14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

Large scale demand response of heat pumps to support the national power system

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Abstract

In a power system with an increased share of electricity from intermittent renewable sources heat pumps can act as a large, aggregated flexibility resource. This can help to balance variations in electricity production and to reduce problems with bottlenecks in the power system. In this study a concept based on using the heat pump manufacturers cloud solutions to communicate demand response between an aggregator and individual heat pumps is investigated. The manufacturers cloud solutions were first released about ten years ago, meaning numerous heat pumps installed are ready to be used for flexibility with the missing piece being communication. Possibilities and constrains related to the concept have been investigated in an interview study with nine technical experts from the major heat pump manufacturers in Sweden. A workshop with those experts and additional stakeholder complemented it. Several barriers to solve were identified. Heat pumps are difficult to securely control rapidly and thus communicating flexibility control on beforehand has clear benefits. The transmission system operator normally has high accuracy demands, something villa heat pumps today cannot meet as most of them lack electricity meters. Here compromising on accuracy is likely necessary. Alternatives to standardize the communication between the aggregator via the cloud services to the individual heat pumps has been investigated. From a heat pump perspective EEBUS and OpenADR are promising.

Keywords: aggregator; demand response; flexibility; heat pump; load control; power system; smart grid

1. Introduction

In a power system with an increased share of electricity from intermittent renewable sources such as wind and solar, the need for demand response is foreseen to increase, to help balance the variations in electricity production. Examples of problems that demand response from residential heat pumps can help to solve are, e.g., peak shaving, reduce problems with bottlenecks in the power system and avoid curtailment of renewable energy sources. This is done by load shifting, where the heat pumps electricity consumption is moved from peak hours to off-peak hours. A standardized way to control heat pumps for demand response would make it easier for aggregators and network owners to use the potential of heat pumps to provide flexibility to the power system.

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1.1. Scope

The scope of this study is to investigate the technical possibilities and constrains for a concept where residential heat pumps are aggregated and controlled via the manufacturers cloud solution in order to support the power system.

- The focus is on technical aspects, other considerations such as legal, and economical are only briefly described.
- The focus is mainly on conditions and available flexibility products for the Swedish power system.
- The solution evaluated is valid for residential heat pumps with hydronic heating systems, meaning ground source, air-to-water and exhaust air heat pumps, that are connected to a manufacturers cloud service.
- Air-to-air heat pumps are excluded because they are (in Sweden at least) relying on direct electric heating as backup. Turning them off at cold weather will likely cause the electric heaters to turn on contradicting the purpose.
- Comfort issues are not thoroughly investigated as demand response will be voluntary and if comfort is too poor, compared to economic benefit, people will terminate their enrollment. In a demand response system comfort can never be the top priority.
- The focus is on space heating as today’s power system congestion hours are mainly in the wintertime when heating is the major need, and domestic hot water (DHW) has constraints making it difficult to use for flexibility.

1.2. Background

In Sweden, as in the rest of Europe, more and more electricity from weather-dependent intermittent sources is being installed resulting in larger variations in electricity production, see Figure 1 below. In Sweden, there is a political goal that 100% of the electricity should be fossil-free by 2040 [1] [2]. At the same time there is an ongoing electrification of the whole society and several of the roadmaps from “Fossilfritt Sverige”, an initiative to reduce the impact on global warming from different industrial sectors in Sweden, point out an increased electrification as the way forward to reduce the climate impact of the industry [3]. In addition, the Swedish government has published an electrification strategy [4] in order to meet the increasing needs for electricity from renewable sources. The strategy is summarized in twelve points and one of them focus on an increased flexible use of electricity, especially mentioning the need to realize a higher degree of flexible electrical heating. This indicates that an increased load on the power system is to be expected, especially from intermittent sources.

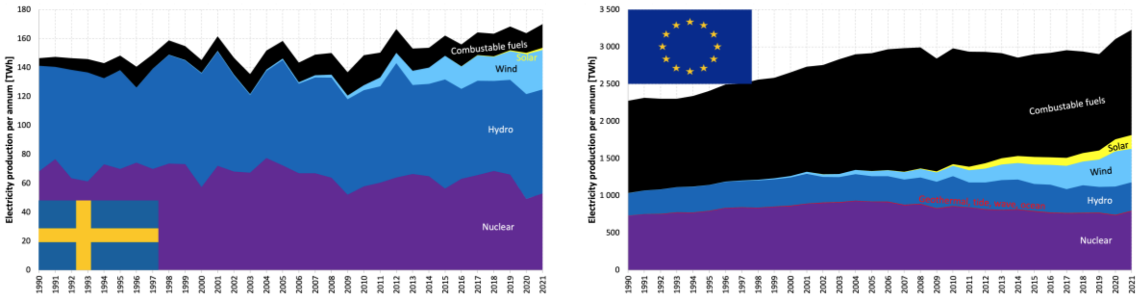

Figure 1. Sources for electricity production in Sweden (left) and EU 28 (right). UK is included, for better readability, in 2020 despite Brexit. Data from Eurostat [5] and the Swedish Energy Agency [6], some data for UK extrapolated in 2020.

Internationally the expected trend with an increasing share of electricity from renewable sources is similar, see Figure 2 below.

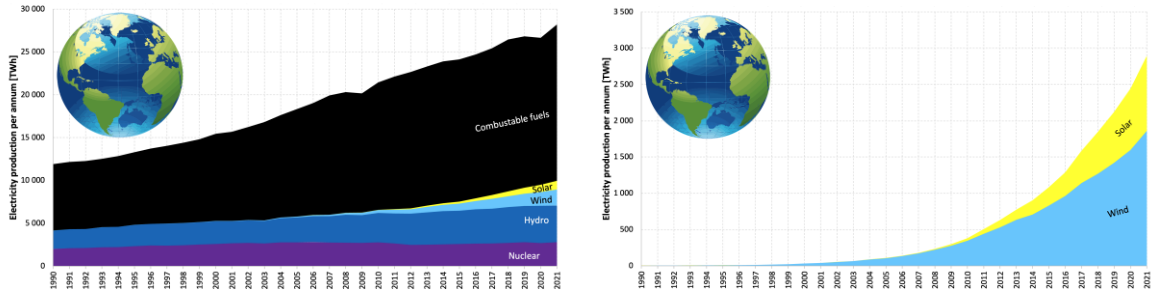

Figure 2. Sources for electricity production of the World (left) and zoom in on wind and solar to see the growth rate (right) [7].

In EUs Renewable Energy Directive towards 2030 [11] there is a binding target for the EU for 2030 that at least 32% of the final energy consumption should come from renewable sources, and there are ongoing discussions to increase the target to 40% as part of the European green deal [10]. Child et.al. has made a scientific forecast that shows how EU will be able to have an almost completely renewable electricity production by 2050. According to the forecast by 2030 60% of the EU's electricity production needs to come from weather-dependent electricity on an annual basis [8].

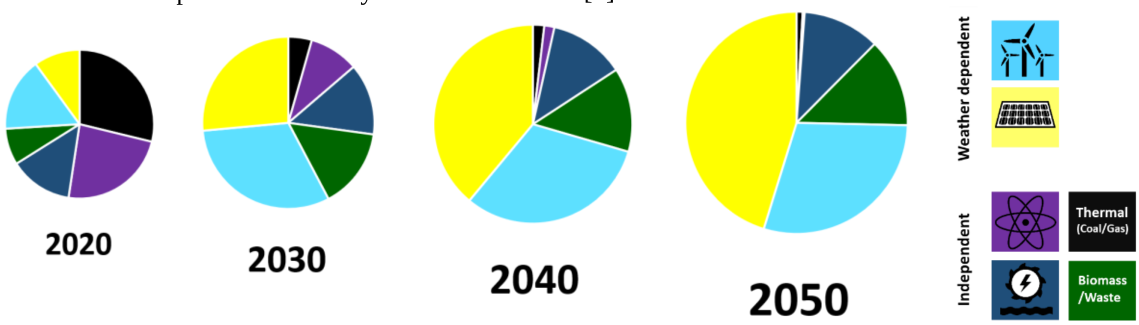

Figure 3. Forecast by Child et. al. [8] to reach a renewable electricity production up to 2050. The diameter of the diagram is proportional to the forecasted electricity produced each year. Note that 2020 also is a forecast here, in reality wind + solar was only 20% in 2020, see Figure 1 above.

1.3. Thermal inertia 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 depends highly on the building's thermal inertia, where heavier building types are more flexible to variable heat production. Weiβ et. al. [9] and Le Dréau and Heiselberg [17] 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, build according to Austrian standards after 1980, at least 50% of domestic heating peak loads could be shifted to off-peak hours during the day, 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 h 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.

1.4. 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 the greatest potential for demand response in Sweden. As described in chapter 1.3 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. But this is a returning load, the loads are only shifted in time and one drawback using heat pumps for demand response is that there is a risk for a new load peak when the heating is started again. Note that, depending on the heating- and ventilation system, a building could have short response to the ambient, especially during cold spells.

Around half of the electricity used by single family houses is used for space heating and production of domestic hot water (DHW), and today there are around 1.5 million heat pumps in operation in Sweden of which 900,000 in hydronic systems, see Figure 4 below. Around 50,000 new hydronic heat pumps are installed every year [13], where many replace older heat pumps.

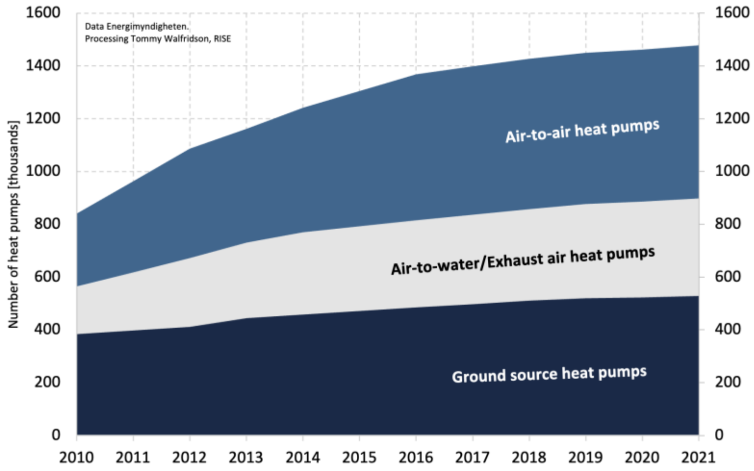

Figure 4. Development of heat pump stock in Sweden. The data source is Energimyndigheten [12] with processing from the author.

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 [22]. 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 [3]. Already today we estimate the theoretical potential flexibility from heat pumps to several hundred MW in Sweden, with an additional flexibility of approximately 125 MW per year from hydronic heat pumps only, as older heat pumps are replaced with new ones.

1.5. Flexibility markets

Using heat pumps for demand response is still in the start-up phase, but there are some potential markets for demand response identified, the most likely are either to deliver ancillary services to the Transmission System Operator (TSO) or flexibility to a local flexibility market. An alternative is to have bilateral agreements with a specific partner 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 all local flexibility markets and all ancillary services from the Swedish TSO, Svenska Kraftnät, the smallest bid size is 0.1 MW or higher [26] [27]. 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 together 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.

In the EU Directive 2019/944 [36] there are requirements 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 markets are primarily used for handle bottlenecks in the grid. In France and UK, the 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 countries identified have finished deploying a full regulatory package on the topic [37]. In Sweden there are a few different local marketplaces for flexibility under development and several of them have run as pilots during the latest years, these include Sthlm Flex [19], Coordinet [20] and Effekthandel Väst [21].

One of the main responsibilities of the TSO is to maintain the balance between production and consumption of electricity. To keep the balance the Swedish 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 [27].

Table 1. Overview of requirement of ancillary services in Sweden [27].

	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) [30] defines the rules for aggregation to implement the EU legislation. The aggregation accuracy is not yet a part of the Ei mission, meaning the accuracy of aggregation is still undefined [29]. Today the accuracy of delivered flexibility is set to the range of 0.5-5% (for FCR-N, FCR-D, aFRR and mFRR) [23] depending on type of nameplate power and position in the power system, but this is as of now not applicable to aggregation [29]. The sampling interval today is 1-10 s [27], meaning each flexibility resource needs to report power consumption or production this often. If an aggregator will have this high sampling rate is still not decided [29].

2. Method

In this study a concept based on using the heat pump manufacturers cloud and application programming interface (API) solutions to communicate demand response between an aggregator and individual heat pumps are investigated. 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 results. As a complement input from a digital workshop was used. The workshop included the above-mentioned experts complemented with experts from two grid owners, a grid owners association and the Swedish heat pump and refrigeration association. The purpose with the interviews and the workshop was to understand and discuss their opinions and knowledge in using heat pumps to provide flexibility to the power system and how to communicate flexibility information via their cloud solutions.

To cover other areas related to demand response from heat pumps the authors of the study have had input and discussions with researchers and project leaders within different research areas from the Swedish research institute RISE, e.g., cyber security, electric power systems and smart industrial automation as well as literature within the field.

3. Concept for external heat pump control

To enable a rapid deployment of heat pumps as a flexibility resource this study investigates the possibilities to communicate the load control to the individual heat pumps via the manufacturers already existing cloud and application programming interface (API) solutions. Using the manufacturers cloud and API solutions requires no hardware changes to get an initial flexibility solution up and running. The investment cost to start using the heat pump 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., [25], have shown that a barrier to use flexibility from heat pumps is to find a beneficial business model for all attending parties.

The manufacturers cloud/API solutions have been in use for approximately ten years, meaning many heat pumps installed are ready to be used for flexibility once the communication is in place. In Sweden all the major hydronic heat pump manufacturers have the functionality for the owners to control and monitor their heat pumps via an app, by connecting the heat pump to the manufacturer's clouds solution. 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 also automatic planning of the heat and DHW production based on the hourly price of electricity is possible for some heat pump models [31]. Control wise there are still pieces missing to be able to deliver flexibility to the power system via these cloud services, but as the hardware is in place since several years the potential is high. Figure 5 show a schematic overview of the proposed communication flow to deliver flexibility from heat pumps to the power system.

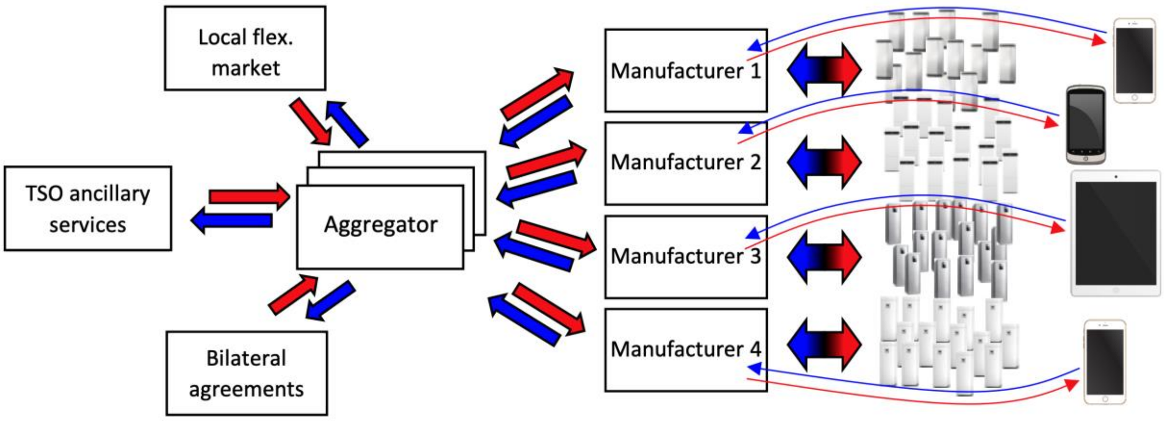

Figure 5. Overview of the communication flow for demand response from heat pumps using the manufacturers cloud solution.

Using the concept proposed in this study the aggregator communicates with the individual heat pumps via the manufacturers cloud services. Depending on how the communication is done and how active the heat pump manufacturer wants to be in the control it gives the manufacturer a possibility to either just forward the control signals to the individual heat pumps or to "translate" the signals for each heat pump type or model. 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, meaning they have the best possibilities to make the heat pump react in the way asked for. Furthermore, this approach adds an additional layer to mitigate cybersecurity risks as the manufacturer can ensure that control signals are withing a reasonable range.

4. Results, evaluation of the concept

In chapter 4 the concept has been evaluated and discussed from different aspects.

4.1. Communication between aggregator and heat pump

With the necessary communication there are signals and feedback sent directly or indirectly between the heat pump and the aggregator. This means that the aggregator could take informed decisions on which heat pumps, or other flexibility resources, that are available, for how long they are available and what the response will be when reduced or increased power consumption is needed.

In most demand response scenarios, there is a need to verify that the agreed change in power consumption has actually happened and there are several options on how this could be done. The problem is that all these options come with different uncertainties, meaning it is not clear what the real outcome of a demand response will be. Domestic heat pumps seldom have dedicated power meters, giving a high degree of uncertainty just there. Examples of functions that can increase the difficulty to calculate the baseline are smart price adaption functionality, meaning the heat pump adapts to the price of electricity or functions to lower the buildings power peaks. Calculating the baseline is thus not trivial. Should it be done before or after the price adaption is set? Huang [28] evaluates seven different methods for baseline calculations with a focus on demand response products currently in use in Sweden.

4.1.1. Placement of logic

There are several options when it comes to where in the information chain different types of logic can be situated. The three main options are:

- The logic is integrated in the heat pump, and the heat pump sends information regarding its availability via the cloud to the aggregator.
- The logic regarding heat pump availability is integrated in the manufacturers cloud.
- The logic is integrated in the aggregator solutions and information is relayed to and from the heat pump via the cloud to the aggregator.

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. It is assumed that the control logic of the normal heat pump operation for space heating and production of domestic hot water is handled locally in the heat pump or in the heat pump cloud service.

There are several different alternative protocols for standardizing the communication between an aggregator and a heat pump to achieve in-home flexibility. A recent study listed several renown protocols, such as OpenADR, EEBUS, EFI, and OCPP [32]. OpenADR was found possible to use alone or in combination with OCPP [33], and EEBUS [34]. From a heat pump perspective EEBUS and OpenADR are promising and are both open access and license free, in opposite to the international standard for communication in the power system, IEC 61850, meaning the hurdle to start using them is much lower.

EEBUS is a European initiative, while OpenADR has its origin in USA, is sprung from the 2002 electricity crisis in California. While the geographical heritage could have relevance to the choice in different regions, cooperation between the two initiatives is seen. None of the initiatives seems to fulfil all needs from an aggregator to individual heat pumps, but hopefully this will emerge from the cooperation. One complete solution, possible to use worldwide would benefit the heat pump industry.

It is worth noting that IEC 61850 is extended with WAN communication and security [35] and should not be ruled out, since if one or more TSOs point out IEC 61850 as their choice the heat pump industry must adapt and offer solutions based on it.

4.2. Technical possibilities and constrains of heat pumps used for flexibility in the power system

The results in chapter 4.2 is based on interviews with the four major Swedish heat pump manufacturers.

4.2.1. 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. The auxiliary electric heater 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 a flexibility resource. In normal operation the use of the auxiliary heater is minimized, to keep performance up. Clear economic incentives are needed if the auxiliary heater should be used as flexibility resource, this 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. Other technical aspect, for example preheating of compressor sump, 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 will take several minutes, often the same is true when turning off the compressor. 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.

4.2.2. Measurement on decrease or increase of power consumption

To measure 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 ±0.5-5% if the voltage is known (as it usually is with VSD heat pumps), else the accuracy is lower as 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 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 accuracy anticipated.

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

4.2.3. Communication to the TSO (Svenska kraftnät) or an aggregator and what product will be possible to fulfill

There are no clear thoughts among the heat pump manufacturers on how to communicate to the TSO (Svenska kraftnät) or to an aggregator. API and ModBus were mentioned. One of the manufacturers states that they have no interest in taking the aggregator roll itself, which could be a possibility, as they don’t 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 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 with limited load change, the others have no answer or answers that “it is difficult”. All manufacturers but one (where 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 claims 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 that solutions are ready, which might well be the case, but rather that they are technically feasible to solve.

4.2.4. 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 to decrease as the temperature in the heating system decrease fast and thus not compensates for cold surfaces (i.e. windows) in the property. Depending on the building envelope this will have different impact on the comfort. How the thermal comfort was before the heat was turned off and how sensitive for variations in temperature the persons living there are also important aspects. Earlier studies based on simulations, see chapter 1.3, indicates that it should be possible to shift heating loads in time and 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 risk to drop fast, and if the heat pump is blocked new DHW will not be produced.

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

Concern regarding dimensioning of the heat pump system was raised, meaning at 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 problem is low as newer heat pumps generally have spare capacity even at cold spells.

4.2.5. Comfort disturbance at increased heat production

The question on comfort disturbances at increased heat production was asked generally, we didn't get any feedback there. Temporarily and unnecessarily high heat production could be of interest in the future, for example to buffer heat in a property during the night to skip heating at later morning congestion hours 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, meaning wind turbines could keep producing and not being curtailed. To some extent DHW could also be used to store energy, but due to legislative limits on temperature the potential is normally low at least without temperature regulation added to the outlet. From a technical point of view the auxiliary electric heater could be used more freely, meaning it could be used 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 don't have this functionality to run the auxiliary electric heater today, it needs reprogramming to work.

4.3. Risks related to cybersecurity

To enable flexibility the heat pumps being part of a 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 historically has mainly been a mechanical business, with only the necessary electronics for the fundamental control functionality. Thus, there is most probably a need to raise the awareness and extend the organizations and solutions to cover cyber security sufficiently.

A few potential ways to recruit (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

It has been shown that high-wattage IoT devices can cause significant impact to the power system [15], [24]. If large amounts of e.g., heat pumps are hacked or otherwise manipulated to operate in a non-favorable way, for the power system, this could lead to disturbances in the power system even causing safety mechanism to trigger. Saleh et.al. [15] has shown the impact on the Polish power system when simulating IoT attacks via air conditioners and heaters. As heat pumps may require similar or higher power, there is a need to work on rising the awareness of cybersecurity in the heat pump industry and 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 involved companies in the supply chain. Hence heat pump manufacturers will face a new set of challenges.

5. 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. Some stakeholders were not included in the interviews (e.g., TSO and heat pump owners) and the study is theoretical and not based on tests or field measurements.

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 several older heat pumps models have had the hardware for several years. This mean the investment costs 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. 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.

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 large 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 accuracy 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 will 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.

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 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 and stopping or running the heat pumps at lower speed at least during the peak hours in the morning and early evening.

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.

6. Conclusion

The study has through expert interviews and literature review investigated the technical possibilities and constrains for a concept where residential heat pumps are aggregated and controlled via the manufacturers cloud solution to support the power system with flexibility. Depending on how the communication is done and how active the heat pump manufacturer wants to be, it gives the manufacturer a possibility to either forward the control signals to the individual heat pumps or to "translate" the control signals for the individual heat pump models. The manufacturers have the deepest knowledge about their products and how to control them, meaning they have the best possibilities to make the heat pumps react in the way asked for with lower risk for decreased comfort.

Technical experts from the four major heat pump manufacturers in Sweden have been interviewed in order to understand and discuss their opinions and knowledge in using heat pumps to provide flexibility to the power system and how to communicate flexibility information via their cloud solutions. The manufacturers are all on somewhat different levels or have different opinions in parts of the discussions, while there is consensus in other parts. As a complement a lively digital workshop with the above-mentioned experts, experts from two grid owners, a grid owners association and the Swedish heat pump and refrigeration association was performed to get consensus on the needed solution and the obstacles still not overcome.

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 electric heater can be controlled within a second, both for decreased and increased power consumption, but most likely they will need updated software to be used as a flexibility resource. 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. Variable speed heat pumps are significantly slower to control. From turned off to the wanted correct speed it will take several minutes, often the same is true when turning off the compressor. From a technical point of view the manufacturers claims that the requirements for the ancillary services FCR-N and FCR-D, where FCR-D has an activation time of 50% within 5 s, is possible for heat pumps to fulfill. While the requirements for FFR, with an activation time of 0.7-1.3 s, seems difficult.

Today's heat pumps lack electricity meters, giving low accuracy to measurements of demand response delivered. VSD heat pumps normally 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%. For on/off heat pumps the manufacturers state the uncertainty around ±10-20%. The uncertainty of the auxiliary electric heater is stated to ±0.5-5% if the voltage is known (as it usually is with VSD heat pumps), else the accuracy is lower.

Alternatives to standardize the communication between the aggregator via the heat pump manufacturers cloud services to individual heat pumps has been investigated. From a heat pump perspective EEBUS and OpenADR are promising. They are possible to use alone or in combination and are both open access and license free. To enable flexibility the heat pumps, 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. It is worth noting that cybersecurity cannot be addressed lightly in the heat pump industry as hacked heat pumps could, at least in the future, cause severe problems to the power system. This means heat pumps risk being used in cyber warfare. After the renewed Russian attack on Ukraine in February 2022 thousands of wind turbines in Germany were attacked and left offline [16], hence the threat is real and should not be underestimated.

Acknowledgements

This work was supported by the Swedish Energy Agency, project "Storskalig laststyrning av värmepumpar i elnätet" [grant number 50258-1] and Vinnova, project "Standard för laststyrning av värmepumpar".

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