power (FHP) was another EU project within the area of flexibility running from 2016 to 2019 [19]. The project investigated how to remotely control heat pump operations and thus their electricity consumption, which showed both limitations in what is practically possible and available solutions for control of the heat pumps electrical load [20]. The evaluation was mainly based on a questionnaire sent out to four Swedish heat pump manufacturers as well as laboratory tests of a ground source heat pump.

6.1.4 Bostäder för flexibilitet

Bostäder för flexibilitet is an ongoing Swedish project led by RISE [21]. In the project, heat pumps in ten single-family houses are controlled based on different control strategies with the aim to provide beneficial load shedding for the local electricity grid. The heat pump control is done in combination with measurements and interviews with the families in the houses. The houses are equipped with measuring equipment monitoring temperature, humidity, power consumption, as well as several heat pump parameters. The heat pumps are then remotely controlled using the manufacturers application programming interface (API). The project analyses the actual grid benefits, heat pump behaviour, as well as comfort and interest from occupants.

The purpose of the project is to better understand the flexibility potential from heat pumps in Swedish homes, as well as to identify complexities and practical issues. The project also aims to find the real potential of flexibility from an aggregated cluster of single-family houses and better understand the practical possible benefits for grid owners compared to the cost and challenges related to aggregating flexibility from villa heat pumps.

6.1.5 Flex+

The Austrian research project “Flex+” ended in 2022 and studied the use of remotely controllable components such as heat pumps, boilers, home storage systems, and e-mobility in short-term electricity markets in Austria [22]. The project had a focus on the economic use of flexibilities at spot and balancing energy markets (frequency restoration reserve), and on the consideration of the end consumers interests. The concepts were tested by simulation and validated in large-scale real operation.

As to heat pumps, the project focused on single-family homes, where the heat pumps were a part of an aggregated pool. The heating system of the individual households consisted of the heat pumps (either air or geothermal) and thermal storage in the form of domestic hot water tanks and in many cases additional buffer tanks as well as the buildings thermal inertia.

Simulation results showed that the total variable energy costs of the heat pump pool could be reduced by up to 12%. The most profitable use case was to participate in the day-ahead spot market and provide balancing services on the automatic frequency restoration reserve (aFRR).

6.2 Thermal inertia and thermal comfort in buildings

The thermal inertia of a building makes it possible to start or stop the heat production without significant impact on the indoor temperature. The possible duration of the on or off cycle highly depends on the building's thermal inertia, where heavier building types have a larger potential for variable heat production. Weiβ *et al.* [23] and Le Dréau and Heiselberg [24] have used simulations to investigate the potential with thermal inertia when shifting electrical heating loads in time. Weiβ *et al.* showed that, for residential buildings in Austria built according to Austrian standards after 1980, at least 50% of domestic heating peak loads could be shifted to off-peak hours during the day, by using a comfort band between 19-22°C. The study by Le Dréau and Heiselberg showed that it is possible to shift the heat production in time for a period of 2-5 hours in poorly insulated single-family houses in Denmark, and still maintain the set comfort conditions. For homes built according to passive house standard, it was possible to switch off the heating system for more than 24 h and still fulfil the comfort criteria. The heating and ventilation systems affects the thermal inertia of the building, especially during cold spells.

Thermal comfort is more than measured temperature. Windows and other cold surfaces will not be compensated for to the same extent if the heating system is reduced or even turned off. This means that individuals in the building will sense a lower operative temperature than before the heating was reduced, even if the air temperature has not decreased much at all. The radiation balance has been shifted and thereby the thermal comfort. A similar effect is the cold air downdraught from windows that are normally eliminated by the upward moving heat from the radiator (when present). When the radiator cools off, the cold air downdraught will reach the floor and risk giving individuals cold feet, the colder the ambient is the colder the feet get.

Another thermal comfort aspect is domestic hot water (DHW). If it is not heated when used, the temperature will decrease and the DHW will risk being too cold for expected comfort. Legionella legislation must also be considered before reducing or stopping DHW production.

6.3 Potential for demand response from heat pumps

The vast majority of Sweden's installed heat pumps are currently installed in single-family buildings These heat loads are considered to have a large potential for demand response in Sweden. As described in chapter 6.2 the thermal inertia of a building allows the heating to be paused for a few hours without any larger impact on the indoor temperature or comfort, which can be used to provide demand response. However, this is a returning load, the loads are only shifted in time, and one drawback of using heat pumps for demand response is that there is a risk of a new load peak when the heating resumes.

Around ⅔ of the electricity used by single-family houses heated with electricity (heat pump or electric heaters) is used for space heating and production of domestic hot water (DHW) [28], and today there are around 1.5 million heat pumps in operation in Sweden, of which 900,000 in hydronic systems [26], see Figure 5 below. Around 50,000 new hydronic heat pumps are installed every year [25], where many replace older heat pumps. Most of them with the possibility to connect to the manufacturers cloud solutions.

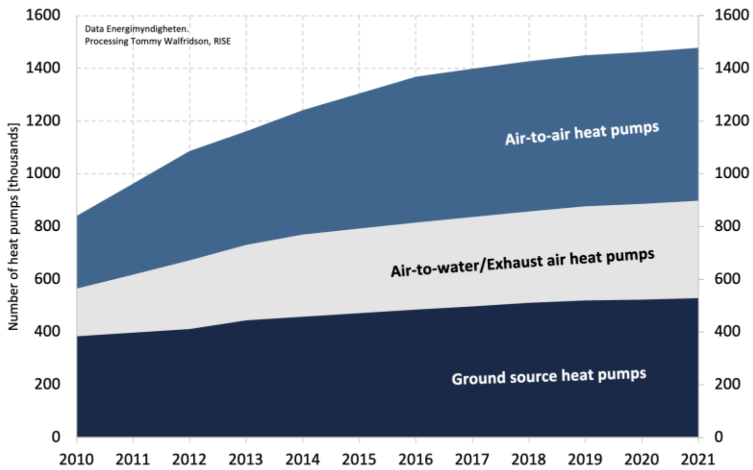

Figure 5. Development of heat pump stock in Sweden. The data source is Energimyndigheten [26] with processing from the author.

Earlier studies have estimated the potential for demand response connected to controlling space heating and production of DHW in Sweden to between 1-6 GW [27]. This can be compared with Sweden's total power need at high load situations which today is about 28 GW and is predicted to increase in the future [7]. Already today, we estimate the theoretical potential flexibility from heat pumps to several hundred MW in Sweden. Assuming an average power consumption per heat pump of around 3 kW, about 150 MW potential flexibility is added per year from new hydronic heat pumps. In reality the flexibility is highly dependent on the outdoor temperature and if the heat pumps really are connected to the cloud solution or not. Lately, the habit of connecting connectable devices have, at least in Sweden, become mainstream. This means that it is highly likely that a majority of the new heat pumps will be connected to the Internet.

6.4 Flexibility in the EU

Flexibility and demand response are broad terms without a clear definition. EU:s Electricity Directive (Directive 2019/944) [29] states that: "*demand response' means the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a price in an organised market … whether alone or through aggregation.*" In other words, flexibility can be achieved in several different ways.

The EU Directive also requires that flexibility must be an option, if it is considered an economically viable alternative to regular options, and there are several local flexibility markets under development in Europe, with partly different purposes. In Sweden, the Netherlands, and Germany, the flexibility markets are primarily used for handling bottlenecks in the grid. In France and the UK, the local flexibility markets are also used for grid planning. The process to develop a regulatory framework has started in several countries in accordance with the EU directive, but none of the identified countries have finished deploying a full regulatory package on the topic [30].

6.5 Flexibility markets in Sweden

Using heat pumps for demand response is still in the start-up phase, but there are identified potential markets for demand response, most of which are likely to deliver either ancillary services to Svenska kraftnät, the Swedish Transmission System Operator (TSO), or flexibility to a local flexibility market. A third alternative is that the aggregator has a bilateral agreement with a specific partner, like the local grid owner, to provide flexibility.

In this study, the aggregator is assumed to be a separate actor, but heat pump manufacturers can in the future possibly take the aggregator role as well. In Sweden, considering all the local flexibility markets and all the ancillary services from the Swedish TSO, Svenska Kraftnät, the smallest bid size is 0.1 MW or higher [31][32]. Since each individual heat pump can only deliver a smaller amount of flexibility to the power system, this means that domestic heat pumps must be aggregated and controlled as a group to accomplish the minimum bid size of 0.1 MW. The aggregator uses its pool of heat pumps to deliver services to the power system. Both a decrease and an increase in power consumption can be of interest for the flexibility buyer, depending on the situation. In addition, the time it takes to activate a flexibility resource is many times of high importance for the buyer of demand response.

In the report *Flexibilitet för ett mer stabilt och driftsäkert elsystem – en kartläggning av flexibilitetsresurser* by Power Circle [33] the area “flexibility” is divided in implicit or explicit flexibility. In particular implicit flexibility includes a voluntary adjustment of the power use to save costs related to variations in electricity price or to lower costs for power tariffs. Explicit flexibility means that the flexibility provider has an agreement, or is active on a flexibility market, to deliver a flexible power use as a service. Figure 6 gives an overview of implicit and explicit flexibility and the different services available based on the type of flexibility.

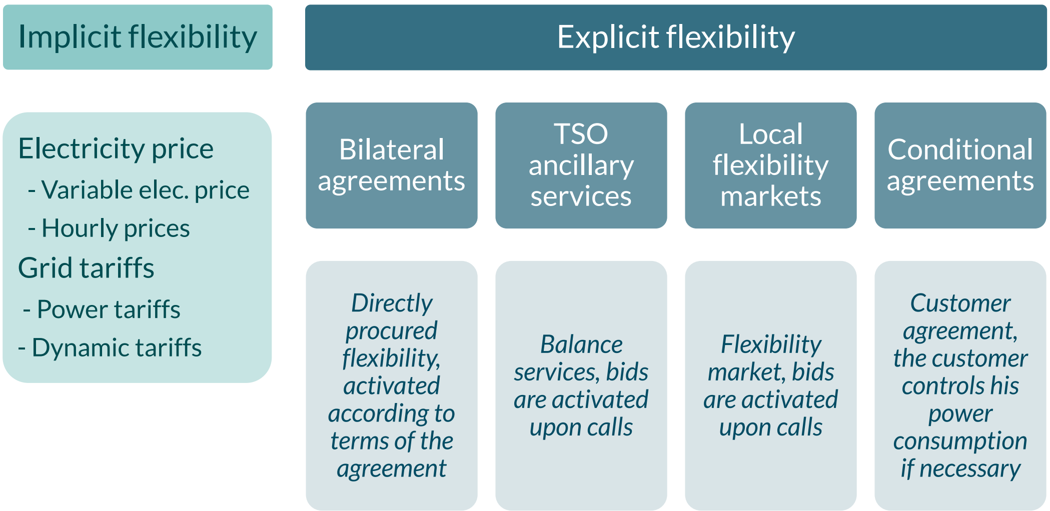

Figure 6. Overview of different flexibility services to the electricity grid, based on [33] with adjustments from the author.

Explicit flexibility has, in this version, been divided in four different types of services, where the markets for the TSOs ancillary services and local flexibility markets have many similarities. The ancillary services are used to stabilize the frequency in the power grid. Local marketplaces for demand response are under development with the aim to support the local grids or reduce problems with bottlenecks. The identified Swedish local flexibility markets today are Effekthandel Väst, SthlmFlex and the now finalized Coordinet project, where Coordinet were located in four different regions. Effekthandel Väst and SthlmFlex are all still in the pilot phase [34]-[36], while the Coordinet project is finalized and at least in the Uppsala region replaced by Uppsala flexibilitetsmarknad. With a bilateral agreement, the flexibility provider has an agreement with, e.g., the grid owner to adjust its power consumption or production according to the terms in the agreement. “Conditional agreements” refer to agreements between network owners and customers that condition the customer’s use of electricity in specific situations. Currently, conditional agreements are used to a limited extent. The primary motivation for customers to enter into such an agreement is the desire for faster connection during periods of network expansion. For network owners, lack of capacity in the higher-level network is a common driving force for conditional agreement forms [33].

One of the main responsibilities of the TSO is to maintain the balance between production and consumption of electricity and thereby stabilize the frequency in the grid. To keep the balance, the TSO, Svensk kraftnät, has a well-established market for ancillary services, see Table 1 for details. The different ancillary services have different requirements and complement each other to cover the required balancing needs [32].

Table 1. Overview of requirement of Svenska kraftnäts ancillary services [32].

	Lowest bid	Volume	Frequency	Activation 1	Activation 2	Endurance	Trade
FFR	0.1 MW	100 MW	49.5 49.6 49.7	0.7 s 1.0 s 1.3 s		30 or 5 s Ready for reactivation within 15 min	Year
FCR-N	0.1 MW	240 MW	49.9–50.1	63% within 60 s	100% within 3 min	1 h	Two (one) day ahead
FCR-D	0.1 MW	<580 MW	49.9–49.5 50.1–50.5	50% within 5 s	100% within 30 s	20 min	Two (one) day ahead
aFRR	5 MW	140 MW	Control signal	100% within 2 min		1 h	A week ahead
mFRR	10 (5) MW	-	Control room	100% within 15 min		1 h	Every hour

Both a decrease and an increase of power consumption can be of interest for the flexibility buyers. In addition, the time it takes to activate a demand response resource is of high importance. A report from the Swedish Energy Markets Inspectorate (Ei) [37] defines the rules for aggregation to implement the EU legislation. The aggregation accuracy is not yet a part of the Ei mission, which means that the accuracy of aggregation is still undefined [38]. Today, the accuracy of delivered flexibility is set to the range of 0.5-5% (for FCR-N, FCR-D, aFRR and mFRR) [39] depending on the type of nameplate power and position in the power system, but this is as of now not applicable to aggregation [38]. The sampling interval today is 1-10 s [32], which means that each flexibility resource needs to report power consumption or production that often. It is still not decided if an aggregator will have to adhere to such a high sampling rate [38].

7 Barriers related to the electricity markets and power grid

7.1 Method

The focus of this chapter is to identify barriers in the electricity market and in the power grid that can hinder a large-scale introduction of demand flexibility from heat pumps in the Swedish electricity system. If possible, alternatives that can handle the obstacles are suggested.

The following methodology has been used for the study. A literature review has been conducted to gain a broader understanding of the subject. Primarily, reports from various government organizations such as the Energimarknadsinspektionen (EI) and Svenska kraftnät (Svk) have been considered, e.g. [40]. The review has been done in order to prepare questions and identify suitable respondents for dedicated interviews. The literature review has been complemented with interviews with relevant stakeholders.

The interviews have focused on gathering information about existing obstacles, regulatory factors, market and grid constraints, and possible solutions to overcome these barriers. Respondents have been selected as likely able to provide a picture of the current situation as comprehensive as possible.

Interviews have been conducted with the following respondents:

- Svenska kraftnät, Svk (Swedish TSO): The contacted individual has extensive experience of Svk's balancing services. The main focus of this interview has been electricity market barriers.
- Vattenfall electricity distribution. The contacted individual has worked on various research projects regarding load flexibility and the power grid. Grid and grid code barriers to load flexibility from heat pumps were discussed in the interview.
- Power Circle (interest organization concerning electrification issues). The contacted individuals have a general industry understanding of both the power grid and the electricity market and what barriers and opportunities exist for load flexibility.
- Ngenic (flexibility service provider). The contacted individual has understanding of technical system aspects of load flexibility and what barriers that exist for the aggregator role. The company represents the flexibility service provider side and has extensive experience of controlling heat pumps in detached houses.
- Energimarknadsinspektionen, EI. The contacted individual has a technical understanding of load flexibility and the legal perspectives for introducing such solutions in the electricity market.

7.2 Results

The results from the interviews and the identified obstacles and possible solutions to overcome them are presented with respect to electricity markets and power grids, respectively.

7.2.1 *Electricity Market Barriers*

These are the primary electricity market barriers for load flexibility from heat pumps. By electricity market barriers, we refer to the obstacles that come by offering load flexibility to the Swedish balancing service markets FCR-D, FCR-N, mFRR, aFRR [41].

Today as a Balance Responsible Party (BRP), one should continuously plan for and if necessary, trade to get in balance. The planning is done per electricity area and is now gradually changing from being done per hour to being done per quarter. If you as a BRP fails to plan in balance, you must pay the costs for your imbalances, that is, what it costs to restore the balance. Today's role as balance responsible, will be divided into two new actor roles, "Balance Responsible Party" (BRP) who is financially responsible for the imbalances that may arise for a market participant and "Balancing Service Provider" (BSP) who provides balancing services such as FCR, aFRR and mFRR. The purpose of the change is to create conditions for increased competition and to give more suppliers the opportunity to offer balance services [42].

The identified barriers are described below.

There are *minimum allowable bid sizes* to participate in the balancing markets. The requirements are on the level of 0.1 MW or more, which requires several heat pumps to reach that volume.

Further, the customers that are aggregated in a bid *must be represented by the same balance responsible party* (BRP). The likelihood of customers having the same BRP is very low, as there are several BRPs in Sweden, which is a significant obstacle to scaling up demand response. The BRP also has the right to deny bids to the balancing market, making a flexibility service provider in a vulnerable position to act on these markets.

A potential solution to manage the BRP issue is to introduce a so-called Balance Service Provider (BSP) role. The design of the BSP role is currently under investigation and not determined, which creates uncertainty moving forward. The current thinking among legislators is that the BSP should take responsibility for all the imbalances it causes - even if it the imbalance is caused by a load flexibility action. This barrier makes it difficult for the aggregator's business model to work as it has to take financial responsibility for the imbalances that arise from load control. The obstacle is difficult to handle, beyond trying to put pressure on the legislators to design the BSP role in a way that is beneficial for aggregators.

Furthermore, it is a market requirement for the balancing service provider to have *real-time measurement* for their flexibility resources. Exceptions may be given if it is difficult or too costly to implement. Real-time connectivity is not required, but the data must at least be sent afterwards to Svk to verify the delivered flexibility.

This can be expensive and technically complicated for an aggregator to establish as individual measurement on the heat pump is not standard today. This obstacle is hard to circumvent. Either real-time measurement needs to be equipped for each heat pump, or the aggregator needs to get an exception from Svk. One alternative might be to use the buildings billing meter for electricity, using the P1/HAN port of the new electricity meters that are installed. However, Svk must give an exception to the aggregator for using such a metering solution.

Another obstacle for heat pumps to participate in the balancing markets is the lack of standards and definitions of load flexibility. For example, there is no standard for verifying delivered flexibility today. Each actor has to describe this by itself. This becomes an obstacle as each actor must put work into defining their own work methods and define how it will measure and evaluate its performance. It will be time consuming and also create potential trust issues from e.g. the market operators and legislators as different actors will work with flexibility in different ways. A natural solution is for Svk together with other relevant actors to design standards and definitions that simplify the work for flexibility providers.

Furthermore, there is a volume limit of about *10%-15% on the FCR market for bids from aggregated resources (centrally controlled resources)* [43]. Today this is not limiting, but a handling of this will be introduced in the future as the pre-qualified supply from these types of resources increases. This means that the market in terms of volume will be limited for load flexibility resources such as heat pumps if these solutions are scaled up.

Each flexibility resource must be accredited by Svk (i.e., approved in advance) to participate in the balancing market. There is something called type-qualification, where aggregation of the same unit can be accredited collectively. Here, it must be described how new units will be added to the aggregation (which must be of the same type as those included in the aggregation from the start). Then, additional units can be added afterward up to a certain level. However, a major change in configuration (new types of units are aggregated or significant up-scale has happened) means that a new prequalification process must be conducted. It is unclear in which cases heat pumps can be included in a type-qualification as there are a large variation in building and heat pump types. If each heat pump installation needs to be accredited by Svk, this presents a major hurdle when it comes to scaling up resources (it will take more time and cost money to add new units to the aggregation).

One way to overcome this hurdle is for demand response from heat pumps to be accredited by Svk per heat pump type and heat pump manufacturer. By doing so, each time that an aggregator wants to add a heat pump to their aggregation pool, it only needs to check that the specific heat pump has already been approved by Svk in the past. If it has been done so, it can be added without accreditation, otherwise, the type of heat pump would need to first go through the accreditation procedure to be approved. This approach by Svk would facilitate the scaling up of load flexibility from heat pumps, but it is not in place today.

7.2.2 *Power grid related obstacles*

Today, there are no direct technical obstacles in the power grid towards controlling heat pumps [44]. It is done to some extent today through services such as Tibber, Ngenic, or the heat pumps' own control services, such as Nibe uplink or IVT Anywhere. These heat pumps are almost exclusively controlled on electricity price.

But if more and more appliances are controlled based on price signals, it can create larger load peaks in the local electricity grids, especially if electric vehicle charging is controlled as well. This could drive a need to expand the electricity networks to handle the higher consumption, or, alternatively, that network owners introduce a power tariff to counteract the negative effects of price control. The power grid tariff will make price control more complex since both the cost for power peaks and the electricity price need to be taken into account. In this way, it is challenging to scale these solutions, especially if electric vehicle charging also becomes flexible.

Another question that is central if demand response is scaled up is which electricity market actor should be prioritized when it comes to flexibility: (i) should the loads be controlled in a way that optimizes the operation of the network owners, or at least is not controlled in a way that jeopardizes their operation? or (ii) Should the flexibility be used to promote the needs of the electricity market, such as balancing services? The needs of the electricity network and the electricity market at a given moment do not necessarily have to coincide, but they can actually conflict.

Most likely, coordinating functions between the central electricity market and the local electricity networks are needed to handle these types of challenges. But such functions are not in place today. This could become a potential obstacle or risk because it is not known how such solutions will be designed and thus affect the profitability of load control.

7.3 Discussion

When introducing flexibility from heat pumps, many problems arise when the solution is scaled up. Examples of this are the introduction of power tariffs to counteract peak loads in local power grids and the bid volume cap in the FCR market. These measures can potentially limit the flexibility potential and reduce incentives for actors to offer flexibility. To handle these problems, careful planning and collaboration between grid owners, authorities, and actors in the energy system are needed to balance the need to avoid overloading the grid.

Another challenge is the lack of standards and the high requirements placed on the delivery of flexibility. These factors can create high entry thresholds for actors who want to participate. To facilitate implementation and promote wider participation, clear standards and guidelines on how flexibility solutions should be designed and function are needed. By establishing uniform standards, the market for flexibility can become more transparent and competitive, which can attract more actors to invest in this technology.

An important factor that affects the implementation of flexibility is uncertainty and risk associated with future regulations and electricity market design. Trust from actors such as Svk and Ei in the technology and its potential is crucial. By collaborating with these organizations and influencing market development, it is possible to create a favourable environment for load flexibility. This may involve including clear frameworks and incentives in the electricity market design to ensure that the technology is utilized and integrated successfully.

8 Technical barriers in the heat pump

8.1 Methodology

The evaluation of the technical barriers focuses on a concept based on using the heat pump manufacturers' cloud and application programming interface (API) to communicate demand response between an aggregator and individual heat pumps, see chapter 5.2 for details. Possibilities and constrains related to the concept have been discussed in an interview study including nine technical experts from the four major heat pump manufacturers in Sweden. Mainly technical issues are evaluated from different aspects and presented in the report. As a complement input from a digital workshop with the project group was used. The workshop thereby included the above-mentioned experts complemented with experts from two energy companies, an association focusing on the electrification and the power system transition and the Swedish heat pump and refrigeration association. The purpose of the interviews and of the workshop was to understand and discuss the opinions and knowledge of the contacted actors in using heat pumps to provide flexibility to the power system, and on how to communicate flexibility information via their cloud solutions.

8.2 The speed of increased or decreased power consumption

The manufacturers have common ground in how fast their heat pumps can be controlled to decrease or increase power consumption. Their auxiliary resistive heaters can be controlled within a second, both for decreased and increased power consumption, but most likely they will need new software to be used as flexibility resources. In normal operation, the use of the auxiliary heater in the heat pump is minimized, to keep performance up. Clear economic incentives are needed if the auxiliary heaters should be used as flexibility resources, in order to compensate for the much lower performance factor and thus higher power consumption.

On/off compressors can also be turned off within a second, but most of them need the brine pump to start before the compressor is allowed to start. This will delay the start with up to a minute. If anti-freeze brine is used, the start delay can likely be removed, but this will need reprogramming of the control systems to be operational. Still one aspect remains unsolved, that is how to make sure that the system to be controlled is actually filled with anti-freeze. Other technical aspects, for example preheating of the compressor pump, could delay startup as well.

The last ten years variable speed drive (VSD) heat pumps have taken a larger and larger share of the market. Today, more than 50% of the ground source heat pumps (GSHP) sales in Sweden are VSD [13]. These heat pumps are significantly slower to control compared to on/off heat pumps. From turned off to the wanted correct speed, it takes several minutes. Based on the interview study turning off the compressor is slow as well, but the field tests indicates that it can be significantly faster, see chapter 9.3. Control wise improvements can likely be done to speed up the process of starting and stopping, but some technical aspects will still limit what is possible.

8.3 Measurement on decrease or increase of power consumption

To be able to provide demand response to the power system, the power consumption needs to be measured or estimated with high accuracy at least at an aggregated level. Measuring the power consumption of today's heat pumps is difficult, as they normally lack electricity meters and installing it afterwards is expensive and need skilled personnel. VSD heat pumps may have the possibility to measure the power consumption within the inverter controlling the speed of the compressor, while on/off compressors have no technical possibility built in to measure power consumption. The manufacturers estimate that the uncertainty of the power consumption of VSD heat pumps is ±2-10%, but this is partly estimated and needs further investigations before conclusions can be drawn.

For on/off heat pumps the manufacturers state the uncertainty from under ±10% to ±20%, meaning much lower accuracy than Svenska kraftnäts requires today. This is due to the lack of electricity measurement, the power consumption is calculated from the operating temperatures of the compressor and known compressor equations. Note that the legislative accuracy demand for aggregation is not yet defined, see chapter 1.5.

The uncertainty of the auxiliary electric heater is stated to be ±0.5-5% if the voltage is known (as it usually is with VSD heat pumps), else the accuracy is lower, as the voltage will vary in the power system. For high accuracy on electricity measurement of the entire heat pump, the power consumption of fans and circulation pumps needs to be monitored as well. It is not clear if these are part of the measurements/calculations that the manufacturers do. The question on accuracy increase with aggregation was not asked in the interviews with the manufacturers, but, according to one manufacturer, the accuracy would increase significantly with larger number of heat pumps. Further studies on the accuracy increase are needed, especially to understand how to validate the anticipated accuracy.

The necessary measurement interval was not discussed with the manufacturers, but a sampling time of 1-10 s as stated today for Svenska kraftnäts ancillary services [27] is likely to be too frequent for today's used control system or for using the buildings electrical meter. A possible solution is extrapolation or other ways of performing high frequency data sampling. As the data management of an aggregator is still pending, it is unclear if the sampling interval will be this short or not [29].

8.4 Communication and requirements

There are no clear thoughts among the heat pump manufacturers on how to communicate to the TSO (Svenska kraftnät) or to an aggregator. An API and the ModBus protocol were mentioned. One of the manufacturers states that it has no interest in taking the aggregator role itself, which could be a possibility, as it does not want that responsibility. Svenska kraftnät has a number of ancillary services to control disturbances in the power system, see Table 1. The possibilities to fulfil the requirements for these services by controlling heat pumps was discussed with the manufacturers.

One manufacturer claims that FFR, the ancillary service with the shortest activation time (0.7-1.3 s), is possible to provide with limited load change, while the others have no answer or answers that “it is difficult”. All manufacturers but one (for which we lack an answer) claims that FCR-N is feasible and for FCR-D, which requires an activation time of 50% within 5 s, all claim that it is possible to fulfil the requirements from a technical point of view. For aFRR and mFRR there are few answers from the manufacturers, since this was not discussed in detail in the interviews, but due to the longer activation time compared to FCR-N and FCR-D, it will likely be possible for heat pumps to fulfil the requirements also for these two services.

The answers should not be interpreted as an indication that solutions are ready, which might well be the case, but rather that the issues in question are technically feasible to solve by adopting such solutions.

8.5 Comfort disturbance at decreased heat production

It was stated by one of the manufacturers that, when the heat is turned off, the thermal comfort risk decreases, as the temperature in the heating system decreases fast, and thus it does not compensate for cold surfaces (e.g.., windows) in the property. Depending on the building envelope, this will have a different impact on the comfort of occupants. Other important aspects are also how the thermal comfort was before the heat was turned off, and how sensitive to temperature variations the people living there are. Earlier studies based on simulations, see chapter 1.3, indicate that it should be possible to shift heating loads in time and still keep a good comfort.

One manufacturer stressed that heat production turned off for one hour could be problematic and that domestic hot water (DHW) is the limiting factor. With a small DHW tank or a high usage, the DHW temperature risks to drop fast, and if the heat pump is blocked new DHW will not be produced.

It was highlighted that underfloor heating (in a concrete slab) should be possible to be turned off without any or small comfort impact, even in winter, as the thermal inertia is very high compared to other types of heating systems.

A concern regarding dimensioning of the heat pump system was raised: With very cold weather, the heat pump could not regain the heat in the building without using the electric backup heater after decreased heat production due to lack of heating capacity. According to the manufacturers, this is not a serious problem, as newer heat pumps generally have spare capacity even at cold spells.

8.6 Comfort disturbance at increased heat production

The question on comfort disturbances at increased heat production was asked generally, and we did not get any feedback about that. Temporarily and unnecessarily high heat production could be of interest in the future, for example in order to buffer heat in a property during the night and then skip heating in the late morning hours that yield congestion in the power system. This needs further discussions to understand what problems could occur. On days with excess electricity production, for example due to windy conditions, buildings with heat pumps could act as heat sinks, i.e., wind turbines could keep producing and not being curtailed. To some extent, DHW could also be used to store energy, but, due to legislative limitations on temperature, the potential is limited without at least temperature regulation added to the outlet. From a technical point of view, the auxiliary electric heater could be used more freely, i.e., without the compressor running. In this way, the heat pump could use more electricity during periods when the power system is in need. Higher electricity consumption, which will be the consequence, will only work at very low electricity prices or other compensations for this aid from the heat pump to the power system. The heat pump manufacturers' control systems do not have this functionality to run the auxiliary electric heater today, which needs reprogramming in order to work.

9 Test and verification

9.1 Methodology

In order to test the evaluated concept in reality, a field test was carried out using three inverter-controlled ground source heat pumps installed in three different single-family buildings based on the heat pump manufacturer's cloud and application programming interface (API) to send control signals to the heat pump and measuring the response of the heat pump. The heat pumps were installed in the south of Sweden and the control commands were sent from RISE office in Stockholm. All the heat pumps were unmodified heat pumps from one manufacturer.

The main scope of the tests has been to evaluate the possibilities to fulfil the demands for Svenska kraftnäts ancillary services (see Table 1 for details), through remote control of heat pumps via the manufacturer's cloud and API.

In the tests, the manufacturer's standard API protocol was used to control the heat pumps like an aggregator would control it. The APIs of the heat pumps provide no direct control functionality neither for increasing, decreasing, turning on, or turning off the compressor, nor for doing the same with the auxiliary heater. The project members have good knowledge of the control of heat pumps and a strategy for using existing API functionalities was defined.

9.2 Increasing the power consumption of the heat pumps

The signal to increase the power consumption was sent serially to the three heat pumps. That is, the first heat pump received the signal a few seconds before the second heat pump, which received the control signal a few seconds before the third one. In the considered setup, which was reused from another project, it was not possible to send individual signals to each heat pump. This meant that only one heat pump, the first one, got a signal that increased the power consumption as intended, see Figure 7 below. The other two ones displayed a smaller or very small power consumption increase, see Figure 7 and Figure 8 below.

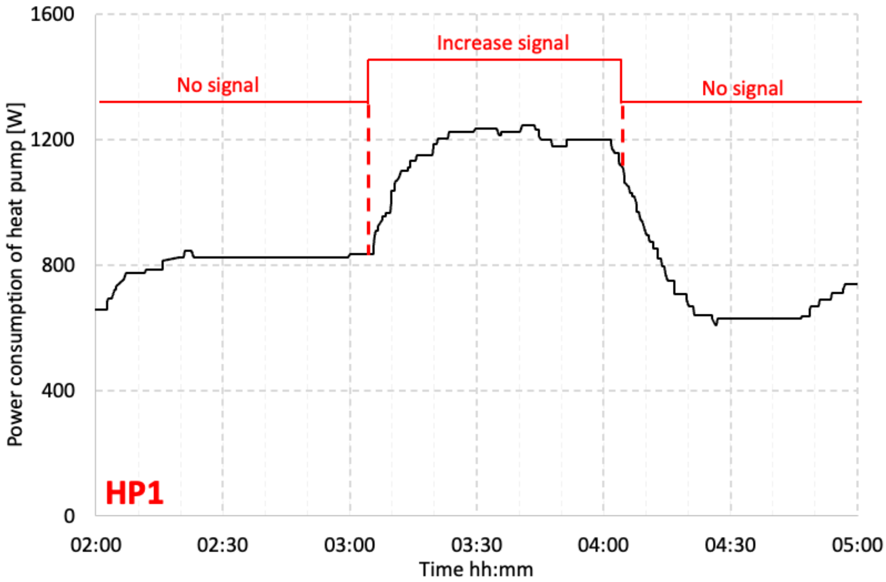

Figure 7. Increase of power consumption on the first heat pump (HP1)

As shown Figure 7 above, the response is slow in increasing the power consumption when the compressor is already running. This is in line with what that manufacturer said but also in line with the other manufacturers statements, see chapter 8. In about 15 minutes, the power consumption had increased around 50%, and the increase was then fairly stable almost until the control signal was removed. After removing the control signal, the power consumption decreased rapidly to an almost 25% lower power consumption compared to when the increase signal was sent. This is logical as the heat production of the heat pump was in balance before the increase signal was sent, and the unnecessary heat produced needs to be compensated.

The power consumption changes of the second and the third heat pumps are shown Figure 8 below.

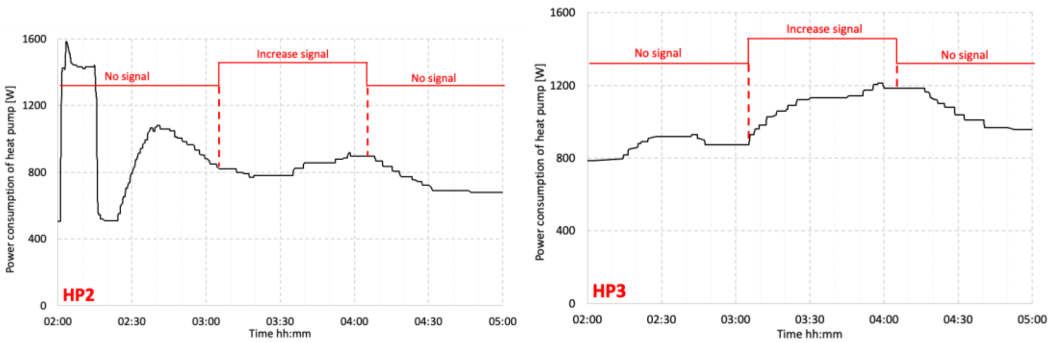

Figure 8. Increase of power consumption on the second (left) and the third (right) heat pump (HP2 & HP3)

The second heat pump was producing DHW from around 02:00 (shown as the square wave form at 02:00-02:15) and was then in a power decreasing phase when the increase signal was sent. The increase signal stopped the decrease of power consumption and kept it steady for half an hour. During the last half hour, the power consumption increased somewhat (around 10 %). To get the second heat pump to increase like the first one, a more aggressive increase signal would have been needed.

The third heat pump initially had stable heat production, with a slight decrease just before the increase signal was sent. The power consumption was increased as the first heat pump, but with a slightly lower increase (35-40%). In contrast to the other two ones, the third heat pump kept the power consumption increase for ten minutes after the increase signal was removed, decreasing after that.

It is evident from these tests that, in order to ensure an effective implementation of increased power consumption commands, specifying the amount of increase is necessary. The commands used in this test, means a learning process is needed in order to understand how each type of heat pump reacts to the commands. Moreover, the heating state before the need for increased power consumption must also be known. To be effective, a command would need to look like this:

"Increase power consumption by 400W from 03:00 to 04:00"

Of course, in a relevant code format and with a stringent time stamp.

9.3 Stopping the heat pump compressor

The second performed test consisted in an attempt to turn off running compressors. This can be useful, with aggregated heat pumps, to help the power system when there is a lack of available electricity. The used off signal will not be disclosed, but the method was very effective, and we have shown that the heat pumps compressor can be turned off for as long as wanted to.

The off signal was sent serially to the three heat pumps like for the increase signal, see chapter 9.2 for details. Each heat pump reacted immediately looking at an hourly timeline, see Figure 9 and Figure 10 below.

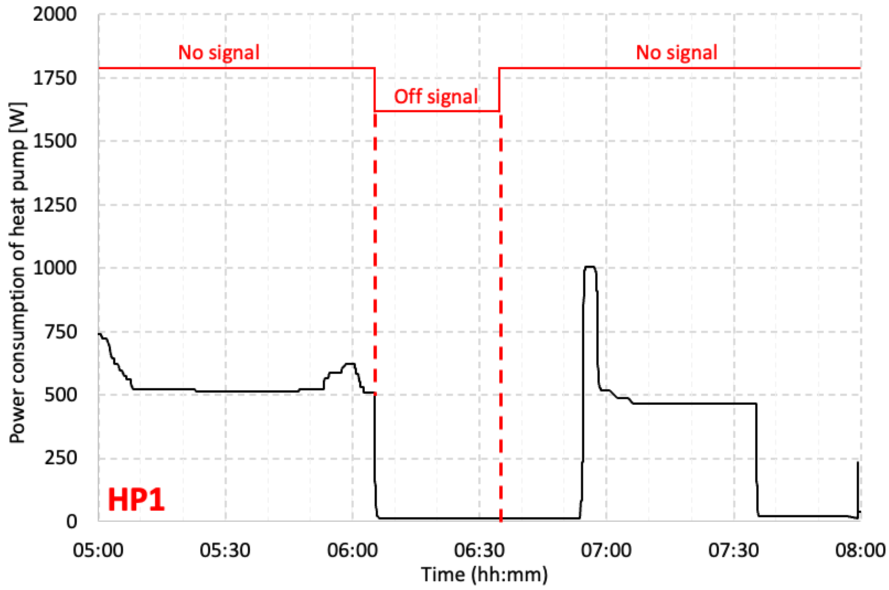

Figure 9. Stopping the compressor of the first heat pump (HP1) with the time scale in hours. Power consumption from manufacturers API.

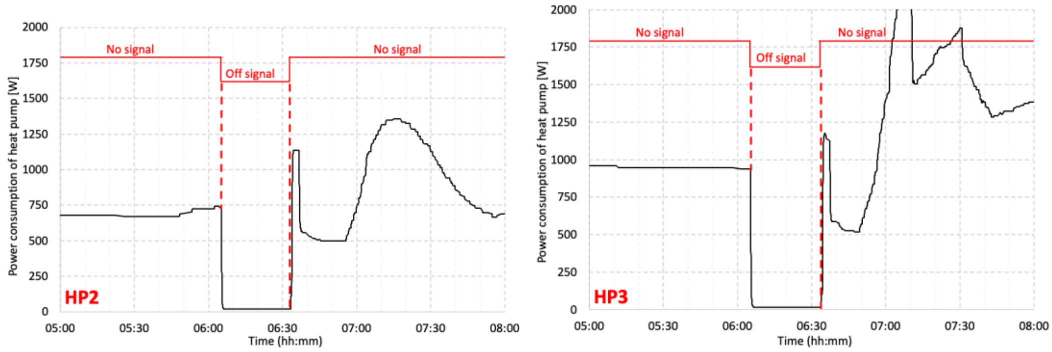

Figure 10. Stopping the compressor of the second (left) and third (right) heat pump with the time scale in hours (HP2 & HP3). Power consumption from manufacturers API.

At a close look, it is evident that the reactions are fast and that the heat pumps are stopped within 5-8 seconds, according to the compressor frequency (blue dashed line, though the manufacturers API) and to the external power consumption measurement (green dashed line) done by RISE, see Figure 11 below. The power consumption measurement according to the manufacturers API (black line) shows a much slower progression, but according to the manufacturer that measurement is incorrect. That measurement is some kind of average of the latter measurements, which means that the progress to the off state will be much slower than in reality. To be used for demand response in Svenska kraftnäts balancing services, the internal measurement of the heat pumps power consumption likely needs to be speed up and controlled better, especially when the faster ancillary services are being targeted.

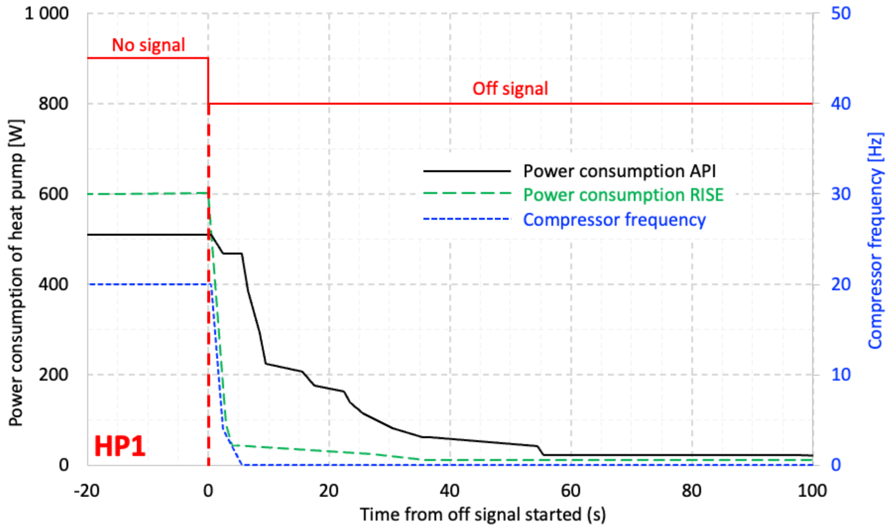

Figure 11. Stopping the compressor of the first heat pump (HP1) with the time scale in <u>*seconds*</u>*. Power consumption (left axis) and compressor frequency (right axis) from manufacturers API with power consumption from RISE as a complement.*

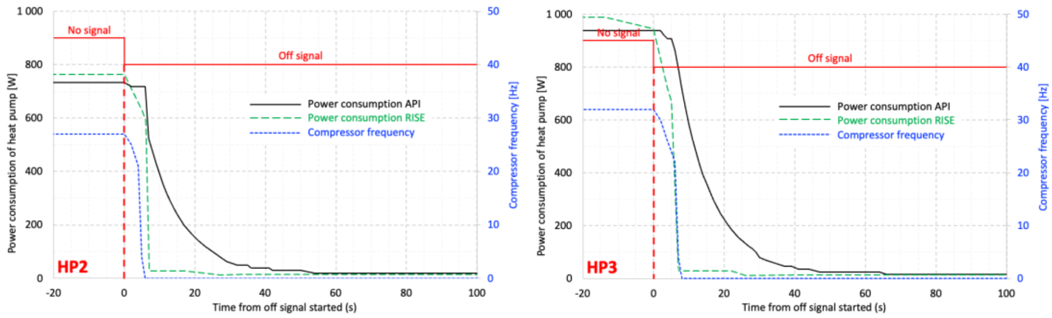

Figure 12. Stopping the compressor of the second (left) and third (right) heat pump (HP2) with the time scale in <u>*seconds*</u>*. Power consumption (left axis) and compressor frequency (right axis) from manufacturers API with power consumption from RISE as a complement.*

Based on Figure 11 and Figure 12 above one can conclude, when detailed checked, that the time to stop the compressor increases with the frequency of the compressor when the stop signal is sent. To investigate the influence of compressor frequency a new test was performed, when the compressor speed first was increased and then the compressor was stopped, see Figure 13 and Figure 14 below.

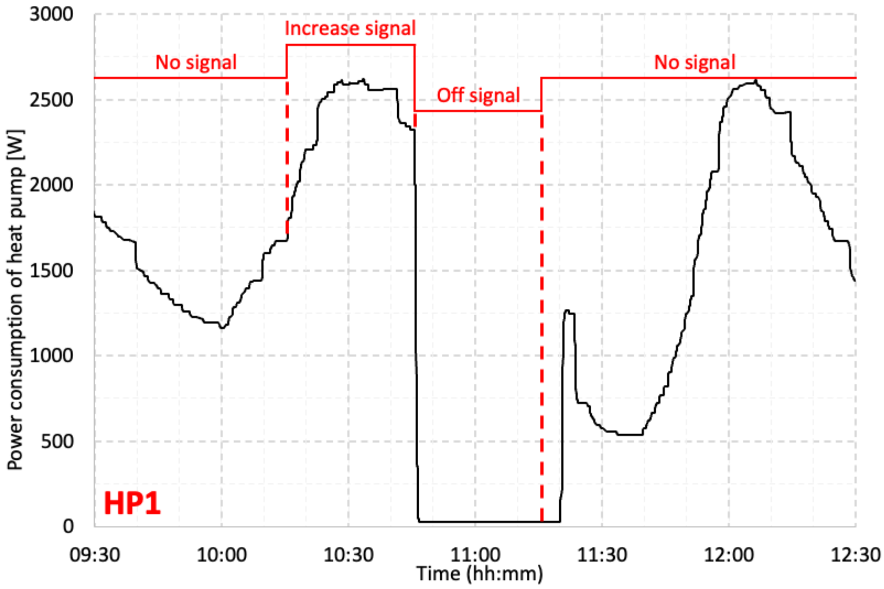

Figure 13. Stopping the compressor of the first heat pump (HP1) with the time scale in <u>hours</u>, after an increase of the compressor speed. Power consumption from manufacturers API.

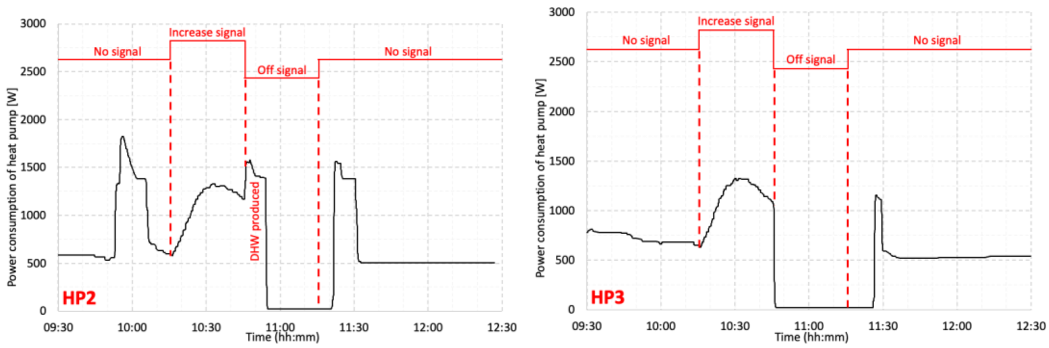

Figure 14. Stopping the compressor of the second (HP2, left) and third (HP3, right) heat pump with the time scale in <u>hours</u>, after an increase of the compressor speed. Power consumption from manufacturers API.

On the hourly time scale the stopping seems immediate, with the exception of the second heat pump where the control system decides to make DHW when the off signal is sent. With the control strategy used we could not control DHW and the second heat pump here shows how problematic this strategy was. Sometimes the heat pump will just ignore stopping the compressor as it is programmed to make DHW as efficient as possible. This amplifies the need for dedicated demand response control signaling to heat pumps to support the power system, where a stop really is a stop *<u>every</u>* time.

Looking at each stop in detail including the earlier tested, see Figure 15, the frequency of the compressor highly influences the time to stop the compressor.

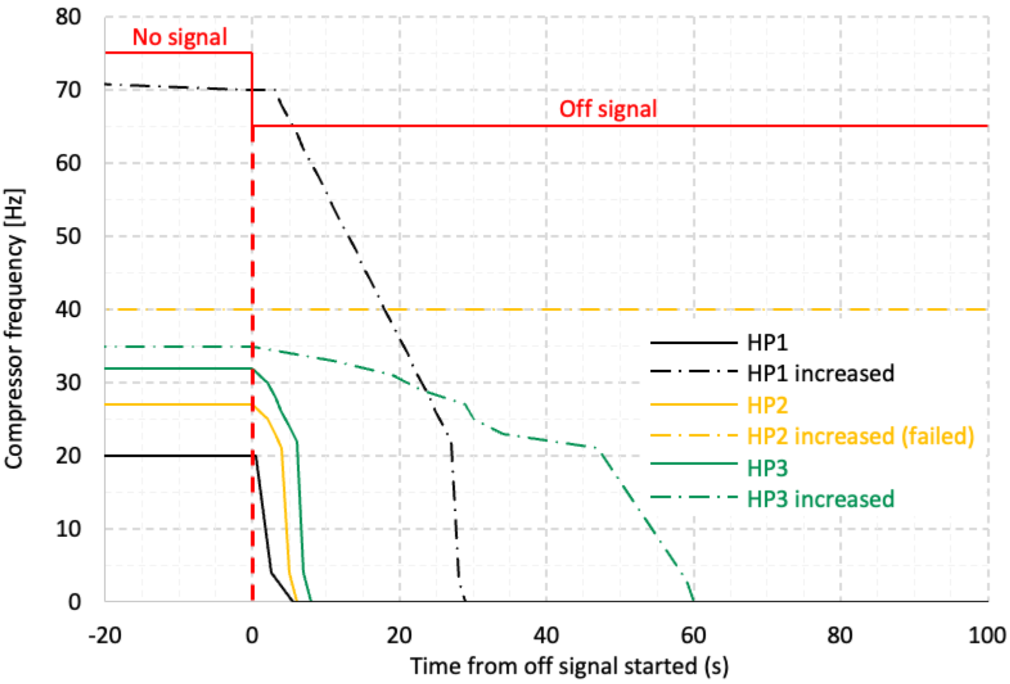

Figure 15. Stopping the compressors with the time scale in seconds, after an increase of the compressor speed. Only compressor frequency from manufacturers API is shown.

The first heat pump (HP1) is running at minimum compressor frequency (20 Hz), thus stopping it takes the shortest time (black solid line), but when we increase the speed of that compressor to 70 Hz before the stop, we had the second longest stopping time measured, around 28 seconds (black dashed line). Without increasing the speed on beforehand the second (yellow solid line) and third heat pump (green solid line) has the same gradient down to 20 Hz as the first from 70 Hz (black dashed line), meaning the rate of decrease of the frequency is normally fixed. The third heat pump (HP3) has after the speed increase a totally different rate of decrease, why is not yet found and the stopping time is very long, 60 second (green dashed line). The second heat pump continued with the same compressor frequency after the increase when doing DHW (yellow dashed line). Operating the same frequency but at higher temperatures means higher power consumption for the compressor type used in this manufacturers heat pump, see left diagram in Figure 14 above. This test was as stated above a failure, which our test method had no possibility to hinder.

9.4 Decreasing the power consumption of the heat pumps

No attempt was done to decrease the power consumption of the compressors, except turning them off (see chapter 9.3 above). In another research project (Bostäder för flexibilitet [21]) RISE has performed tests to control the same heat pumps and the outcome of that project showed that decreasing compressor speed was difficult and sometimes lead to the stopping of the compressor. From those tests we showed that it is likely that decreasing the compressor speed, with the existing control system of the heat pumps, is as slow as increasing the speed as shown in chapter 9.2 above. An example of a rapid decrease in power consumption is seen after the increase signal was removed and the control system tries to quickly rebalance the system, see right diagram of Figure 16 below.

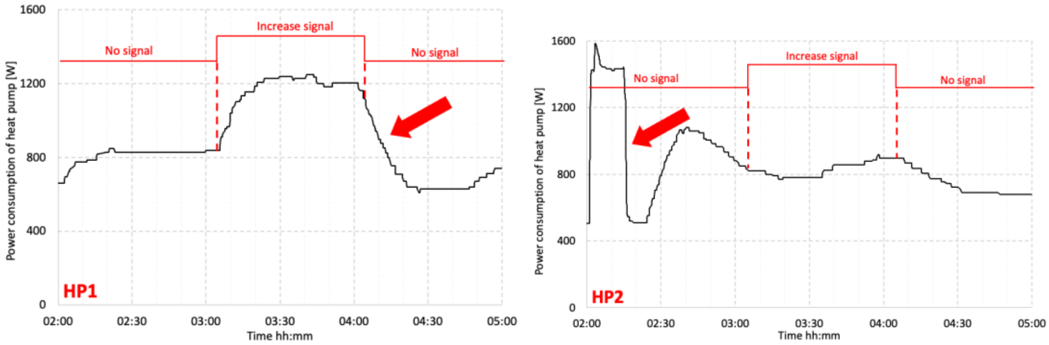

Figure 16. A fast power consumption decrease rate is seen after the increase signal is removed (left) and very fast change when the control system changes from DHW heating to space heating (right). Power consumption from manufacturers API is shown. (Note that these diagrams are copies of Figure 7 and Figure 8 above).

The decrease from 1200 W to 800 W takes around 12 minutes, despite the control system being in unbalance and trying rapidly to fix it. It has been noted that normally the control system decreases the power consumption much slower than this rate. The exception seems to be when the heat pump has made DHW. Then the change rate is allowed to be higher, see right diagram of Figure 16 above.

9.5 Starting the heat pump compressor

Tests within the project have showed that it is possible keep the heat pump turned off as long as wanted meaning, we can during heating season thus start the heat pump as we want, by keeping it off and then send an on signal. This heat pump control system always starts the compressor with the same start-up phase, with a higher frequency (40 Hz) the first minutes, meaning reaching the desired power consumption is slow. See Figure 17 below.

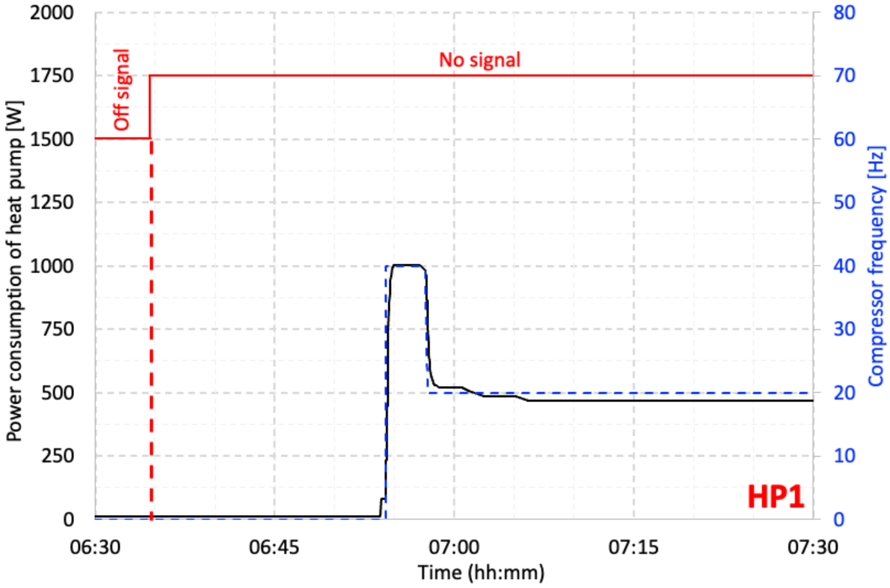

Figure 17. Example of start-up phase of the compressors with a time scale of one hour, when heating need is low. Power consumption and compressor frequency from manufacturers API. Note that the heat pumps heating needs were fulfilled even after the off signal was removed and the heat pump control system started the heat pump with a delay.

As the control system of the heat pump assumes that the heating need is low after a start the compressor it always decreased to 20 Hz directly after, meaning reaching high power consumption from stand still is very slow. Figure 18 below shows an example, where reaching 1500 W of power consumption from the compressor took around 25 minutes.

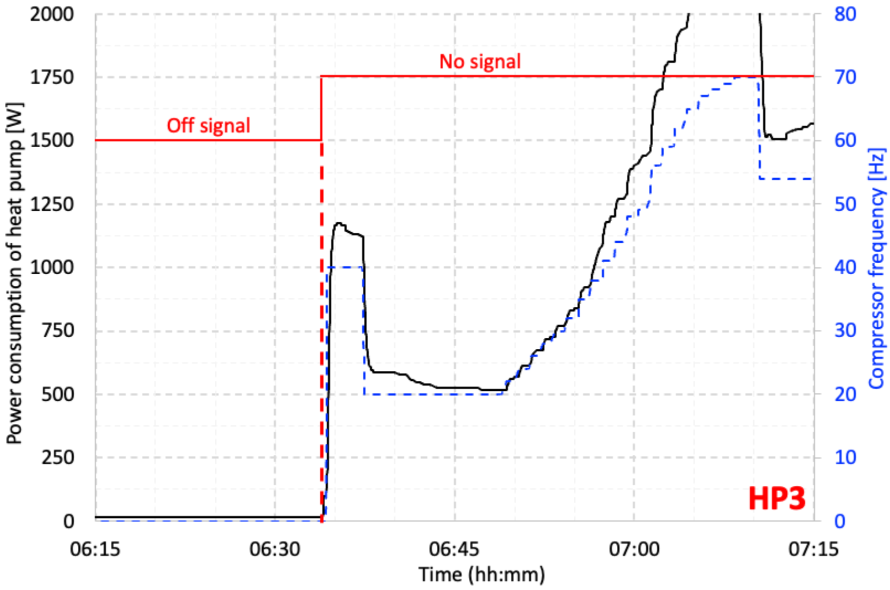

Figure 18. Example of start-up phase of the compressors with a time scale of one hour, when heating need is high (due to imbalance after our test). Power consumption and compressor frequency from manufacturers API.

9.6 The auxiliary heater

Starting and stopping the auxiliary heater needs the compressor to be in operation, it cannot be started just itself with today's control system. Therefore, it was not tested, except when it was started in other tests. We did not see that the auxiliary heater could be started or stopped within a second in our tests, as all the manufacturers state. Either reprogramming or a better test strategy is needed for rapid start or stop of the auxiliary heater.

10 Control signals and communication standards

10.1 Methodology

This work is a continuation and summary of the close collaboration between this project and the work financed by Vinnova that resulted in the report *Standard for load control of heat pumps [4]* which gives additional information within the area.

Flexibility in future Swedish electrical systems is envisioned to solve several different challenges related to variations in electrical power and frequency. In order to address this, appliances like heat pumps, solar cells, batteries and charging stations in buildings are expected to be connected via Internet to aggregators [33].

The focus in this chapter is on communication methods and the most relevant standards that has been identified in this project and the project "Standard för laststyrning av värmepumpar". The communication standards evaluated are mainly higher-level protocols, also referred to as communication middleware, that include application parameters and/or data models. A literature study was conducted with the focus on identifying and getting a high-level overview of available communication protocols suitable for demand response from heat pumps. This was complemented with discussions with project partners about their experiences with the protocols.

The chapter also provides an overview of different alternatives for locating the logic in the communication chain, referred to as the "resource manager," as well as alternatives for calculating the baseline.

10.2 Placement of logic

Demand response information exchange can rely on one-way or two-way communication. For one-way communication, the flexibility service provider (FSP) acts according to a trigger signal and follows a predefined logic. If the FSP can deliver flexibility according to its predefined logic, it will do so. In this case, the flexibility buyer will not receive confirmation if the resource's flexibility potential was activated. However, a DSO could measure the response from a smart meter and calculate the baseline afterward. For two-way communication, signals and feedback are sent directly or indirectly between an FSP and an aggregator. This means that the aggregator could make informed decisions on which FSP resources are available, for how long, and what the response will be when reduced or increased power consumption is needed.

There are several options when it comes to where in the information chain different types of logic, also referred to as "Resource manager" (RM), could be situated. Some options are, but not limited to:

- All logic is situated at the aggregator and information is relayed from the heat pump via the cloud to the aggregator.
- All logic is integrated in the heat pump, and the heat pump sends information regarding its availability continuously to the cloud and the aggregator.
- All logic regarding heat pump availability is calculated at the manufacturers cloud.

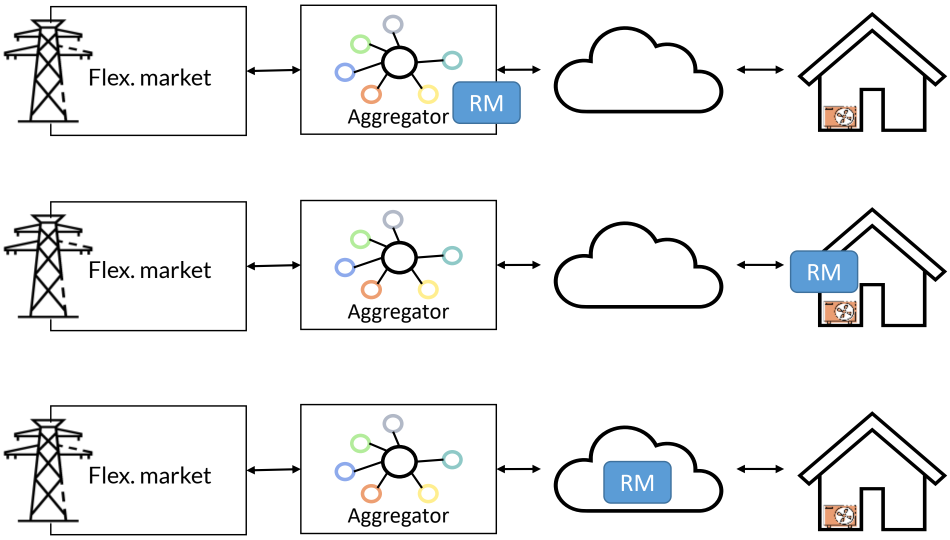

Figure 19. The resource manager (RM) can be located at different locations in the information chain.

Depending on where the logic is situated the information sent between the heat pump, the cloud and the aggregator will be different. However, the information needed could be the same in all cases.

10.3 Communication Standards

Protocols mainly intended for, e.g., electric vehicle charging and building automation are not part of the scope, since they may not contribute to large scale control of heat pumps for electrical grid flexibility. Therefore, protocols like, OCPP, OSCP, ISO 15118, KNX, Modbus, Z-Wave, and Zigbee are not included. For a more complete list of building automation protocols, see [45].

Key factors that are investigated are:

- Availability – how open is the access to the documentation and are there commercial and/or open-source software implementations available?
- Flexibility – which energy flexibility mechanisms are supported, and how well do they match the needs posed by heat pumps?
- Cybersecurity – how well is cybersecurity described and which mechanisms are supported/described?
- Adoption – how is the market adoption in relation the maturity and how is interoperability verified?

10.3.1 EEBus

EEBus is a licence free standardized communication protocol suite for devices that communicate energy information between electrical consumers and producers, like Distribution System Operators, Energy Management System Manufacturers and Device Manufacturers. EEBus is managed by the non-profit organization EEBus Initiative e.V., founded in 2012.

The core protocol of EEBus is called SPINE (Smart Premises Interoperable Neutral-Message Exchange). The SPINE data model in not specific to any domain and enables holistic application by building upon use case specifications. The protocol enables coordination of energy flows between intelligent power grids and individual components in buildings, such as solar panels, battery storage, heating, and EV charging [46]. EEBus needs an Energy Management System (EMS) to manage devices such as heat pumps. As a result, devices can be controlled within the building, without requiring a manufacturer to provide a cloud solution [4].

Availability

The protocol specifications can be downloaded from the EEBus homepage [47][48] at no cost, once registering a free account. The standard is stated not to have any intellectual property associated with it, and while the EEBus initiative in not an accredited standard organization the SPINE data model has been harmonized with CENELEC and the European Smart Appliance Standard EN50631 for white goods [46]. Currently, there seems to be a few open-source implementations available; Enbility [49], with an MIT licence, written in the programming language go, with the source code on GitHub [50], and the Java-based framework OpenMUC [51] driven and maintained via the Fraunhofer Institute for solar Energy Systems in Freiburg, Germany, licenced under GPL.

Flexibility

The EEBus use case solutions are aiming at avoiding conflicting power grid interests when connecting a building, highlighting use cases such as power limitation, tariff management, preventive capacity allocation, and self-consumption optimization [47][48].

Cybersecurity

EEBus Technical Specification Smart Home IP mentions using cipher suites, such as RSA and TLS encryption for WebSocket communication. Devices seems to be possible to be verified via PINs.

Adoption

The current EEBus SPINE protocol version is 1.1.1 released back in December 2018. EEBus has according to their homepage 60 member companies and associations with roughly 10 full-time staff employed by the initiative with the headquarter located in Cologne and an office in Brussels. The initiative is stated to be active in standardization bodies such as, CENELEC, ETSI, DKE and IEC. As mentioned earlier, EEBus in not a standardization body, despite this there seems to be some sort of interoperability tests offered by a company that build EEBus stacks that offer "validation and test soft equipment for EEBus implementations" and the VDE Institute [46]. Furthermore, have new use cases organized joint plugfests an independent testing before publication [46]. However, it is worth noting that both the news on the VDE Institute homepage and the EEBus SPINE specification itself are a few years old, thereby questioning the momentum and adoption by the market. This may mean that the work has moved into other standards.

10.3.2 EFI / S2

The organisation FAN (Flexible Power Alliance Network) behind the EFI/S2 was established in 2013 with the goal to create a broad support base for flexible energy market. The EFI/S2 (Energy Flexibility Interface) is an open-source communication protocol developed by TNO that enables end users to control various smart devices, such as washing machines, air conditioning units, solar panels, and car chargers, in order to enable flexible energy solutions [52]. During the last years EFI has been developed further into "S2", a formal European smart energy standard, approved in 2022 (EN 50491-12-2:2022) [53].

Availability

The protocol specification can be downloaded from the FAN GitHub page [54], at no cost, and there are no claims of associated intellectual property. The EFI 2.0 Specification was updated on GitHub four years ago. Also on GitHub, an Apache 2.0 Licence, an XSD schema, and several XML examples are available. Note that the FAN organization is not a standardization organization although the EFI/S2 protocol is stated to be input to CENELEC EN50491-12-1 [46].

Flexibility

The protocol focuses on flexibility and supports four categories of energy flexibility: inflexible, shiftable, storage, and adjustable. EFI/S2 is stated to be independent of equipment, focusing on the end user's energy need. Market participants like aggregators should not need specific knowledge about the equipment to utilize the flexibility, and it is also stated to be independent of smart grid technology.

Cybersecurity

Cybersecurity is not mentioned in the specification. A note on the scope states EFI/S2 is designed to work on bidirectional communication channels like, XMPP or Websockets.

Adoption

The FAN has 15 members with different areas of expertise and the protocol claims to be used in pilot and commercial projects. It is worth noting that no organized events or certification program seem to be in place [46].

10.3.3 IEC 61850

IEC 61850 is an international standard, established in 2004, for communication in different parts of the electrical grid, but mainly used in electrical substations. While initially focused on sub-station communications, 61850-7-420 has been developed specifically for communication with distributed energy resource assets outside of the substation [55][56].

It enables the integration of all protection, all control, measurement, and all monitoring functions in the station. The data models defined in IEC 61850 can be mapped to several different protocols and the protocols can run over TCP/IP networks or substation LANs.

Availability

IEC 61850 could be used to communicate demand response, but it is not open access and described as complex to its nature. The standard "IEC 61850-7-420:2021 – Basic communication structure – Distributed energy resources logical nodes" is the best alternative to use. From the standard [57]:

"*IEC 61850-7-420:2021 defines the IEC 61850 information models to be used in the exchange of information with distributed energy resources (DER) … DERs include distribution-connected generation systems, energy storage systems, and controllable loads, as well as facility DER management systems, including aggregated DER, such as plant control systems, facility DER energy management systems (EMS), building EMS, campus EMS, community EMS, microgrid EMS, etc.*"

Flexibility

In the standard, a function for power utility automation is achieved by a set of "Logical Nodes" that work together and are distributed over "Intelligent Electronic Devices" (IEDs). IEDs are typically used for protection, control and monitoring. A Logical Node (LN) is a virtual representation of the communication interface for e.g. a device, control function or measurement value. It summarizes multiple data objects that contain numerous attributes including quality, time stamp, etc. Logical Nodes are grouped into "Logical Devices" that are implemented in IEDs. The standard allows free allocation of functionality to various IEDs [59].

From the standard, some important facts can be highlighted [58]:

- In IEC 61850 two types of participants are defined: server (or publisher), and client (or subscriber).
- IEC 61850 is mapped in specific communication services including: 1) SV (Sampled Values). 2) GOOSE (Generic Object-Oriented Substation Events). 3) MMS (Manufacturing Message Specification).

The GOOSE messages contain information that allow the receiving device to know that a status has changed and the time of the last status change.

Cybersecurity

Cyber security technologies for communication protocols in IEC 61850 is based on the IEC 62351 series of standards [60]. The IEC 62351 standards use existing Internet standards whenever possible to meet domain-specific needs.

IEC 62351 also defines the cybersecurity requirements for implementing security technologies in the operational environment, including objects for network and system management, role-based access control, cryptographic key management, and security event logging.

Adoption

IEC 61850 is a part of the International Electrotechnical Commission's (IEC) Technical Committee 57 reference architecture for electric power systems. IEC 61850 started during a conference in 1989 with the development of the Electric Power Research Institute (EPRI) Utility Communications Architecture (UCA). The IEC 61850 standard has become a leading international standard for electrical system communications [55][56].

10.3.4 IEEE 2030.5

The IEEE 2030.5 standard (formerly known as Smart Energy Profile 2 or SEP 2) formalizes the requirements for many aspects of the smart energy ecosystem including device communication, connectivity and information sharing requirements. It is an IP-based application protocol for smart metering and automation of demand response and load control in local- or home-area networks. It can be used in residential and commercial building to connect and manage devices for smart grid operation. The protocol is based on the IEC 61968 common information model and the IEC 61850 information model for distributed energy resource (DER). It follows a RESTful architecture utilizing widely adopted protocols such as TCP/IP and HTTP. The specification not only describes the messages, but it also has an extensive description of registration, discovery, the transport protocol and security [46].

Availability

The IEEE Standard for Smart Energy Profile Application Protocol is available from the IEEE website [61] and IEEE-2030.5-Client is available on Github [62]

Flexibility

The protocol defines device properties that can be manipulated. These properties (also known as "resources") work together in logical groups. The protocol adopts the IEC 61850-7-420 logical node classes for DER components and anticipated extensions are intended to be made consistent with IEC 61850 extensions for DER. The protocol is broad, and the function sets are defined in a generic way, which means that it can be used in a wide range of areas.

The control of a distributed energy resource is based on an “IEEE 2030.5 event”, with a fixed start time and a limited duration. IEEE 2030.5 currently manages multiple different devices in different ways, such as the set point for a thermostat or volume of water for a pump. It also has the possibility to monitor the status of a distributed energy resource, as well as the capability to manage groups of devices, not only single units [55].

Cybersecurity

IEEE 2030.5 meets NIST Cyber Security Requirements NISTR 7268. The protocol uses cryptographic algorithms that comply with the NSA Suite B standard [63].

Adoption

Work on the standard began in 2008 and it formally became an IEEE standard in 2013, adopted as IEEE 2030.5-2013. The protocol has been adopted as the default communication standard for utility communication to residential distributed energy resources (DER) such as solar, storage and EV systems in the state of California in the US [55].

The standard has been updated in order to address gaps in the IEEE 2030.5 specification related to communications with distributed energy resource and to make the standard consistent with IEC 61850 extensions for distributed energy resource. Today, further development of the protocol is being done in an IEEE working group. Test tools are available and used in an "IEEE 2030.5 Conformance Test Program” by two testing laboratories, i.e., one in the US and one in Korea.

10.3.5 OpenADR

Open Automated Demand Response (OpenADR) is sprung from the 2002 California electricity crises. The Demand Response Research Center at Lawrence Berkeley National Laboratory (LBNL) developed the first version of OpenADR, that was donated to the Organization for the Advancement of Structured Information Standards (OASIS) and UCA (Utilities Communication Architecture) International Users Group [4]. This led to a group of industrial stakeholders forming the OpenADR Alliance in 2010, with the mission to foster the development, adoption and compliance of the standard [64].

The OpenADR 2.0 standard allows for two-way communication between DR-resources. It comes in two profiles a and b, where b is the currently most advanced profile. OpenADR is a communication data model, which rely on other standard such as HTTP and XML for data exchange. The standard defines two roles: the Virtual Top Node (VTN) and the Virtual End Node (VEN). The VTNs publish information and the VENs subscribe for it. In OpenADR 2.0, there are several operational services, including, registration, enrolment, market context reporting, dynamic pricing, availability, opt in opt out.

Availability

The specifications can be downloaded from the OpenADR Alliance homepage at no cost and are claimed to have no intellectual property associated with it [46]. While OpenADR Alliance is not an accredited standards organization, the OpenADR 2.0 a and b profiles have been adopted by the OASIS organization. Furthermore, IEC has approved the 2.0.b profile as a full IEC standard, known as IEC 62746-10-1:2018. To foster interoperability, the OpenADR Alliance has published a set of demand response guides, along with organizing interoperability test events, and offering testing and certification tools. There seems to be several open-source implementations of OpenADR. On the Alliance homepage, there is a certified open-source implementation in C-Sharp of OpenADR 2.0b VEN & VTN by Electric Power Research Institute (EPRI) promoted, with the source code on GitHub [65][66]. Another implementation in Python by LF Energy [67] is also available on GitHub [68].

Flexibility

The OpenADR alliance has several examples of different demand response programs. The programs can be found in their Demand Response Program Implementation Guide [69]. Examples using bilateral agreements and aggregators are among the different presented demand response programs, e.g., Critical Peak Pricing, Capacity Bidding Program, Thermostat Program, Fast DR Dispatch, Residential Electric Vehicle DR, Public Station Electric Vehicle Real-Time, and Distributed Energy Resources DR Program.

Cybersecurity

Cybersecurity seems to receive proper attention in OpenADR that refers on their homepage to NIST Cyber Security guidelines and state that security is an important component of the Smart Grid. The OpenADR Alliance maintains its own Public Key Infrastructure (PKI), using server and client-side certificates to ensure that client and servers can mutually authenticate in a strictly controlled way. This results in the requirement for both manufacturers of VTN servers and VEN clients to purchase certificates to achieve mutual authentication. The PKI infrastructure has mechanisms in place for control, authorization, issuance and revocation of certificates. Different certificates for testing, evaluations and productions are offered to manufacturers. The security mechanisms used include the TLS protocol suite, RSA, and ECC algorithms [64].

Adoption

The current version of OpenADR was updated in 2013. The specification is more like a communication middleware as it includes several details to the messages in the protocol, such as registration, transport protocol and security. Certification assistance are offered to Alliance members via a test lab or other facilities, or via a certification testing tool that can be purchased by the members. The Alliance has roughly 130 member companies today, and the database contains more than 100 products. It is worth noting that the standard has been adopted for use in the US, South Korea, Japan, and Canada and are stated to be under consideration in Europe [46].

10.3.6 PowerMatcher

In the EU project EcoGrid 2.0 (Lund & et al, 2016) a control agent called PowerMatcher were developed and tested in order to use for external control of heat pumps. It had the possibility to send an off signal to the heat pump for a certain duration [20].

<u>Availability</u>

The PowerMatcher agent was developed by TNO and is available on an open-source platform [70][71]. In the EcoGrid project, it was concluded that the controllability of the heat pumps using the PowerMatcher agent was limited when it comes to heat pump control as there was only the ability to turn off heat pump systems or block them from starting to run. In the end, the project decided to replace the PowerMatcher device with a simpler price-reactive agent (the “TNO price agent”) [17].

<u>Flexibility</u>

The PowerMatcher control uses a price agent, which sends a stop-signal to the installed heating controllers according to a chosen flexibility degree when the prices were high, and the measured temperature is above a threshold defined by the user. When the lower threshold is met or when the chosen flexibility level is spent, a release signal is sent to the installed system, allowing the heat system to start up again if needed.

The PowerMatcher system can control air to water- and ground source heat pumps. Heat Pumps installed with the PowerMatcher control could choose a minimum temperature threshold and a flexibility degree. For the PowerMatcher agent the flexibility degree equals a temperature band above the lower temperature threshold.

1. Low flexibility gives a temperature band of 1°C
2. Medium flexibility gives a temperature band of 2°C
3. High flexibility gives a temperature band of 3°C

Note that the PowerMatcher only reduces the electricity consumption by stopping the heat pump, the agent cannot actively start the heat pump or control it to increase the electricity consumption, only release it for operation.

<u>Cybersecurity</u>

No information found.

<u>Adoption</u>

There are only a few identified projects using PowerMatcher [72]. One of them, focusing on heat pump control, was the EU-project EcoGrid. No new projects based on PowerMatcher has been identified and no updates have been made to the protocol since 2017, when PowerMatcher 2.1 was released.

10.3.7 SG Ready

Smart grid ready or “SG ready” is a standard for smart control of heat pumps defined by the German Bundesverband Wärmepumpe e.V. [73] and is used in Germany, Austria, and Switzerland. The SG Ready certification helps identify heat pumps that can be addressed via a defined interface for load management for grid support. The interface can be used by network operators to control the device but can also be used for other purposes, like in order to achieve the highest possible self-consumption in combination with a solar power system.

The activation of each mode is done via a digital signal that changes how two terminals are open or closed. The setting of the terminals activates different setting of the heat pump [73].

Availability

The SG ready standard is developed for heat pumps only. Heat pumps that have this function built in can get a “SG ready” label [73]. Today over 2600 heat pump models have the label, meaning it is a widespread standard for heat pumps in German, Austria and Switzerland [74]. For heat pump models with an SG ready label but sold on other markets the models normally have the functionality för SG ready installed even though it is not activated or used. The regulation can be downloaded from the BWP homepage at no cost together with application forms [75].

Flexibility

In the standard, four different heat pump working modes are defined [73][76]:

1. Swished off: Heat pump is switched off, until the storage reaches its lower allowed temperature level. This mode is active for minimum 10 minutes, maximum 2 hours and activated for maximum three times a day.
2. Normal operation: Heat pump operates with normal set-points (hysteresis controller).
3. Recommended on: Heat pump is recommended to switched on, hysteresis is increased.
4. Forced on: Heat pump is switched on, if possible, according to allowed temperature levels. Storage temperatures are increased to the maximum temperature allowed by the heat pump.

When one of the modes are activated, the heat pump is programmed to respond in a certain way. Despite the blocking mode, the heat pumps response to each mode is defined by each manufacturer and is not fully set by BWP. The control is not direct, and the SG Ready documentation does not clearly demand that either. It is thus unclear when and how much the power consumption is reduced or increased when the control signal is received by the heat pump. There is no information back from the heat pump to the aggregator or grid owner.

Cybersecurity

No information found.

Energimyndigheten

Adoption

Version 1.1 of the SG Ready regulations was valid as of 2013 and was followed by an updated version (2.0) in 2020. A lot of heat pumps models available in Germany, Austria, and Switzerland today have the regulation implemented [73][74].

10.4 Baseline and outcome of demand response

In most demand response scenarios, there is a need to verify that the demand response resource has done what it has agreed to do. There are several options for how this could be done. The problem is that all these options come with different uncertainties, i.e., it is not always clear what the real outcome of load controlling a resource for demand response will be. Domestic heat pumps seldom have dedicated power meters, thus giving a high degree of uncertainty.

Some heat pumps on the market today have a function to plan their heat production based on the hourly electricity price, in order to minimize the heating cost. In the future, we might also see other functions that control the heat pump in different ways. For example, this may include controlling the heat pump to lower the buildings power peaks. Hence, appropriately calculating the baseline, e.g., before or after the price adaption is set, could be difficult. There is no single truth for all the methods since one ultimately compares predictions with the outcome of a DR signal.

The report *Baselinemetoder för flexibilitetsprodukter [77]* evaluates seven different methods for baseline calculations with a focus on demand response products currently in use in Sweden. A summary of the investigated methods is shown in Table 2.

Table 2. Baseline calculation methods

Baseline method	Short description
Nomination	A prediction is made by the FPS. The FPS can use different methods
Meter before meter after	Measuring the power consumption right before and right after the DR-signal
Historical baseline without same day adaption	A selection according to some predefined rules are chosen as baseline, either based on a median or mean value for each time.
Historical baseline with same day adaptation	A historical baseline, with some adaptation to the current days data.
Control group	By using a reference group which behavioral patterns are like the FPS the baseline can be defined.
Regression model	A regression model using historical and or external parameters are used to calculate a baseline
Calculation models	A baseline is calculated using external parameters, usually without any historical data.

All methods mentioned above are possible to implement in the case of domestic heat pumps. The source of the data will however differ. Either data will come from an internal electrical meter (which is normally not available in today's heat pumps), or data can be calculated from the heat pumps operational data. A third alternative is to use the grid owner's electrical meter installed in the house. The used method and data could vary from case to case depending on local conditions.

10.5 Discussion

To recommend a specific communication standard among the ones evaluated in Section 10.3 is not easy, but some seems more suitable than others.

The two alternatives which seems to have the most momentum globally today are both from US, OpenADR and IEEE 2030.5. OpenADR is a protocol that is used for demand response and seems to be well adapted for load control of heat pumps. IEEE 2030.5 is a building automation protocol that has been adopted as the default communication standard for utility communication to residential distributed energy resources in the state of California in the US. It seems to cooperate with the standard ICE 61850. Both includes information about how cybersecurity is handled which is an important factor. A disadvantage is that the standards are not yet widely used in Europe. Interesting European alternatives are EEBus and EFI/S2. All four alternatives mentioned can be downloaded for free or be bought at limited costs. Comparing EEBus and EFI/S2, EEBus seems to be more widespread. In addition, we have not found much information about how EFI/S2 handles cyber security, which, if not addressed in a proper way, results in a clear disadvantage.

Compared to the above-mentioned communication protocols IEC 61850 have been a formal standard for several years. However, IEC 61850 is not open access and is described as complex in its nature. Hence, IEC 61850 is for now unlikely to be the preferred choice for the communication link to individual heat pumps. While many standards tend to look attractive on paper, implementing, maintaining, and evolving with the standards may be both a huge and costly effort. Hence, further studies of the specifications with hands on experiments are needed before making any clear recommendations.

Based on discussions with the heat pump manufacturers in the project, it is suggested that the communication between the heat pump and the heat pump cloud services are handled by the heat pump manufacturers. There is no consensus between the manufacturers about how active they think they, as manufacturers and providers of the cloud service, should be in the control of the individual heat pumps for demand response. They have different opinions on whether their cloud services should only forward the signal from the aggregator to the end users heat pumps or if they should process the signals somehow to guarantee the comfort for the end user. They think that standardization of the communication between a potential aggregator and the heat pumps is good in general, but they have no clear recommendations about specific communication standards to use or exactly what information to standardize.

It is worth noting that several building automation protocols and solutions that are built upon them are evolving and start targeting functionality controlling and shaping buildings energy profile, like IEEE 2030.5. As mentioned earlier, this standard originates from the Smart Energy Profile maintained and developed by the same organization as the new home automation standard called Matter that was announced at the end of 2019. One of the most interesting aspects about Matter is that it is a collection of several home automation protocols that are supported by several big companies, such as, Amazon, Apple, Google, Philips Hue, and IKEA. The aim of the standard is to give smart home devices a way to talk to each other, thereby making the home automation faster and more responsive. The standard is developed and maintained by the Connectivity Standards Alliance, formerly known as the Zigbee Alliance, is based on the Internet Protocol (IP) and works through one or several compatible border routers, thus avoiding the use of multiple proprietary solutions. One of the bigger benefits from a resilience perspective is that Matter products run locally and do not require an Internet connection, while the standard is designed and able to talk to the cloud easily. The local system can be used as an Energy or Building Management System (EMS/BMS) that consider different energy consumers, e.g., heat pumps, EV chargers and producers like solar in combination. This may lead to limited/slower adoption from e.g., a roll out point view, as configuring an EMS in each building is time consuming compared to using a manufacturers cloud solution. Nevertheless, solutions like EEBus and Matter will likely be a good complement to individuals wanting to set up their own control systems in their homes.

This project has however focused on a technical solution where the communication between the aggregator and the heat pump is going via the manufacturers cloud service, and thereby these types of solutions have been out of scope since they use alternative ways to communicate with heat pumps. However, it is worth noting that an EMS would add an additional layer of security between the heat pump and the Internet which can be a benefit, due to the longevity of heat pumps. In case of newly discovered cybersecurity vulnerabilities, it may be hard or impossible to upgrade a heat pump that is 10-15 years old.

One trend that has been seen for several of the proposed protocols is that they tend to be combined with other adjacent standards. For example, OpenADR has been combined with EEbus, to give the possibility to communicate to a DSO for controlling the heat pump to provide grid services such as demand response [78].

During the finalization of this project the EU commission has released the final draft of "Code of Conduct on energy management related interoperability of Energy Smart Appliances (V.1.0)". The use cases described that are mandatory for the heat pump manufacturers signing the Code of Conduct are "Monitoring of Power Consumption" and "Limitation of Power Consumption" where the latter "support grid stabilization, prevention of overload in the low-voltage distribution network as well as the prevention of exceeding the maximum value of the grid connection point (technical or contractual)". This work could be of significant value for the standardization of future demand response for heat pumps in EU, but still much work seems to be needed.

11 Cybersecurity

This section overviews the contribution provided in the area of cybersecurity and include two parts, high-level cyber security guidelines and a description of the confidential cybersecurity assessment that has been carried out within the project.

11.1 Methodology

The first section provides high-level considerations and recommendations for the adoption of cybersecurity solutions. The considerations and recommendation were also presented by the RISE Cybersecurity Unit, during the SLAV plenary meeting held on 2022-12-14.

In the second section, it is reported that the Cybersecurity Unit of RISE has performed a first cybersecurity assessment of the networked system of one of the Heat Pump manufacturers participating in the project, hereafter simply referred to as "manufacturer". This activity was based on internal documentation provided by the manufacturer about its networked system for controlling heat pumps.

The performed assessment has focused on aspects related to network and communication security, access control, and management of keying material and authentication credentials.

The results of the cybersecurity assessment build on incremental exchanges between RISE and the manufacturer. The consolidated outcome has been compiled in a confidential technical report, which RISE has shared exclusively with the manufacturer.

11.2 High-level Cybersecurity Guidelines

In the remit of the SLAV project, focus has been put especially on securing the communications between Manufacturers and the respective heat pumps deployed in the fields. Such communications happen to be the most relevant to consider and address from a security point of view, as well as the least controversial.

However, similar considerations are likely to hold also for different communication legs. This is the case, e.g., for the communication leg between Manufacturers and End Users (if admitted altogether), with the Manufacturer as ultimate mediator of the interactions between the two. Another case is the communication leg between Aggregators and Manufacturers, which however requires strong agreement and cooperation between Manufacturer and Aggregator (or that the same entity takes both roles).

While the following points are here put in the context of heat pump operation and management, they are in fact of more general applicability when considering IT- and networked-systems. In the same spirit, one can in general largely abstract away from the particular use case in question and consider heat pumps and backend (cloud) systems as hosts that run Software and are connected to a computer network (typically over the Internet).

From a high-level perspective, a security assessment should be conducted according to the following steps.

1. Consider a real networked system for controlling heat pumps.
2. Consider common and specific security requirements.
3. Look for security vulnerabilities, deficiencies, and gaps, both in the system as such as well as in the security solutions it currently uses. Clearly, the security areas that are possible to consider in this phase depend on the available expertise.
4. Adopt additional security solutions and/or adapt those currently used. This aims at filling identified gaps and fixing flaws altogether, as well as at improving the current security level.
5. If the achieved security level is not acceptable yet, move to step 2 and repeat the process on the latest versions of the system under assessment.

With particular reference to the SLAV project, the expertise available in the project, and the security assessment mentioned in chapter 11.1, focus has been put on investigating the security level of communications among the actors involved in the networked system, throughout the typical workflow of Heat Pump operation. Consistent with steps 1-3 of the approach outlined above, specifically considered areas are encrypted and authenticated communication, access control of users and devices, as well as management of authentication credentials and cryptographic keying material.

When considering security requirements, those can be fairly classified into two categories.

On one hand, some security requirements are high-level, typical and always to be considered in every IT system. Nonetheless, elaborating those requirements requires a clear of at least: i) The network architecture of the considered system (e.g., communications occur over IP and the Internet); ii) the actors involved, the trust assumptions on those and their security relation; iii) how the actors interact at a high-level (e.g., the workflow of their information exchange).

On the other hand, other security requirements are low-level and more detailed, as they are related to specific aspects of used technologies and protocols for (secure) communication. elaborating on these requirements requires to know the details of such used technologies and protocols and of the way they are used.

With respect to the particular security areas mentioned above, the following aspects should be taken into consideration when assessing the security level of the system.

- Network and communication security - This is mostly related to assessing and enforcing the protection of messages exchanged among the communicating parties, with the main intent of fulfilling security properties such as confidentiality, integrity, authentication and replay protection of exchanged messages. These properties can be more difficult to fulfill in advanced setups, such as those providing one-to-many group communication, which might be conducive to better performance. Another aspect relevant within this area is ensuring system availability, e.g., by making the system robust and resilient against (Distributed) Denial of Service (DDoS) attacks.

- Management of authentication credentials and cryptographic keying material - This is mostly related to ensuring that authentication credentials and keying material used in the system are properly and securely managed, with respect to the following aspects: i) their establishment, typically as part of setting up a secure channel or a security association; ii) their update and renewal, which may present additional challenges when considering advanced setups, and that should aim in turn to attain forward security, backward security, and forward secrecy; iii) revocation, which often occurs hand-in-hand with the decommissioning and eviction of a device from the system.

- Authorization and access control - This is applicable to users or devices (generally referred to as "subjects"), to be first of all identified and authenticated. Based on the outcome, the goal is to limit and enforce a subject access only to the particular resources at the particular server hosts, as per the authorization information issued for that subject by an authoritative party. At the same time, it is important to ensure that access control is enforced in a way which is not only secure, but also fine-grained and flexible.

It is worth noting that today there are several available, open standard solutions and protocols that make it possible to address the areas mentioned above. Clearly, they have to be adopted correctly, and they are subject to evolution, update and replacement in the future.

Further areas than those discussed above are certainly to be taken into account and addressed. Although such areas have not been explicitly considered in the assessment activities performed within the SLAV project, the following provides high-level guidelines and considerations on those as well.

- Hardware security - The hardware platforms used in the IT system have to perform their processes and interact with the physical environment according to expectations. At the same time, hardware can be faulty or bugged, or include vulnerabilities and backdoors, which should prompt to decommissioning and replacement when detected. Furthermore, hardware platforms should ideally be tamper-proof, so that tampering with those is practically infeasible of that an authoritative evidence of tampering is promptly made available to system maintainers.

  Practically, service providers and end customers are encouraged to rely on good and trusted device manufacturers. In turn, device manufacturers should rely as much as possible on tamper-proof hardware platforms and enforce the update/maintenance of the Firmware and Software running on their device, also after the end of the warranty period.

- Software security - The Software running on deployed devices has to correctly perform what is expected and as expected from it. Software can be bugged and include vulnerabilities and backdoors.

  Practically, service providers and end customers should rely on good and trusted Software authors, as ensured to release regular updates of running software to be duly installed. Furthermore, when a security issue or vulnerability is found, Software authors should ensure that it gets promptly fixed and documented, and amended by an update released to be promptly installed. After that, it is recommended to not hide the discovered issue or vulnerability, and instead perform a responsible disclosure of the issue itself, together with the now available solutions against it.

As general advice, we believe that the following high-level points especially apply.

- Cybersecurity is about fulfilling **non-operational** requirements. This assumes that the following information is known and well understood: i) the system and network to protect, as well as its properties; ii) the threat and adversary model applicable to the system and network to protect; iii) the amount of resources available to protect the system and network.

- Absolute, total security is **not** attainable. Instead, a realistic goal consists of: i) making an attack practically infeasible to mount for the strongest expected adversary; ii) accordingly deploy preventive and reactive solutions, preferably based on open standards to leverage their public scrutiny, their consensus-based development, and the high-degree of interoperability among different vendors.

- Cyber security is not a "safety net" against the following issues: i) a system badly designed from an operational point-of-view; ii) poorly trained or untrusted personnel, that can easily (be induced to) make mistakes; iii) errors and bad decisions from (honest) human operators and administrators; iv) things that can generally go wrong from an operation point-of-view.

Additional considerations on cybersecurity measures for heat pumps and the electricity grid in Sweden have been compiled by the RISE Centrum för Cybersäkerhet [79] and are publicly available at [80].

11.3 Confidential Cybersecurity Assessment

No security vulnerabilities have been found, while recommendations for improvements in the manufacturer's system and its related internal documentation have been provided. Note that this does not exclude altogether the presence of security vulnerabilities or attack vectors that were not identified while carrying out this assessment, or the possibility for such vulnerabilities or attack vectors to be introduced, enabled or exploited in future versions of the system as it evolves.

From the moment when the execution of this assessment was agreed and until the release of the technical report including the results, the assessment has been carried out in a strictly confidential fashion. In addition, the individuals from RISE who have been involved in the cybersecurity assessment obtained a Swedish Security Clearance before the assessment began to be carried out.

The only communication means used to share information, preliminary outcomes and the final report with the produced results has been a Github repository owned by the manufacturer. Access to such repository has been limited to the few, involved authorized individuals from the manufacturer and RISE, as relying on Github authenticated access based on both two-factor authentication as well as on validation of allow-listed source IP addresses.

Consistently, especially the information and outcomes compiled in the final technical report are strictly confidential and intended only to the manufacturer.

11.4 Discussion

To enable flexibility the heat pumps being part of large-scale flexibility, systems need to be remotely controllable, which as of now means controllable over the Internet. This opens for cybersecurity risks, as for all Internet connected devices. The heat pump industry has historically mainly been a mechanical business, with only the necessary electronics for the fundamental control functionality. Thus, ought to become aware and accordingly extend the organizations and solutions to cover cyber security appropriately.

A few potential ways to compromise (hack) connected heat pumps are:

- Cloud service – could have insufficient isolation between users, be misconfigured, have insufficient physical protection.
- Communication – could be unencrypted, contain safety holes, or have become outdated due to the lifetime of the product.
- Device – could expose services by mistake, contain weak or hardcoded passwords, have unsecure software update.
- Employees – needs to be protected against leakage of sensitive information, either by mistake or by extortion.

RISE has shown that a large-scale cybersecurity attack on heat pumps can already today cause significant impact on the Swedish power system [81]. Moreover, it has been shown that high-wattage IoT devices can cause significant impact to the power system by other authors [82][83]. If large amounts of, e.g., heat pumps are hacked or otherwise manipulated to operate in a non-favourable way, for the power system, this could lead to disturbances in the power system even causing safety mechanisms to trigger. Soltan et.al. [82] has shown the impact on the Polish power system when simulating IoT attacks via air conditioners and heaters. This clearly shows that there is a need to work on adopting and enforcing cybersecurity solutions in the heat pump industry according to the current state-of-the-art and best practices, and to evaluate the system architecture including the communication between individual heat pumps and the server solution.

One of the more challenging effects of cyber security is related to the longevity of the systems. While end-customers traditionally expect a heat pump to last for 15-

20 years, new vulnerabilities may require software and hardware updates. This is an additional cost due to the Internet connectivity that must be motivated and provide an additional value. Furthermore, as high-wattage IoT devices start offering flexibility services to the electricity grid, they become a critical part of the electricity infrastructure. This also includes all the companies involved in the supply chain. Hence, heat pump manufacturers are also expected to face a new set of challenges.

12 Discussion

The focus in the study is on technical aspects of the heat pumps with less focus on thermal comfort in the heated buildings, business models or to get the concept attractive for the heat pump owners. Moreover, the study is focused on explicit flexibility, meaning heat pumps supporting the power system directly with information about the support being exchanged. The alternative to control the heat pumps based on price signals and power tariffs, so called implicit flexibility, has not been evaluated. The benefit of implicit flexibility is the predictability, where the need for challenging fast changes of the heat pump is avoided as the price signal is present long before the flexibility needs to be executed. Heat pump owners were not included in the interviews, meaning we have not investigated their view on demand response and what incentives are needed for them to join it.

The demand response potential in Sweden with cloud solution-controlled heat pumps is as of 2023 several hundred MW when assuming each heat pump will run their compressor at full speed. The potential is increasing with around 150 MW per year at today's installation rate. But each heat pumps compressor is not running at full speed all year around, the power consumption of the heat pump is highly dependent on the ambient temperature, where much more heat is needed during a cold winter day compared to for example a mild spring day. On the coldest days the potential for reducing power consumption could be higher, as many older heat pumps run the auxiliary resistive heater those days. But reducing heating then risk to cool the houses and give a backlash of higher power consumption later. Increasing power consumption of a heat pump could be done most days, but at days with low heating demand the potential could be slim as the heating system in many cases, if not controlled by the heat pump directly, could be closing down the radiators not to overheat the house. Not all cloud enabled heat pumps are really connected to the internet, meaning they cannot be used for demand response. The share of the heat pumps that are connected to the internet is unknown, but the trend of connecting everything to the internet now is clear and soon most newly installed heat pumps will likely be connected to the manufacturers cloud solutions.

The actual monetary incentive is still unclear with flexible heat pumps aiding the power system. Smart price adaption, meaning producing more heat at low-cost hours is not considered a real direct aid (explicit flexibility) to the power system, but is still a clear and easily understandable way to save money. In Sweden this today normally means producing heat during the night, during the heating season, and stopping or running the heat pumps at lower speed at least during the peak hours in the morning and early evening. During summertime there is instead a clear trend for lower prices at mid-day, meaning solar and wind power are decreasing electricity prices when it is warm, sunny, and windy enough.

Giving the power system, on national level, help to manage congestions or loss of power production is already controlled with the products from Svenska kraftnät (the Swedish TSO), but economic model to distribute the income gained is still not fully mature. On local or regional level, the market is even more immature, there are a few research projects ongoing in Sweden.

The benefits with the flexibility concept evaluated in the study is that all hardware needed to control the heat pump for demand response is already in place and many older heat pumps models have had the hardware for several years. This mean the investment costs, but also the effort needed, to use heat pumps as a flexibility resource will be lower compared to the alternatives. It could make the potential for demand response from today’s heat pumps more rapidly accessible for aggregators. What may be missing is whether electricity meters will be required to measure the delivered demand response from the individual heat pumps. Additional hardware to control the heat pump or meters to measure the electricity consumption will require larger revenues for short enough payback time and will slow the process significantly.

But even if the hardware is in place, there are still several barriers to overcome before the system efficiently can be up and running. Standardization is important, to have the communication standardized will make it easier for the parties involved. The aggregators will know better what is possible to achieve and how to control their heat pump pool and the manufacturers will know what to implement in their control systems. In the longer run an international standard would be optimal, avoid developing different solutions in different countries.

During the finalization of this project the EU commission has released the final draft of “Code of Conduct on energy management related interoperability of Energy Smart Appliances (V.1.0)”. The use cases described that are mandatory for the heat pump manufacturers signing the Code of Conduct are “Monitoring of Power Consumption” and ”Limitation of Power Consumption” where the latter “support grid stabilization, prevention of overload in the low-voltage distribution network as well as the prevention of exceeding the maximum value of the grid connection point (technical or contractual)”. This work could be of significant value for the standardization of future demand response for heat pumps in EU, but still much work seems to be needed.

To use many small units aggregated as a flexibility resource is new compared to what historically has been used, when balance services mainly were delivered by large electrical producers and industrial units. Thus, the requirements need to be adopted to these new flexibility resources to give high enough functionality. One typical example is the low accuracy of electricity metering in heat pumps, meaning the measurement of delivered flexibility risk to be low. Today no villa heat pump identified has a dedicated electric meter factory installed. The first alternative method is to estimate the power consumption through the heat pumps inverter or with help from the operating temperatures, this is in the study shown to have low accuracy. The second alternative is to use the electricity meter of the building, but as it is metering the entire building it could have even lower accuracy than the estimations in the heat pump. High accuracy demand will thus be difficult to fulfill and if it later becomes mandatory it will likely erase older heat pumps as a flexibility resource, as it is costly and time consuming to add meters. Possibly aggregating large number of heat pumps could statistically increase accuracy, but that has not been investigated in the project nor how to validate that accuracy.

Heat pumps are distributed over the grid and can also be used to balance the power system locally. New local flexibility markets might be able to adapt their requirements more easily as they are under development and their needs are different. One example is the activation time, where the local markets have no frequency control need and the activation could thus be slower or even planned in advance. This means heat pumps could both deliver flexibility and at the same time decrease the risk of too low comfort.

Delivering flexibility to the power system is a new area for the heat pump industry and these new functions are outside their core business today. It is still open how the heat pump manufacturers are going to handle this new opportunity and how an aggregator can communicate through the heat pump ecosystem. Will any manufacturer see the benefit in taking the roll as aggregator themselves? It could mean more accurate control of the heat pumps as the manufacturer has superior knowledge on their different control strategies and heat pump types compared to any other player. Likely at least some manufacturers will distance themselves from controlling their heat pumps in non-comfort optimized way, which any demand response or flexibility solution risk to do, and simply let another company take the risk. Saving money and at the same time giving the heat pump owners lower comfort level is a delicate path to walk and could risk that company's reputation if it is not handled in a good way.

It has been shown in tests that heat pumps are slow to change speed when the compressor is running but also starting a compressor to a predefined power consumption is slow. It takes several minutes in both cases. Turning off a compressor could often be done within a few second, but variable speed drive compressors are slower, especially from higher speeds. Likewise, the auxiliary resistive heater can be turned on or off in a second, meaning it could be used even for the fastest ancillary services. But to use them the control system of the heat pumps needs reprogramming. Today the auxiliary heater is used as a backup when the compressor is not sufficient or has stopped working for some reason. To use a reprogrammed axillary heater can be a way forward to use heat pumps more actively for demand response. The auxiliary heater is easy to control and might, depending on the system, have spare capacity a large part of the year for down regulation services. But the much lower efficiency of the auxiliary heater means that the economic compensation needs to be high.

One parameter needing further investigations to fully use heat pumps for faster ancillary services is the communication time over internet, to make sure heat pumps always can deliver, in time, what is needed and agreed upon with the TSO. It should be emphasized that being a part of the ancillary services comes with obligations, failing to deliver will lead to penalties from the TSO and could even risk qualification to deliver the service. Today there is a volume limit of about 10%-15% on the Swedish TSOs FCR market for bids from aggregated resources, giving an indication how cautious the TSO is on these new flexibility resources.

13 Conclusions

The project has investigated possibilities and constrains for a concept where residential heat pumps are aggregated and controlled via the manufacturers' cloud service to support the power system with explicit flexibility with focus on Svenska kraftnäts ancillary services, local flexibility markets or bilateral agreements. The study used a variety of research methods including expert interviews, literature review and field tests.

13.1 Barriers related to electricity market and power grid

The electricity market has several barriers that hinder heat pumps from offering demand response, such as:

- There are minimum allowable bid sizes to participate in the balancing markets, making it necessary to aggregate several heat pumps.
- Having the same balance responsible party (BRP) for all customers in a bid is a requirement, but there are several BRPs in Sweden. This makes it hard to find customers with the same BRP and risks to limit the demand response from heat pumps.
- There is a market requirement for the balancing service provider to measure their flexibility resources in real-time. This can be costly and difficult for an aggregator because heat pumps are usually not measured individually today.
- Flexibility has no clear standards or definitions. For instance, how to verify the flexibility provided is not standardized. Each actor has to define this verification on their own.

Trust and collaboration with actors like Svenska kraftnät (the TSO of Sweden) and Ei (The Swedish Energy Markets Inspectorate) are essential to promote demand response from heat pumps.

13.2 Technical barriers in the heat pump

The experts from the heat pump manufacturers have common ground in how fast their heat pumps can be controlled to decrease or increase power consumption.

- The auxiliary heater can change its power in a second, but it may need new software to work as a flexibility resource. On/off compressors can also stop in a second, but they need some time to restart. Variable speed heat pumps are much slower to change their power. They can take minutes to start or stop.
- The experts say that heat pumps can technically meet the requirements for FCR-N and FCR-D services, which need 50% activation in 5s. But they doubt that heat pumps can meet the FFR service, which needs activation in less than 2s.
- The current heat pumps lack electricity meters, giving low accuracy to measurements of demand response delivered. The estimated errors, based

on discussions with the experts are as follows: VSD heat pumps can measure their power consumption with an error of 2-10%. On/off heat pumps have an error of 10-20%. The auxiliar heater has an error of 0.5-5% if the voltage is known, otherwise the error is higher.

13.3 Field tests

Field tests carried out on three inverter-controlled ground source heat pumps in three single-family buildings showed that:

- The response to a control signal to increase the heat pumps' power consumption is slow when the compressor is already running.
- The heat pumps stop quickly when they get an off signal, the heat pumps stop within 5-8 seconds if the compressors run at a low frequency when the stop signal is sent. But the time to stop the compressor increases with the frequency of the heat pump compressor.
- With the control strategy used it was not possible to control the domestic hot water production. If the heat pump makes domestic hot water the stop signal will be ignored. This shows the need for better demand response signals for heat pumps.
- Tests within the project have shown that it is possible during the heating season to keep the heat pump turned off as long as wanted and start it on demand.

13.4 Communication standards

The project has investigated different ways to communicate between the aggregator, the cloud services, and the heat pumps. Seven different communication standards were evaluated, mainly higher-level protocols, also referred to as communication middleware.

OpenADR and IEEE 2030.5 are two US-based standards that have great potential for enabling demand response from heat pumps. OpenADR is a protocol that is used for demand response and seems to be well adapted for load control of heat pumps. IEEE 2030.5 is a building automation protocol that has been adopted as the default communication standard for utility communication to residential distributed energy resources in the state of California in the US. A drawback is that these protocols are not common in Europe today. Interesting European alternatives are EEBus and EFI/S2. All these four standards are free to use or can be bought at limited costs. They are not ranked here as further work is needed to recommend any of them before the others.

13.5 Cybersecurity

Heat pumps need to be controlled over the Internet in order to effectively contribute to flexibility. This can, as for all Internet-connected devices, make them vulnerable to cyberattacks. On top of ensuring secure interaction with heat pumps, a key cybersecurity challenge stems from the long lifespan of the heat pump systems. Heat pumps are expected to operate for at least 15-20 years, but cyber threats will demand software and even hardware updates.

Cyberattacks are a serious issue for the heat pump industry as hacked heat pumps could, at least in the future, cause severe problems not only for the heat pump owner but also to the power system as a whole. RISE has shown in another project that a large-scale cybersecurity attack on heat pumps can already today cause significant impact on the Swedish power system.

A few potential ways to compromise (hack) connected heat pumps are:

- Cloud services – may suffer from poor isolation between users, misconfiguration, or insufficient physical protection.
- Communication – may lack encryption, have security flaws, or become obsolete over time.
- Devices – may unintentionally expose services, use weak or hardcoded passwords, or rely on insecure software update procedures.
- Employees – may inadvertently or intentionally leak sensitive information.

A cybersecurity assessment can help to find and fix the weaknesses in the heat pumps and their IT-system. A security assessment should follow these steps:

1. Pick a real system that controls heat pumps over the Internet.
2. Analyze the security needs that are common and specific.
3. Find the security problems and gaps in the system and its current security solutions.
4. Use new or improved security solutions to close the gaps and fix the problems.
5. If the security level is still not good enough, go back to step 2 and repeat the process with the updated system.

14 Publication list

Scientifically reviewed articles

1. Walfridson et al. (2023). *Large scale demand response of heat pumps to support the national power system*, 14th IEA Heat Pump Conference, 15-18 May 2023, Chicago, USA (see Appendix B)

Other publications

1. Article in HPT Magazine, manuscript to be sent in July 2023.
2. Article in Kyla&Värme, manuscript to be sent in July 2023.
3. Input to IEA Heat Pumping Technology TCP Annex 57 "Flexibility by implementation of heat pumps in multi-vector energy systems and thermal networks". Results from the Swedish project will be included in international reports and dissemination activities from the Annex.
4. The project will be presented in a fact sheet within IEA Heat Pumping Technology TCP Annex 56 "Internet of things for Heat Pumps".

Presentations

1. Termo Webinar, Online, 2023-04-13.

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16 Appendix A. Excluded energy related protocols

Table 3 and Table 4 show some interesting energy related protocols that were omitted, since they do not explicitly support flexibility, aggregators or energy providers.

Table 3. Excluded building automation protocols [45]

1-Wire
BACnet
BatiBUS
C-Bus
CC-Link
DALI
DSI
Dynet
EnOcean
EHS
EIB
INSTEON
KNX
LonTalk
Modbus
oBIX
UPB
VSCP
xAP
X10
Z-Wave
Zigbee

Table 4. Excluded protocols evaluated in TKI Urban Energys report "In-home energy flexibility protocol" [46]

ECHONET Lite
KNX
OCF
OCPP
Modbus