ANNEX
57

FLEXIBILITY BY
IMPLEMENTATION OF
HEAT PUMPS IN
MULTI_VECTOR
ENERGY SYSTEMS
AND THERMAL
NETWORKS

IEA Heat Pumping Technologies Annex 57

FLEXIBILITY BY IMPLEMENTATION OF HEAT PUMPS IN MULTI_VECTOR ENERGY SYSTEMS AND THERMAL NETWORKS

Task 4 report: Flexibility Assessment and Analyses of different options

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https://heatpumpingtechnologies.org/annex57/

December 2023

1 Executive Summary

This report includes flexibility assessment and analyses of different options, and focuses on flexibility delivered from heat pumps to support the power grid. Both heat pumps for single family buildings and larger heat pumps connected to thermal grids are included in the scope of the study. The increasing production of electricity from renewable, intermittent sources as well the ongoing electrification of the society increases the demand for electricity and puts pressure on the existing grid infrastructure. Here the need for flexibility to balance variations in electricity production and consumption will increase to achieve a resilient and efficient power system. Flexibility can also help to reduce problems with bottle necks and shortage of capacity in the electricity grids. A sector coupling unit, like heat pumps, can support by connecting the electricity sector with the heating sector. Thereby, heat pumps can provide flexibility to the electric power system by exploitation of thermal inertia and storage capacities available in the heating sector.

Available flexibility services can be divided in implicit or explicit flexibility, where 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.

1.1 Flexibility services to the power grid

There are several identified markets where a heat pump controlled in a flexible way can be active. Heat pumps are already active in some markets, like the Day-ahead market, for others there are still barriers to overcome.

The **Day-ahead market** enables trading of electricity with a lead time of around one day before physical delivery. The market participants can submit their bids and offers based on the most recent generation and demand forecasts for their units. Heat pumps can be operated flexibly in response to day-ahead market prices, which can help reduce operational costs. For heat pumps in thermal grids, it is common to operate them based on the hourly variations in electricity price. The startup time for heat pumps is shorter than that for other heat production units for district heating, like boilers with wood chips. Technically it is possible to start or stop heat pumps almost immediately, but a least in Sweden the district heating companies looks at the longer trends for the electricity price and in practice the minimum running time for heat pumps lasts from at least 3-4 hours to 12 hours in most grids. The reason given by the companies is that frequent start and stop increases the risk of higher maintenance costs, especially for older heat pumps.

The **Intraday market** is conducted after the Day-Ahead market. It allows the market participants to react to schedule deviations or to manage unforeseen changes, for example power plant outages. Active consumers can bid directly on this market (directly or via aggregators). This allows to gain more short-term flexibility and additional revenue. To our knowledge, heat pumps do not regularly operate on the Intraday market today. However, it could be an interesting alternative in addition to other market options, like the day-ahead market or ancillary services.

For customers with larger power demands a price component based on the maximum power peaks might be added, and in recent years some grid owners have started with **power tariffs** also for end-users in single family buildings and this is a slowly growing trend. The introduction of power tariffs makes the control of the large electricity consumers in the home, like the heat pump or EV charger, more complex in order to keep the electricity cost down. The homeowner should not only focus on using electricity when the electricity price is low based on the Day-ahead market, but also keep the buildings power peaks down.

The transmission system operator (TSO) is responsible for operating the transmission system and to ensure that the electricity generation and demand are balanced at any time. This ensures that the grid frequency is kept constant at 50Hz within the synchronous area. The TSO is responsible for outbalancing any unforeseen variations by activating different **ancillary services**. Ancillary services comprise different measures to contain the frequency deviation and restore the frequency to the nominal frequency. The various services primarily in the required response time and duration of activation, i.e. how fast a unit should be able to adapt its load and for how long the unit is able to run at the adapted load. The TSO has six different markets for ancillary services:

- FCR
- aFFR
- mFFR
- FFR
- FCR-D
- FCR-N

Figure 1. Overview activation time for ancillary services

There are international examples of heat pumps in thermal grids participating in TSOs ancillary markets. One example is the CO_2 heat pump in Søndre Felding, which is the first in Denmark to obtain the official qualification to deliver aFRR regulation. In Denmark, this requires a start-up time of maximum 5 minutes and a minimum bid size of 1MW.

Local flexibility markets are under development with the aim to support the local grids or reduce problems with bottlenecks. Since several of the local markets are still in the pilot phase, the requirements to fulfil are still under development. **Renewable Energy Communities** (REC) also work on a local level, where they give heat pumps the possibility to use their flexibility on a community level, which provides different benefits. In Austria, RECs will for example get a reduction of grid tariffs for electricity transferred between participants. Energy communities also allow for more of the generated photovoltaic (PV) electricity to be used on a local level. The energy community can also help to reduce greenhouse gas emissions by sharing renewable energy within the community.

There are also **bilateral agreements**, where the flexibility provider has an agreement with a specific partner, 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.

The **imbalance settlement** is a financial settlement mechanism for balance groups to be charged or paid for their deviations from their schedule (=imbalances). Imbalance settlement is designed to reflect the real-time value of energy by considering both balancing, and wholesale market prices in imbalance settlement prices. The administrative control of the Balancing Groups is carried out by Balancing Responsible Parties (BRP). The BRP is financially liable for its imbalances and is required to submit the resulting internal and external schedules of the Balancing Group to the Control Area Operator or TSO.

1.2 Technical possibilities and constraints

It can be expected that a demand driven operation will result in a larger number of part-load hours, while the operation according to electricity prices will favor an on-off operation to exploit the hours with lowest electricity prices. Supplying ancillary services using heat pumps requires the ability to adapt the load quickly, operate efficiently in part-load and an exact control of the power uptake. In general, the capacity of heat pumps is adapted by changing the load on the compressors. Depending on the compressor set-up there are two common ways for capacity control in large-scale heat pump systems – variable speed drive and on/off compressors. The former is applicable to all systems, while the latter is typically used in systems with many compressors in parallel or in older systems. Variable speed drives enable precise and step-less control of the compressor speed. For low part loads the efficiency does however drop considerably, this is caused by a drop in the efficiency of the electric motor and increased compression losses.

Depending on the type of flexible service, it may be a requirement on the time it takes to adapt the load of the heat pump and on how exact the power uptake needs to be controlled. Some frequency regulation services require the ability to continuously adapt the power uptake, while other only have a requirement on the ramping rate, the minimum duration of the service and the maximum waiting time before the system needs to be able to react again. This operation requires a dedicated control design of the heat pump plant to ensure safe operation of the thermodynamic cycle as quick load changes may lead to sudden changes in evaporation and condensation pressure and thereby increased wear (Meesenburg, Markussen, et al., 2020).

To be able to control the power uptake of heat pumps it is necessary to be able to measure the power uptake and to actively control it. Normally, heat pump controls are set up to be able to control the heating capacity (directly, or indirectly by controlling the source capacity and outlet temperature) and the supply temperature. The power uptake will in this case result from the heat pump operating conditions and heat demand. However, many flexibility applications, like balancing services, require high resolution measurements and guaranteed values of the electric power uptake.

1.2.1 Large heat pumps in thermal grids

There are several factors limiting the ramp-up times of large-scale heat pumps:

- Pressure and temperature fluctuations: Starting a compressor at full speed can cause sudden pressure and temperature fluctuations in the system. These fluctuations may put stress on various components like the compressor, heat exchangers, and others.
- Component stress and wear: The pressure and temperature fluctuations during rapid start-ups can result in increased stress and wear on the components of the Vapor Compression Heat Pump (VCHP). Over time, this can lead to premature failure of the components.
- Heat pump configuration: The aim is to ensure a stable built-up of the thermodynamic cycle. The cycle design influences the achievable ramping times.
- Refrigerant: The refrigerant may influence both the thermal capacity of the system compared to the energy flow rate as well as the required cycle complexity to a certain extend and thereby poses a natural limit of the achievable ramping times.
- Compressor type: Different compressor types behave differently during ramp up, resulting in differences in the required ramping times:
    - Turbo-compressors can adapt their load within a few seconds. The limiting factors are the time constants implemented in the compressor control.
    - Piston compressors: During start-up the pistons are coupled in after each other and the speed needs to be ramped up to full load. This process may be limited by dead times between coupling-in of pistons.
- Load Fluctuations: Rapid starting can lead to load fluctuations in the system, including the secondary streams.
- Peaks in electric load: Fast start-ups can lead to high start-up currents, which stress the electrical infrastructure.

- Initial conditions: Many of the factors limiting the allowable ramp-up times may be reduced if warm start-up can be ensured.
- Absorption heat pumps have longer ramp-up times compared to conventional vapor compression heat pumps, due to larger thermal masses and inherent heat and mass transfer processes.

The flexible operation of heat pumps may lead to increased numbers of start-stop cycles. Before starting up again after a shut-down, a minimum waiting time is typically required. The reason for this is:

- To allow the refrigerant to settle in the foreseen receivers/vessels in the system and to stabilize the conditions within the cycle. This is mainly to ensure that no liquid is compressed in the compressor and that the valve is fed with liquid to ensure a safe and stable start-up.
- To prevent overheating and/or increased wear on the electric motor of the compressor. Typically, large scale motors have a limited amount of consecutive starts as well as maximum starts per year, an example is given below.

1.2.2 Heat pump for buildings

In the Swedish research project SLAV (Lindahl et al, 2023) technical experts from four heat pump manufacturers was interviewed about technical possibilities and constraints to use heat pumps for flexible operation, focusing on heat pumps for single family buildings. The manufacturers have a common ground in how fast their heat pumps can be controlled to decrease or increase the heat pumps 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.

There is also 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. This obstacle can be hard to circumvent. Either real-time measurement needs to be added to each participating heat pump, or the aggregator needs to get an exception from the TSO to instead measure or calculate the delivered flexibility in another way. As the current heat pumps lack electricity meters, alternative ways to measure or estimate the power consumption was discussed with the heat pump manufacturers focusing on the measurement uncertainty. Variable speed drive (VSD) heat pumps may have the possibility to measure the power consumption within the inverter controlling the speed of the compressor. On/off compressors have no technical possibility to measure the power consumption, instead it needs to be calculated based on operating temperatures of the compressor and known compressor equations. Based on discussions with the experts, the estimated measurement uncertainty of the power consumption for VSD heat pumps is 2-10%, while on/off heat pumps have an uncertainty of 10-20%. The auxiliar heater has an uncertainty of 0.5-5% if the voltage is known, otherwise the uncertainty is higher.

1.2.3 Communication protocols

There are different ways to communicate between an aggregator and the heat pumps. In the SLAV project 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 as further work is needed to recommend any of them before the others. There are also several building automation protocols, and solutions that are built upon them, that are evolving and can potentially be used for demand response from heat pumps.

2 Table of Content

3 Introduction

The transition to a low-carbon energy system requires a high penetration of renewable electricity sources, which are often intermittent and variable. This poses challenges for the power system, which needs to balance the supply and demand of electricity at all times. Moreover, the ongoing electrification of the society increases the demand for electricity and puts pressure on the existing grid infrastructure. Here the need for flexibility to balance variations in electricity production or consumption will increase in order to achieve a resilient and efficient power system. Flexibility can also help to reduce problems with bottle necks and shortage of capacity in the electricity grids. An advantage of using a combination of heat pumping technology and thermal networks is the greater flexibility in heat production and storage options that it entails.

The European Union (EU) is committed to achieving a climate-neutral economy by 2050 and has set intermediate targets for 2030. According to the Renewable Energy Directive (EU, 2018), the EU should reach a share of at least 32% of renewable energy in its final energy consumption by 2030. However, this target could be increased to 40% as part of the European Green Deal. In addition, the EU should reduce its greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels as stated in the Climate Law Regulation (European Parliament, 2022). To achieve these goals, the EU is undergoing an electrification of its energy system, which involves the deployment of electric vehicles, heat pumps and other electric devices in various sectors (ENTSO-E, 2023-1). This implies that the electricity demand is foreseen to increase significantly in the future and that a large share of it will be met by renewable sources.

According to the IEA World Energy Outlook dispatchable thermal power plants and hydropower currently provide most of the flexibility to the power system, independent of the time scale (IEA, 2023). However, in future scenarios developed by IEA, much of the additional short-term flexibility will be provided by batteries and demand response, while thermal power plants and hydropower continue to provide seasonal flexibility. The scenarios presented in the World Energy Outlook report predict that the short-term needs for flexibility on a global level will significantly increase in the following years, see Figure 2, showing the results for the “Announced Pledges Scenario”. The main reason for the growing need for flexibility is the foreseen increased use of solar PV, while batteries and demand response are seen as new crucial suppliers of flexibility. Here heat pumps have a role to play supporting the power system with demand response.

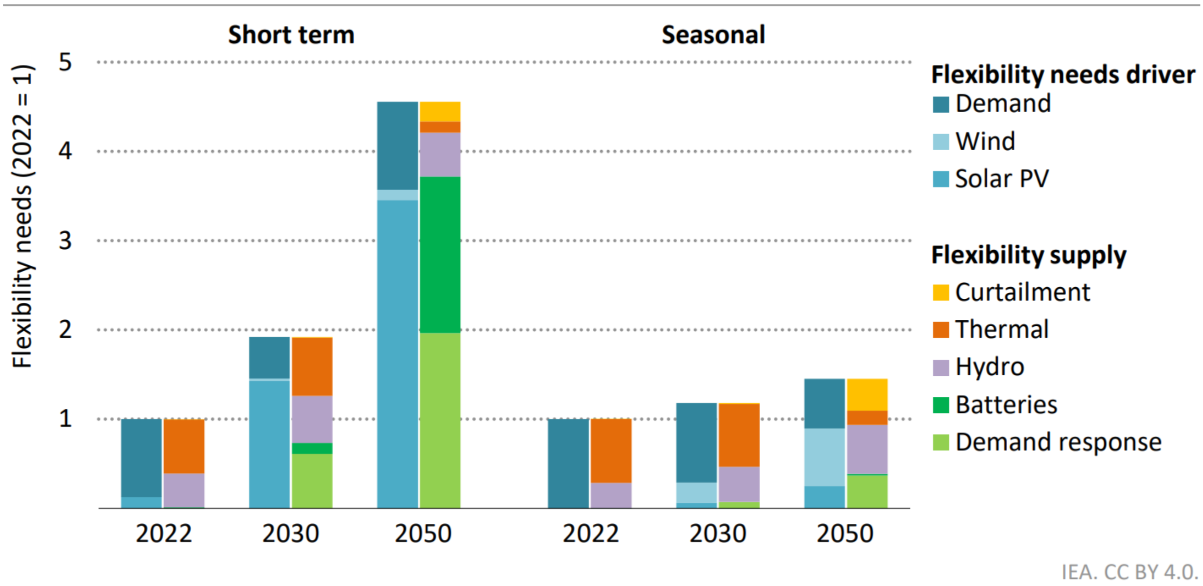

Figure 2. Global power system flexibility needs and supply in the "Announced Pledges Scenario" Source: (IEA 2023)

3.1 Goal and scope

This report includes flexibility assessment and analyses of different options and focuses on flexibility delivered from heat pumps to support the power grid. Both heat pumps for single family buildings and larger heat pumps connected to thermal grids are included in the scope of the study.

3.2 Definition of "flexibility"

First, some terms must be defined to create a common understanding of the meaning of flexibility within the scope of the HPT Annex 57. An increased share of renewable electricity generation can be accommodated in the energy system by better integration between different energy sectors. This can also help to reduce problems with bottle necks and shortage of capacity in the electricity grids. Here a sector coupling unit, like a heat pump, can be supported by connecting the electricity sector with the heating sector. Thereby, heat pumps can provide flexibility to the electric power system by exploitation of the thermal inertia and storage capacities available in the heating sector. This does however mean that the availability of heat pumps to provide operational flexibility is limited by the requirements of the heating side and technical constraints of the heat pump.

Electric- and thermal flexibility

Since heat pumps are part of the electric and the thermal domain, they can provide both electric and thermal flexibility. Electric flexibility of demand side units, such as heat pumps, can be defined as the capability of a plant to change the consumed electric power at a defined node of the electric grid. This electric flexibility can for example be used to support the electric grid, avoid congestion in the distribution grid, provide ancillary services, or participate in the electricity markets (Suna, et al, 2022), (Ester, et al, 2022). The capability of adapting the power uptake or generation can be characterized using three parameters:

- power provision capacity, i.e. by which amount can the power uptake be changed
- ramp rate, i.e. how fast can the power uptake or generation be adapted

- Energy provision capacity, i.e. for how long a change in power uptake can be sustained, this is defined by the available storage capacity in the system.

Along the same lines, thermal flexibility can be defined as the capability of a plant to change the generated or consumed thermal power at a defined node in the thermal grid. This thermal flexibility can for example be used to improve the efficiency of the plant or the thermal grid or to balance fluctuations in heat demand over the year.

Positive and negative flexibility

One can further distinguish between positive and negative flexibility. Positive flexibility can be defined as the increase or upwards regulation in electric power for generators and the decrease in electric power for consumers. Negative flexibility can be defined as the decrease or downwards regulation in electric power for generators and the increase in electric power for consumers (Esterl, et al, 2022). Heat pumps can provide both types of flexibility; they can increase their consumption for negative flexibility and decrease their consumption for positive flexibility.

Short-, mid- and long-term flexibility

Short-term flexibility can be used to balance hourly fluctuations within a day as well as provide balancing services with a really short duration, like the TSO's market for ancillary services where the fastest service (FRR) has an activation time of 0.7-1.3s and a duration of a few seconds. Mid-term flexibility can balance daily fluctuations within a week or weekly fluctuations within a month. Long-term flexibility can balance monthly fluctuations within a year. (Esterl, et al, 2022)

The HPT Annex 57 focusses mainly on short-term and mid-term flexibility, since those are the time scales which can be provided by typical storage in buildings and thermal grids. Long-term flexibility, for example to seasonally shift heat production, requires very large storage facilities and is out of scope of this project.

4 Flexibility services to the power grid

Available flexibility services can be divided in implicit or explicit flexibility (Power Circle, 2022). 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 3 gives an overview of implicit and explicit flexibility and the different services available based on the type of flexibility.

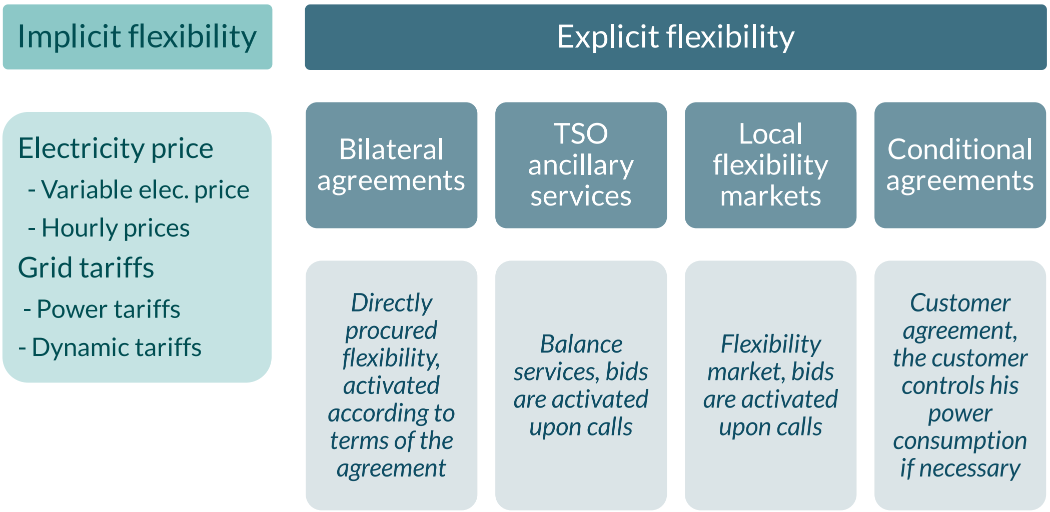

Figure 3. Overview of different flexibility services to the electricity grid, based on (Power Circle, 2022) with adjustments from the author.

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.

There are several technologies that can provide flexibility to the power grid, some examples are EV chargers, batteries or industrial processes like electrolysis (Oliva et al. 2023), but this report focuses on heat pumps.

4.1 Spot market

There are two different spot markets identified, the day-ahead market and the intraday market.

4.1.1 Day-ahead market

The Day-ahead market enables trading of electricity with a lead time of around one day before physical delivery. The market participants can submit their bids and offers based on most recent generation and demand forecasts for their respective generation fleet or demand units.

There are various power exchanges across Europe, where Day-Ahead trading takes place. The largest power exchange in Europe is the EPEX Spot, which offers Day-Ahead trading in thirteen European countries (Austria, Belgium, France, Germany, Great Britain, Luxembourg, The Netherlands, Switzerland, Denmark, Finland, Norway, Sweden, Poland). The products on EPEX Spot are traded via a blind auction, which takes place every day all year round. The European Hourly Day-Ahead coupled auction closes one day before energy delivery at 12:00. This includes all the aforementioned countries, except Great Britain and Switzerland. Results are published as soon as possible from 12:57 for all Day-Ahead coupled markets. The contracts are traded in the form of single hour, quarter hour and block products. The price limit is between -500 and +4000 €/MWh. The minimum tradable volume is 0.1MW and the minimum price increment is 0.01 €/MWh (EPEX Spot Market Operations (2023)). Heat pumps can be operated flexibly in response to day-ahead market prices, which can help reduce operational costs. Usually, the heat pumps will not act directly at the power exchange themselves, but via an electricity supplier. Some suppliers offer variable electricity prices, which closely follow the prices at the power exchange where they are trading at. An example for this is the Austrian supplier aWATTar, who directly bills their customers the hourly day-ahead spot market prices (plus 3% on top for their services) (aWATTar, 2023). They also have a collaboration with the Austrian heat pump manufacturer iDM, who offers heat pumps which can react to those hourly price signals and adapt their heating behavior accordingly.

In Sweden some manufacturers of heat pumps for single family houses, e.g. Nibe and Thermia, has implemented the function to make their premium heat pump models communicate with the electricity exchange Nord Pool in order to get information about variations in the hourly electricity prices the next day. Based on this, heat production can be planned to minimize the heating cost. To make this work the house owner also needs an hourly power contract. (Nibe, 2023) (Thermia, 2023).

For heat pumps in thermal grids, it is common to operate them based on the hourly variations in electricity price. The startup time for heat pumps is shorter than that for other heat production units for district heating, like boilers with wood chips, and technically it is possible to start or stop heat pumps almost immediately. But based on answers from an interview study carried out with Swedish district heating companies with heat pumps in their grids (Song et al., 2023), the heat pumps are not controlled from hour to hour, but the district heating companies looks at the longer trends for the electricity price and in practice the minimum running time for heat pumps lasts from at least 3-4 hours to 12 hours in most Swedish grids. The reason given by the companies is that frequent start and stop increases the risk of higher maintenance costs, especially for older heat pumps.

4.1.2 Intraday market

The Intraday market is conducted after the Day-Ahead market. It allows the market participants to react to schedule deviations or to manage unforeseen events, for example power plant outages. The volume of products sold on the intraday market has increased in the past years, due to the growing share of renewables leading to a larger variation in production and loads. Active consumers can bid directly on this market (directly or via aggregators). This allows us to gain more short-term flexibility and additional revenue.

The largest power exchange for Intraday trading in Europe is EPEX Spot. They enable their market participants to trade intraday products across bidding zones via the European Cross-Border Intraday (XBID) Solution. The price determination is carried out via continuous trading or auctions.

To our knowledge, heat pumps do not regularly operate on the Intraday market today. However, it could be an interesting addition for other market options. First, intraday prices usually have wider spreads than day-ahead prices. If heat pumps can react to those short-term changes, they can profit from even lower electricity prices. Second, short-term trading on the intraday market can help to rebuy electricity after an activation for ancillary services or in case of unforeseeable schedule deviations. All these aspects were examined in the Austrian research project Flex+ (Hemm, et al., 2022).

4.2 Grid- and Power tariffs

For the majority of grid operators in Sweden, the design of grid tariffs is quite homogeneous, being separated into a variable component related to a price per energy unit and a component for fixed monthly cost. The size of the two components is based on the end-users' fuse size. For customers with larger power demands a price component based on the maximum power peaks might be added, and in recent years some grid owners have started with power tariffs also for end-users in single family buildings and this is a slowly growing trend. It is however still only a minority of the grid operators that have implemented capacity tariffs also for the smallest fuse sizes. With increasing fuses sizes, it gets a bit more common, still not very common though, at 80A fuse there are some 50 grid operators with capacity tariffs. Thereby they got a cost structure that better reflects that it is more costly to use capacity when the grid is under strain which gives the end-users incentives to not use to large amount of capacity at any given time.

The introduction of power tariffs makes the control of the large electricity consumers in the home, like the heat pump, more complex in order to keep the electricity cost down. One should not only focus on using electricity when the electricity price is low based con the Day-ahead market, but also keep the buildings power peaks low. In the ongoing research project “När elbilen flyttar in” (RISE, 2023) focuses on control strategies that takes both aspects into account in order to keep the total electricity costs low for a Swedish home with both heat pump and EV charging. Preliminary results shows that the potential saving with a coordinated and optimized control of the heat pump and the electric car charging is several hundreds of Euros per year.

4.3 TSO's market for ancillary services

The transmission system operator (TSO) is responsible for operating the transmission system and to ensure that the electricity generation and demand are balanced at any time. This ensures that the grid frequency is kept constant at 50Hz within the synchronous area. The central tools to ensure a balance between demand and generation are the spot market and the intraday market, as described above. However, neither demand nor generation can be predicted perfectly, and deviations will result in imbalances. The TSO is responsible for outbalancing any unforeseen variations by activating ancillary services. Ancillary services comprise different measures to contain the frequency deviation and restore the frequency to the nominal frequency. The various services primarily differ in the required response time and duration of activation, i.e. how fast a unit should be able to adapt its load and for how long the unit is able to run at the adapted load. The services with the shortest reaction times are called frequency containment reserve and ensure that the frequency does not deviate too much. The services with longer reaction times are called frequency restoration reserve and their task is to bring the frequency back to the nominal frequency and to free up the frequency containment reserve. An overview of the different services is given in Table 1.

Table 1. Overview of ancillary services (EnergiNet, 2023)

		Required reaction time*	Regulation direction	Required duration of activation*	Objective
Central European	Primary frequency reserve or frequency containment reserve (FCR)	≤ 30s to full bid regulation capacity	Upwards- and downward regulation as a symmetric product	N/A	Frequency stabilization
	Secondary frequency reserve or automatic frequency restoration reserve (aFRR)	≤ 5min to full bid regulation capacity	Upwards- and downward regulation as a symmetric product	7 days	Frequency restoration
	Tertiary reserve or manual frequency restoration reserve (mFRR)	≤ 12.5min to full bid regulation capacity	Upwards regulation as an asymmetric product	1 hours	Balance settlement
Primary reserve services in the Nordic regulation zone	Fast frequency response (FFR)	0.7 - 1.3s	Upwards regulation as an asymmetric product	5 seconds	Frequency stabilization
	Frequency containment reserve disturbances (FCR-D)	86 % within7.5s, 100 % within 30s	Upwards regulation and downwards regulation as two asymmetric products	N/A	Frequency stabilization
	Frequency containment reserve normal (FCR-N)	63 % within 60s, 95 % within 3min	Upwards- and downward regulation as a symmetric product	N/A	Frequency stabilization

* Based on data for Denmark

The **frequency containment reserve (FRC)** or primary reserve in central European synchronous area is activated to stabilize the frequency when there is an imbalance between the generation and the demand. All TSOs within the synchronous areas are responsible to deliver a share of the overall FCR demand corresponding to the share of the sum of electricity generation demand within their regulation zone compared to the generation and demand of the total synchronous area. FCR is a symmetric service, meaning that units delivering this service need to be able to provide both upwards- and downwards regulation proportional to the current frequency deviation in the grid. The reaction time for this service is 30 seconds.

The **automatic frequency restoration reserve (aFRR)**, or secondary reserve, has the main purpose to restore the frequency to 50Hz after the frequency has been stabilized by the primary reserve (FCR). When the aFRR takes over the primary reserve is made available again to stabilize any further frequency deviations. aFRR is also used to outbalance deviations from the agreed transport capacities at the cross-border connections. In Denmark, aFRR is a symmetric service, meaning that providers need to be able to regulate upwards and downwards. Current developments include the shift from monthly auctions to weekly auctions with the aim of improving the availability and competition. Further, the European TSO's are working towards an integrated European aFRR market platform (PICASSO). PICASSO has gone live 1st June 2022 and the first TSOs are already coupled to the new platform. It is expected that the TSOs of 20 European countries will connect to the PICASSO by mid-2024 (ENTSO-E, 2023)

Manual Frequency restoration reserve (mFRR) or tertiary reserve aims at restoring larger imbalances in the grid, when activated it frees the secondary reserve and it is used to balance the grid during longer unforeseen deviations in production or demand. mFRR is an asymmetric service, meaning that upwards regulation and downwards regulation are traded separately. The manual reserves are currently being integrated into a common European market platform called MARI, similar to the integration of the secondary reserves.

The **fast frequency reserve (FFR)** has been introduced in 2020 to be able to react to imbalances in the system in situations where the inertia in the grid is low. This is the case in hours with large shares of renewable electricity generation and few thermal power plants in operation. The fast frequency reserve (FFR) is activated in around a second to absorb large drops in frequency by instantaneous upwards regulation, typically by cutting the power uptake of demand side units or by increasing the electricity production of fast responding units already being in operation.

The frequency containment reserve is divided into two services, **FCR-D (Disturbance)** and **FCR-N (Normal operation)**. FCR-D is also called primary reserve and is similar to the FCR service in the central European synchronous area. Upwards regulation and downwards regulation are two separate asymmetric services. Units supplying FCR-D need to be able to deliver 86% of the bid capacity within the first 7.5 seconds and the full bid capacity needs to be available within 30 seconds (based on the requirements for Denmark). The service is activated at deviation larger than 0.1Hz and the activated capacity is proportional to the deviation in frequency up to a maximum deviation of 0.5Hz (corresponding to 100 % activation of FCR-D). FCR-N is activated for frequency disturbances of up to 0.1 Hz (positive and negative). It is a symmetric service, and the activated capacity is proportional to the frequency deviation within the frequency band between 49.9Hz and 50.1Hz. Both FCR-D and FCR-N are activated automatically based on a frequency measurement in the grid.

The Danish TSO, Energinet, predicts an increasing demand of all ancillary services, mainly due to increased electrification and increased shares of renewable electricity generation in Europe.

4.4 Local flexibility markets

Local marketplaces for demand response are under development with the aim to support the local grids or reduce problems with bottlenecks. In Sweden as an example there are a few identified local flexibility markets today, Effekthandel Väst in the Gothenburg area, SthlmFlex in Stockholm and the now finalized EU-project Coordinet, where Coordinet were located in four different regions. Effekthandel Väst and SthlmFlex are all still in the pilot phase (Göteborg Energi, 2022) (Svenska kraftnät, 2022-2 and 2022-3), while the Coordinet project is finalized and at least in the Uppsala region replaced by Uppsala flexibilitetsmarknad. Since several of the local markets are still in the pilot phase, the requirements to fulfil are still under development.

One example of heat pumps participating in local flexibility markets comes from the Swedish energy company Stockholm Exergi. The company participates in the newly started local market, SthlmFlex, and delivers flexibility by controlling the power consumption of 17 large-scale heat pumps used for production of district heating. When the flexibility is activated, and the heat pumps are switched of, the energy company uses alternative methods to produce district heat. The participation has started in small scale and during the winter 2021/2022 1MW electric load from Stockholm Exergies heat pumps was activated twice, this should be compared to 140MW, which is the total maximum electricity capacity needs of Stockholm Exergi´s heat pumps in the production sites Hammarby and Värtan.

4.5 Renewable Energy Community

According to the Clean Energy for All Europeans Package of 2019, all EU member states are obliged to enable the establishment of energy communities within their regulatory framework (Fina et al, 2022). At the moment, the EU member states are at different stages of this implementation. However, in the near future, the founding of renewable energy communities (RECs) and citizen energy communities (CECs) will be possible in all EU member states. (Fina et al, 2022)

This provides the possibility for heat pumps to use their flexibility on a community level, which provides different benefits:

- **Reduction of grid tariffs**: In Austria, RECs will for example be incentives by a reduction of grid tariffs for electricity transferred between participants. The grid tariffs are especially reduced if only the low voltage grid is used. If the medium voltage grid is used, there are still some reductions in grid tariffs. (Fina, et al. 2021)
- **Reduction of electricity costs**: Energy communities allow for more of the generated photovoltaic (PV) electricity to be used on a local level, thus feeding less of it into the main grid. This also means less electricity needs to be bought from conventional suppliers, leading to a reduction of electricity costs. (Fina, et al. 2022)
- **Reduction of greenhouse gas emissions**: When energy is shared within an energy community, this can also help to reduce greenhouse gas emissions. More of the generated photovoltaic energy can be used within the community and less is fed into the grid, which is financially beneficial in many countries and thus can lead to an increase in PV in the system. (Schram, et al. 2019)

Support of the electric grid: When heat pumps are part of an energy community, the amount of PV energy fed into the main grid can be reduced, since the electricity can be used on a local level. This helps to support the electric grid, since extensive feed-in of renewables can often lead to grid problems. (Fina, et al. 2022). A potential drawback with heat pumps is that the possibility to run the heat pump when the PV power is produced is limited due to small heating demands in summer times. The large heating demand occurs in winter times and during nights, when the PV production is low.

4.6 Bilateral- and Conditional agreements

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 (Power Circle, 2022).

4.7 Imbalance settlement

The imbalance settlement is a financial settlement mechanism for balance groups to be charged or paid for their deviations from their schedule (=imbalances). Imbalance settlement is designed to reflect the real-time value of energy by considering both balancing, and wholesale market prices in imbalance settlement prices. To allow easier balancing, the producers and consumers are united into what is known as balancing groups. Balancing groups are an important concept within the power sector which helps to organize the production/consumption schedules, stick to these schedules to the best possible way and disincentivize deviations from the schedule. The administrative control of the Balancing Groups is carried out by Balancing Responsible Parties (BRP). The BRP is financially liable for its imbalances and is required to submit the resulting internal and external schedules of the Balancing Group to the Control Area Operator / TSO at the latest by 2:30 pm Day-Ahead.

Heat pumps can use their flexibility to help reduce imbalances within their balancing group in two different ways:

- **Reduction of their own imbalance**: When heat pumps participate on the day-ahead spot market and announce their schedule in advance to their BRP, in the next step they try to follow the schedule as closely as possible. This could be done by either changing their energy consumption accordingly or by trading any occurring imbalances on the intraday market.

- **Reduction of the BG's imbalance**: In the future, heat pumps and other flexible units could also help reducing the overall imbalance of their balancing group. The BRP could send signals to the heat pump requesting their flexibility in case of an imbalance, similar to the activations for ancillary services.

5 Technical ability and constraints for flexible heat pump operation

Chapter 5 discusses the technical possibilities and constraints for using heat pumps for flexibility. In subchapter 5.1 the possibilities for heat pumps in buildings is evaluated, while subchapter 5.2 focuses on heat pumps in combination with thermal grids.

5.1 Heat pumps for buildings

The findings in chapter 5.1 fucuses on heat pumps for single family buildings producing both space heating and domestic hot water, but many of the results are also valid for heat pumps with a larger heating capacity. Since each individual heat pump for single family buildings can only deliver a smaller amount of flexibility to the power system, domestic heat pumps must be aggregated and controlled as a group to accomplish the minimum bid size. 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.

5.1.1 Heat pump reaction time and speed of ramping up and down

In the Swedish research project SLAV (Lindahl et al, 2023) an interview study including nine technical experts from the four major manufacturers of heat pumps for single family buildings active in Sweden was conducted, with focus on technical issues. As a complement the issue was discussed during a digital workshop 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 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 by 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 (Svenska Kyl & Värmepump Föreningen, 2022). 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 field tests carried out within the same project indicate that it can be significantly faster. Control-wise improvements can likely be made to speed up the process of starting and stopping, but some technical aspects will still limit what is possible.

5.1.2 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 for single family buildings is difficult, as they normally lack electricity meters and installing it afterwards is expensive and needs 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 for example the Swedish TSO, Svenska kraftnät, requires today when participating in ancillary services. 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.

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 (Svenska kraftnät, 2022-1) is likely to be too frequent for today's used control system or for using the buildings electrical meter

5.1.3 Decentralized heat pumps in thermal grids

The technical constraints for decentralized heat pumps located at end consumers in thermal grids are similar to the constraints for heat pumps in buildings described earlier in chapter 5.1.

5.2 Centralized heat pumps in thermal grids

5.2.1 Vapour compression heat pump systems

The flexible operation of heat pumps according to signals from the electricity grid (Price signal, frequency regulation) will in general result in larger losses (storage, lower source temperature, etc) on the thermal side due to deviations from the ideal heat production schedule. It is advantageous to take the expected operation into account when designing the heat pump system, since the amount of operation hours in part-load, the number of starts and stops as well as the required reaction time depend on the planned operation. It may be expected that a demand driven operation will result in a larger number of part-load hours, while the operation according to electricity prices will favor an on-off operation to exploit the hours with lowest electricity prices. Supplying ancillary services using heat pumps requires the ability to adapt the load quickly, operate efficiently in part-load and an exact control of the power uptake. In the following an overview is given about the suitability of different capacity control methods to comply with these requirements.

5.2.1.1 Capacity control

In general, the capacity of heat pumps is adapted by changing the load on the compressors. Depending on the compressor set-up there are two common ways for capacity control in large-scale heat pump systems – variable speed drive and on/off compressors. The former is applicable to all systems, while the latter is typically used in systems with many compressors in parallel. Both methods may also be combined, by having (N-1) compressors running on of plus 1 running with variable speed drive. Variable speed drives enable a precise and step-less control of the compressor speed. For low part loads the efficiency does however drop considerably, this is caused by a drop in the efficiency of the electric motor and increased compression losses.

For reciprocating compressors the compressor load may be further decreased by decoupling cylinders, thereby reducing the displacement volume of the compressor. Decoupling cylinders typically takes place at a defined rotational speed, therefore it may be necessary to adapt the rotational speed before and after coupling of cylinders, resulting in a delay when adapting the load. Further, the efficiency is reduced by the pistons running idle. For screw compressors the displacement volume and thereby the capacity may be further reduced by using a slide valve.

For systems with multiple compressors in parallel, shutting off compressors for reducing the capacity constitutes an a very efficient method to reduce the load. The advantage is that all other compressors may run at (or close to) nominal speed, i.e. at high efficiencies. The control for this system needs to be designed carefully to allow for continuous reduction of capacity, while preventing cycling of compressors which could result in continuous pressure fluctuations and increased wear of cycle components and the electric motor.

Depending on the type of flexible services, there may be a requirement on the time it takes to adapt the load of the heat pump and on how exactly the power uptake needs to be controlled. Some frequency regulation services require the ability to continuously adapt the power uptake, while other only have a requirement on the ramping rate, the minimum duration of the service and the maximum waiting times, before the system needs to be able to react again. This operation requires a dedicated control design of the heat pump plant in order to ensure safe operation of the thermodynamic cycle as quick load changes may lead to sudden changes in evaporation and condensation pressure and thereby increased wear (Meesenburg, Markussen, et al., 2020). The limitations for fast start-up discussed in chapter 5.2.1.2, also apply in this case. Special attention is necessary in the design of the secondary side, to be able to accommodate the fast load changes of the heat pump. In case the system is not designed for fast operation, quick load changes may even lead to component failure. An example of this would be the risk of condensation in the suction line for ammonia heat pumps. This phenomenon may occur, when the evaporation pressure and thereby the saturation temperature suddenly rise, while the suction line is still at a temperature below the saturation temperature (Meesenburg et al., 2019). Sudden rises of the evaporation pressure may occur when the load is decreased quickly into part-load, or when sudden temperature of flow changes in the sink and source conditions occur (Meesenburg et al., 2023). While this phenomenon has been described for ammonia systems with flooded evaporators, it may be expected that sudden variations in the evaporation conditions also require special attention for direct expansion evaporators with superheat control, to avoid too little superheating during fast changes of the operating conditions.

To be able to control the power uptake of heat pumps it is necessary to be able to measure the power uptake and to actively control it. Normally, heat pump controls are set up to be able to control the heating capacity (directly, or indirectly by controlling the source capacity and outlet temperature) and the supply temperature. The power uptake will in this case result from the heat pump operating conditions and heat demand. However, many flexibility applications, like balancing services, require high resolution measurements and guaranteed values of the electric power uptake. To actively control the power uptake, the control needs to be changed to allow for a direct control of the power uptake or a model needs to be implemented in the control that correlates the power uptake with the corresponding set-values of heat load and/or temperature under the current operating conditions.

5.2.1.2 Ramp-up times

There are several factors limiting the ramp-up times of large-scale heat pumps. These are:

- Pressure and temperature fluctuations: Starting a compressor at full speed can cause sudden pressure and temperature fluctuations in the system. These fluctuations may put stress on various components like the compressor, heat exchangers, and others. Further, pressure peaks above normal operating conditions in the condenser and below normal operating conditions in the evaporator, may lead to condensation- and evaporation temperature that are too high or low, respectively. This may result in amplifying effects on the heat pump system or problems in the secondary streams.
- Component stress and wear: The pressure and temperature fluctuations during rapid start-ups can result in increased stress and wear on the components of the Vapor Compression Heat Pump (VCHP). Over time, this can lead to premature failure of the components.
  - Especially, for heat pumps supplying high temperatures to the sink, the ramping times are constraint by the maximum temperature gradients in the heat exchangers. Example of maximum allowable temperature gradients are 10K/min for plate heat exchangers, (personal communication with Danfoss) to 2K/min for shell-and-tube heat exchangers (Oehler et al., 2021).
  - Moreover, the lubricity of oil is reduced at cold starts and develops its full lubricity at higher temperatures. The compressors used in VCHP can produce some noise during operation, especially during start up. Gradually ramping up the VCHP can help to reduce the sudden noise associated with starting-up the compressor at full load.
- Heat pump configuration: The aim is to ensure a stable built-up of the thermodynamic cycle. The cycle design influences the achievable ramping times, due to:
  - Thermal capacity of components: Especially large amounts of refrigerant hold-up in intercoolers and flooded evaporators/separators increase the thermal capacity of the system. If the thermal capacity of the system is large compared to the energy flow rate delivered by the compressor, it takes longer to bring the cycle into the desired point of operation. This means simple cycle designs with small refrigerant hold-ups and small thermal capacity of the refrigerant mass relative to the energy flow rates favour fast start-ups.
  - Cycle complexity: Complex cycles (multiple stages, complex heat exchanger networks, multiple parallel compressors, etc.) require a careful coordination of the different control loops during start-up to ensure a stable built up of the operational cycle. This may further limit the allowable ramp-up time (Jensen et al., 2023). The number of stages is mainly dictated by the increase in saturation temperatures of the refrigerant for the required temperature lift, taking compressor limitations of pressure ratios and allowable discharge temperatures into account. A large number of heat exchangers is typically chosen to maximize the COP of the system. The choice of compressor type and number of compressors depends on the required pressure ratio, the volume flow rate and the capacity of the system and is thereby again influenced by the choice of the refrigerant.

- Refrigerant: As explained above, the refrigerant may influence both the thermal capacity of the system compared to the energy flow rate as well as the required cycle complexity to a certain extend and thereby poses a natural limit of the achievable ramping times. Especially, for fast load changes further aspects like the minimum required superheating out of the evaporator or the risk of droplet formation in the suction line depend mainly on the type of refrigerant and limit the allowable ramp-rates (Meesenburg, Markussen, et al., 2020).
- Compressor type: Different compressor types behave differently during ramp up, resulting in differences in the required ramping times:
  - Turbo-compressors can adapt their load within few seconds. The limiting factors are the time constants implemented in the compressor control. These are necessary to protect the compressor from unstable operation, which could potentially lead to mechanical damage of bearings, etc. Further, too large pressure changes (>60 bar/min) may lead to break down of sealing materials and the maximum allowable current from the variable speed drive need to be respected During start-up the load is increased by increasing the rotational speed and adapting the guide vanes. During start-up the load is increased by increasing the rotational speed and adapting the guide vanes.
  - Piston compressors: During start-up the pistons are coupled in (often in pairs of two, depending on the piston arrangement) after each other and the speed needs to be ramped up to full-load. This process may be limited by dead times between coupling-in of pistons. A quicker start-up could be possible if a larger inertia could be allowed. Then the compressor could start-up with all pistons coupled in and just ramp-up in rotational speed. Piston compressors are highly sensitive to liquid entering the compressors. Even small droplet may damage the valves. This limits the ramping times further, as it needs to be ensured that no liquid is sucked into the compressor during sudden start-up.
- Load Fluctuations: Rapid starting can lead to load fluctuations in the system, including the secondary streams. The secondary side (hydronic loop) needs to be able to follow the fast dynamics to avoid temperature peaks that may affect the heat pump operation negatively due to sudden changes in the condensation pressure and evaporation pressure. Further, sudden changes of the secondary flow may cause problems in other parts of the system (demand side, network, neighbouring supply units) if the secondary side is not designed to handle fast variations in flow and temperature.
- Peaks in electric load: Fast start-ups can lead to high start-up currents, which stress the electrical infrastructure. Sharp cycling should be avoided as this leads to increased strain on the electronic components and thereby reduces the lifetime of the system.
- Initial conditions: Many of the factors limiting the allowable ramp-up times may be reduced if warm start-up can be ensured. This may be helped by keeping the evaporator and condenser in contact with the sink and source streams, providing suitable receivers for the refrigerant at the higher pressure level and preheating the compressor block, oil reservoir and suction line. This does however require an additional energy consumption during shut-off periods.

By using start-up ramps, the heat pump system gradually reaches its operating conditions, allowing the pressure, temperature, and load to stabilize smoothly. This controlled approach reduces stress on the components, minimizes inefficiencies, and helps to prolong the life of the heat pump system. Due to fluctuations (e. g. temperatures and pressures) which can occur when a compressor shuts down immediately, ramps are used not only during startup, but also during shutdown.

5.2.1.3 Case studies ramp-up time

The ramp-up and ramp-down times result in a delay between the request of a VCHP and its provision of the requested heat output and therefore can impair the VCHP's flexibility. In the following, the start-up and shut-down times of three exemplary case studies are presented:

Case 1 - Combined system to provide heating and cooling to a dairy plant (AT)

The measurement data of ramp-up and ramp-down times of a compressor of a two-stage R717-heat pump with flooded evaporator and reciprocating compressor which provides heating capacities at the heat sink (h) of approx. 0.55MW at sink outlet temperatures ($t_{SI,out}$) of up to 90°C are presented in Figure 2. As shown, the ramp-up time is approx. 10min and the shut-down time is approx. 15s. Therefore, the exemplary VCHP shows a delay caused by the ramps of approx. 615s which have to be considered additionally to minimal run time of the VCHP in an on-off-cycle (Rieberer et al., 2021).

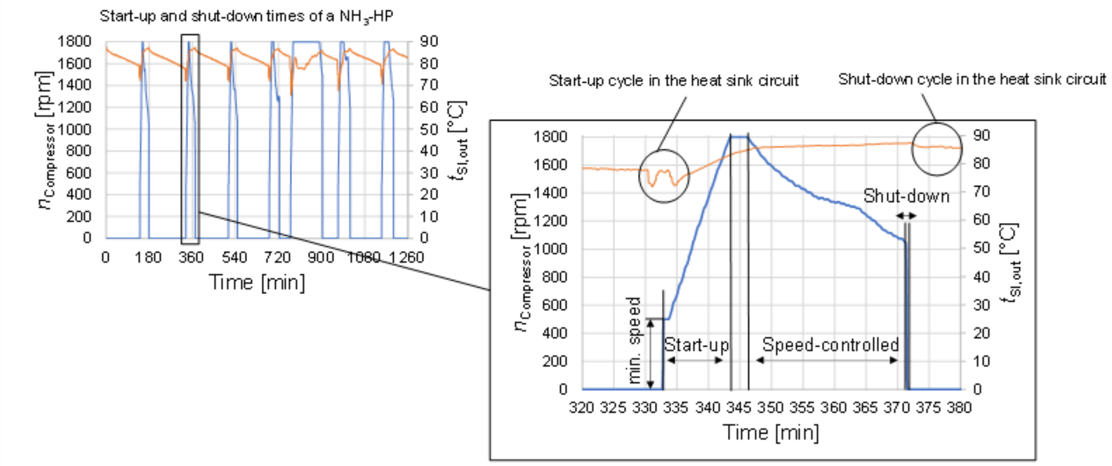

Figure 4. Compressor-speed and temperature at the heat sink outlet vs. time in a R717-VCHP (adapted from Verdnik et al., 2022)

Case 2 - FlexHeat – Two-stage ammonia heat pump supplying district heating (DK)

The FlexHeat heat pump is a two-stage ammonia heat pump with flooded evaporator, reciprocating compressors and open intercooler. The nominal heating capacity is 800kW, the system uses groundwater at 10.5°C as heat source and provides district heating and forward temperature of 60°C to 82°C. The measured start-up and shut-down times for this system are depicted in Figure 5 and compared to the required ramping times of different frequency regulation services in Eastern Denmark. The start-up times were found to be around 4.5 minutes, while the shut-down time was between 30 seconds and 1 minute. Further, the heat output, power uptake and COP during start-up were compared to full-load operation. The results are depicted in Figure 4. It may be seen that the heat output is reduced to a larger extent than the power uptake during start-up, resulting in a reduction of COP during start-up of 17% to 24% (disregarding stored energy).

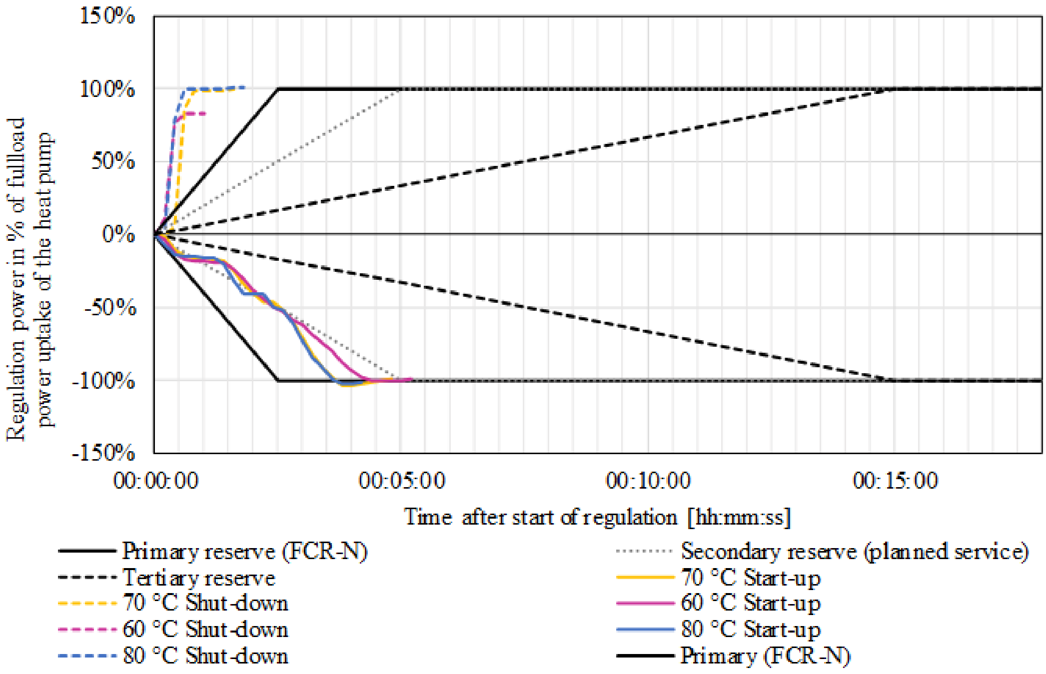

Figure 5. Start-up times and shut-down times of FlexHeat heat pump compared to required regulation times in Eastern Denmark (Meesenburg, 2020)

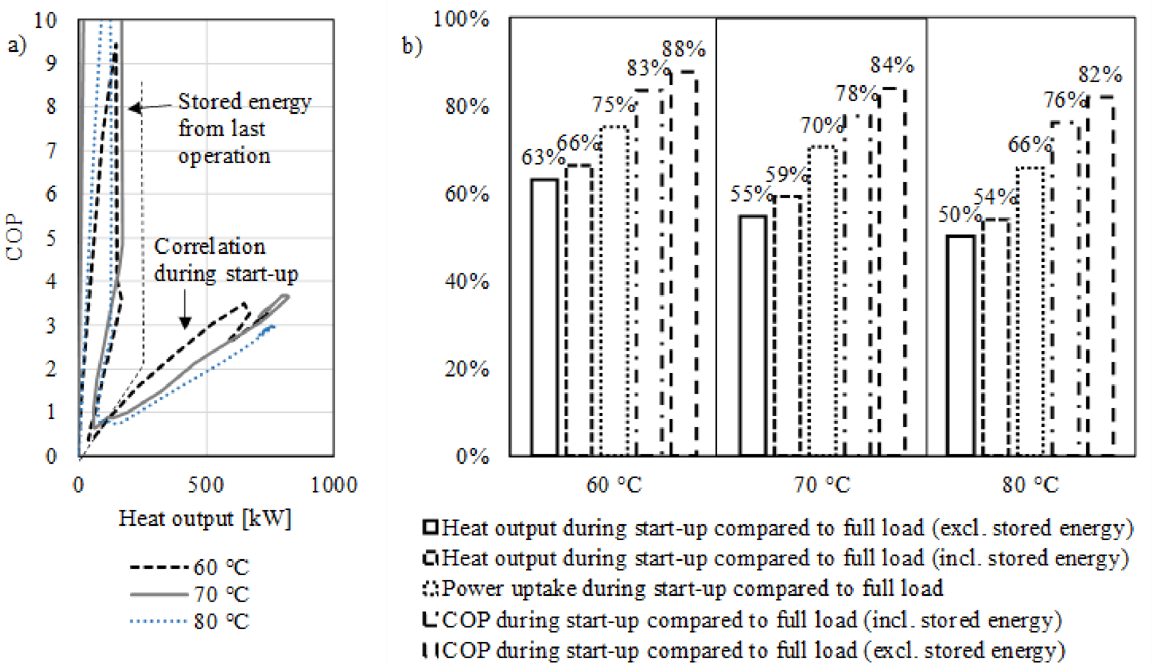

Figure 6. a) COP during start-up as a function of the heat output for three different forward temperatures, b) performance during start-up compared to full load (Meesenburg, 2020)

Case 3 - Søndre Felding - 3.3MW transcritical CO_2 heat pump supplying district heating (DK)

The CO_2 heat pump in Søndre Felding (Denmark) is the first one that has obtained the official qualification to deliver secondary frequency regulation (aFRR) in Denmark. The system is a transcritical cycle with an intermediate pressure level for flash-gas removal. The aFRR market requires a start-up times of 5 minutes or below. These fast start-up times were obtained by removing recirculation of water on the secondary side to preheat the water and prevent cold volumes of water entering the heat exchangers (which may result is sudden pressure variations in the heat exchangers if they occur). Further, the controller parametrization has been optimized to allow for a faster reaction. Even faster reaction times could be obtained if the cycle could be run without the intermediate pressure level, since the intermediate compressor control is currently limiting the reaction times. Figure 7 shows the measured results when the heat pump has been operated for delivering flexibility compared to the limits to fulfill for aFRR. The dashed line is the signal defining the set-point value for the power uptake, the thin lines show the system response and the green areas the allowable reaction times (5 minutes until full capacity adaption) (Jensen et al., 2023)

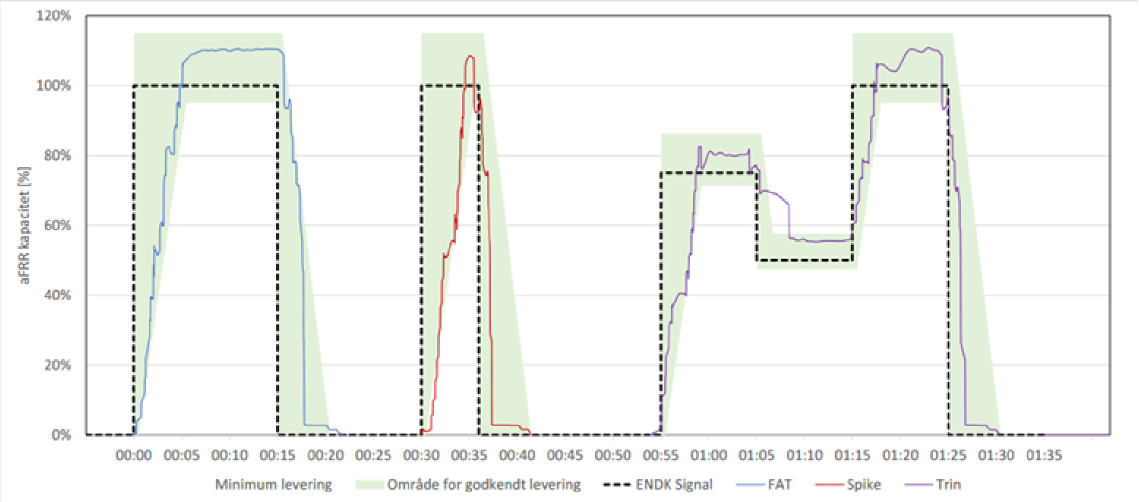

Figure 7. Measured power uptake of CO2 heat pump in Søndre Felding, DK. (Jensen et al., 2023)

5.2.1.4 Stand-still / idle times

The flexible operation of heat pumps may lead to increased numbers of start-stop cycles. Before starting up again after a shut-down, a minimum waiting time is typically required. The reason for this is:

a. To allow for the refrigerant to settle in the foreseen receivers/vessels in the system and to stabilize the conditions within the cycle. This is mainly to ensure that no liquid is compressed in the compressor and that the valve is fed with liquid to ensure a safe and stable start-up.
b. To prevent overheating and/or increased wear on the electric motor of the compressor. Typically, large scale motors have a limited amount of consecutive starts as well as maximum starts per year, an example is given below.

Therefore, it is important to ensure that the planned flexible operation is taken into account already in the design phase, such that the electric motor can be chosen accordingly and that the vapor compression cycle can be designed such that the required times for settling of the refrigerant are reduced.

5.2.1.5 Temperature flexibility

The temperature flexibility of heat pumps is confined by the inherent constraints of the working fluids (such as saturation pressures) utilized and the operational limits of the components (like the compressor) used. For compressors these limits occur e. g. due to a maximum of discharge temperatures. In Figure 5 the operating limits of a specific propane compressor are shown, which enables evaporating temperatures between -30 °C and 18 °C and condensing temperatures between -

8 °C and 65 °C. Therefore, the choice of refrigerant and components must be taken into account as early as the design stage and results in a reduced flexibility.

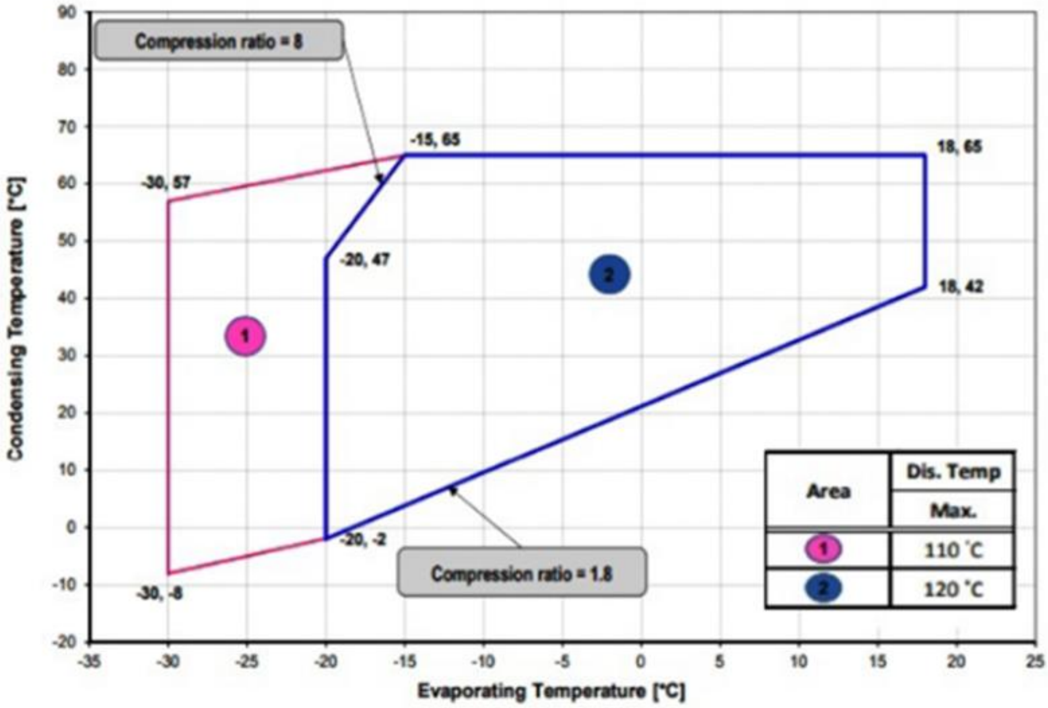

Figure 8. Operating area of a propane compressor (adapted from SIAM Compressor Industry Co. Ltd., 2019

In the context of flexibility, it is especially important to discuss limitations with regard to how fast temperatures and flows on the secondary side may be changed. As mentioned above, the rate of change is limited by the maximum allowable temperature gradients in the heat exchangers and the maximum allowable pressure gradients to avoid agitation of the system, increased wear of the compressor and motor, and to allow for the cycle control to ensure superheating at the compressor inlet at all times.

Changes in the temperature or flow on the secondary side may be caused by quick changes in the heat pump load, by suboptimal control or design of the hydraulic system or through planned or unplanned sudden variations in the operation of upstream systems or components.

Example of a fast change in source temperature for a direct expansion evaporator system

A fast change in source temperature results in inefficiency or may cause the refrigerant to remain partially liquid after the evaporation process, which in turn can cause serious problems for the compressor. This is exemplarily shown in Figure 9~~Figure 9~~ which presents simulation results of a VCHP utilizing R717. In the simulation, the source temperature was decreased from 20°C to 10°C within 40s whereby the evaporation temperature decreased by 13K and the refrigerant left the evaporator in two-phase state. The risk of partially liquid refrigerant at too fast variation of the operating point must be taken into account and reduces flexibility. To reduce the risk of two-phase refrigerant entering the compressor, a quick expansion valve with a fast control might be used. Another possibility is installing an accumulator after the evaporator from which the compressor sucks (saturated) vaporous refrigerant.

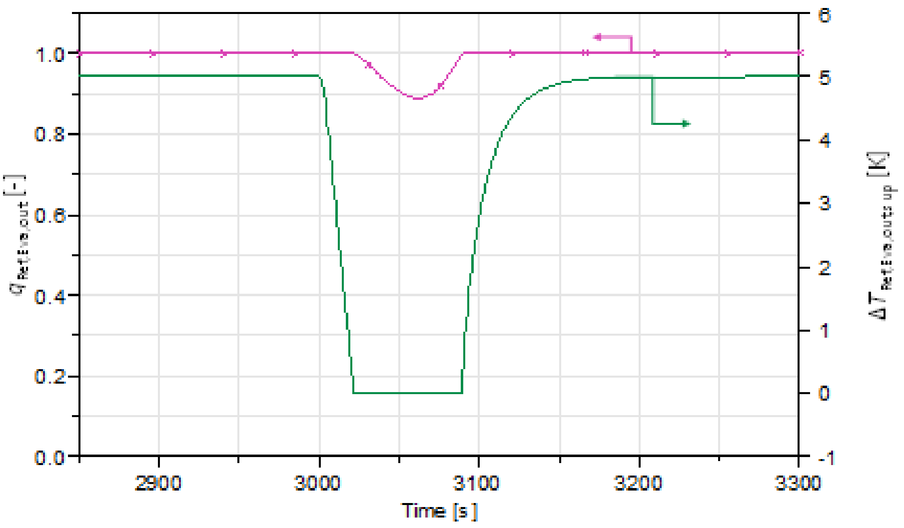

Figure 9. Impact of a quick change of the heat source inlet temperature in the evaporator on the superheating and quality of the refrigerant at the compressor inlet of a R717-VCHP (Simulation)

A similar study for a one-stage ammonia system with flooded evaporator has shown that the allowable gradients in evaporation and condensation pressure depend on the absolute operating pressures and the gradient of the saturation temperature with pressure (Meesenburg et al., 2023).

5.2.2 Absorption heat pumps

In the following, the influence of absorption heat pumps (AHP) operating characteristics on flexibility-provision is discussed, whereby only factors deviating from vapor compression heat pumps are considered.

5.2.2.1 Ramp up times / transient operation

Absorption heat pumps have longer ramp-up times compared to conventional vapor compression heat pumps (e. g. due to larger thermal masses and inherent heat and mass transfer processes). Following key factors contribute to these extended start-up durations:

- Heat Source "activation": Desorption of vaporous refrigerant depends on a high temperature heat source. The time it takes for the heat source to reach the required operating temperature (e. g. biomass combined heat and power plant) is a critical factor affecting the ramp-up period.
- Heat and Mass Transfer:
    - The absorption process (condensation and absorption of the refrigerant) involves the transfer of heat from the solution to the heat sink. The desorption process involves the transfer of heat from the high temperature heat source to the solution. The amount of heat and mass transferred depends, among others, on temperature differences and the efficiency of the heat exchangers. Additionally, the absorption and desorption process rely on chemical kinetics which need some time to reach equilibrium (especially when using a salt as a solvent).
    - The dimensions and design of the absorption heat pump system are also significant factors in determining ramp-up times. Smaller systems with lower thermal mass may reach operational temperature more quickly than larger and more complex setups.

The high inertia of absorption heat pumps (AHP) does not only result during ramp up in long period with transient behaviour but at operating point changes too. This is exemplarily shown in Figure 10 and Figure 11~~Figure 11~~. Figure 10 shows the transient behaviour of the generator and absorber of a

NH_3/H_2O-absorption chiller with a nominal evaporator capacity of 12.5kW. Figure 11~~Figure 11~~ shows the transient behaviour of the generator and absorber of a H_2O/LiBr-absorption chiller with a nominal evaporator capacity of 15kW. Comparing the results of Figure 10 and Figure 11~~Figure 11~~ shows that the inertia differs between the two absorption chillers (ACH). Reasons for this are, e. g., that the H_2O/LiBr-absorption chiller has higher thermal masses and that absorption of water in an aqueous salt solution is a slower process than solving water in an aqueous ammonia solution.

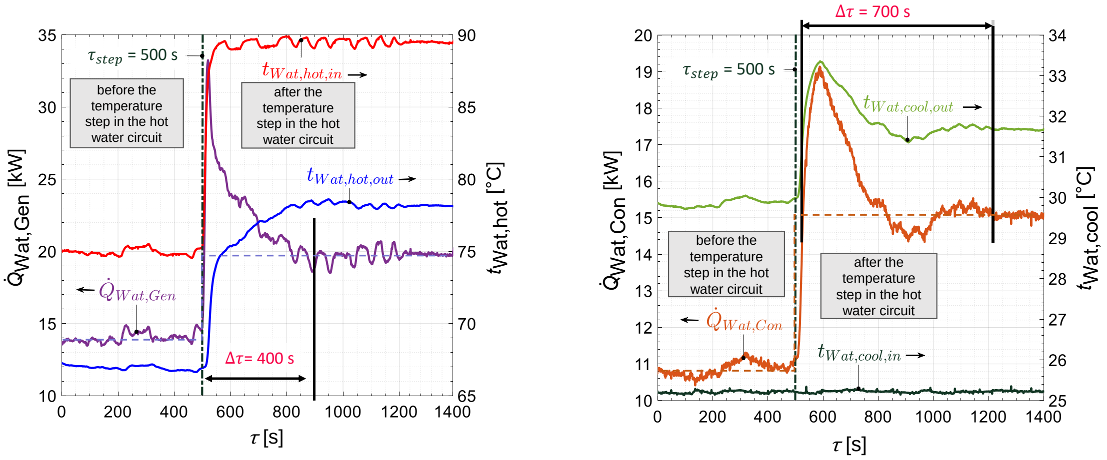

Figure 10. Transient heat exchanger behaviour of a NH_3/H_2O-ACH ($\dot{Q}_0$ =12.5 kW; left: generator; right: absorber) (adapted from Wernhart et al. 2019)

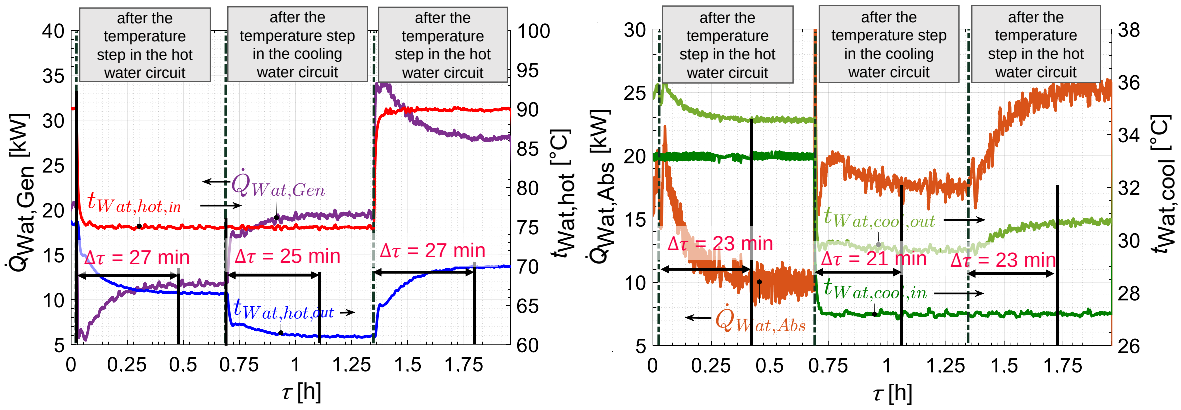

Figure 11. Transient heat exchanger behaviour of a H_2O/LiBr-ACH (($\dot{Q}_0$ =15 kW; left: generator; right: absorber) (adapted from Wernhart & Rieberer 2021)

AHP with higher capacities have larger thermal masses which result in higher thermal inertia. Wagner et al. (2021) concluded from measurements of a H_2O/LiBr-AHP with 8 MW heating capacity (see Figure 12) that a shut-down for 15 min results in transient operation for 1.5 hrs “around” the nominal operating point which can be reached approximately after 25 min.

The long ramp up times can result in a reduced flexibility of district heating systems (DH-systems) containing AHPs. This has also been found by Arnitz & Rieberer (2018) who investigated a H_2O/LiBr-AHP with a nominal heating capacity of $20MW_{th}$ which utilizes flue gas condensation of a biomass CHP ($50MW_{th}$, $10MW_{el}$). They concluded that fast capacity adjustments to cover morning and evening peak loads (e. g. increase from $15 MW_{th}$ to $54 MW_{th}$ within 30 minutes in the morning) of the investigated DH-system are challenging due to the high the thermal inertia of the biomass CHP and the AHP.

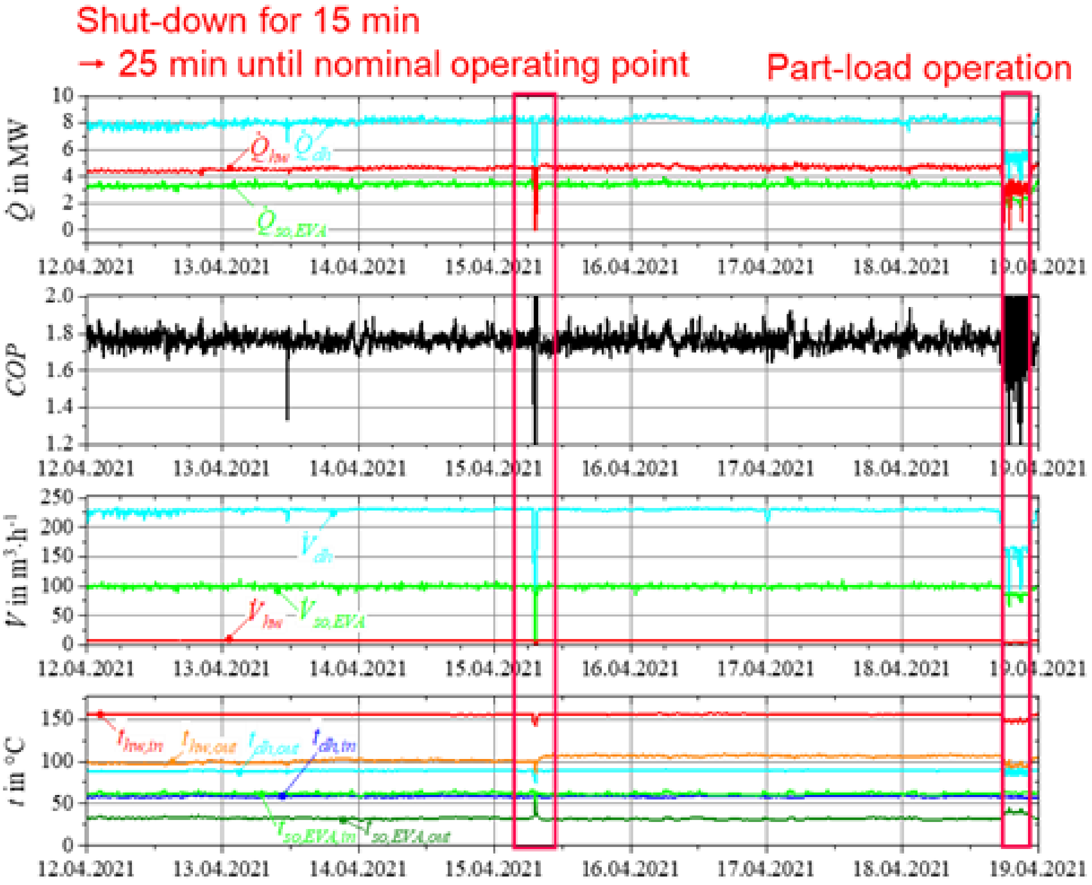

Figure 12. Transient heat exchanger behavior of a H2O/LiBr-AHP (($\dot{Q}_h$=8 MW) (adapted from Wagner et al. 2022)

5.2.2.2 Capacity control

Absorption heat pumps and absorption chillers are usually designed for specific operating conditions (e. g. temperatures and volume flows in a district heating system). During operation the operating conditions might differ from design criteria, e. g. when varying:

- Pump speed (using a frequency control (FC))
- Source and sink temperatures as well as mass flow rates. The impact of deviating from the nominal operating point is discussed using Figure 13 which shows the operating characteristics of a H2O/LiBr-ACH ($\dot{Q}_0$=15 kW) as well as Figure 14 which shows the measurements of a H2O/LiBr-AHP ($\dot{Q}_h$ =8 MW).

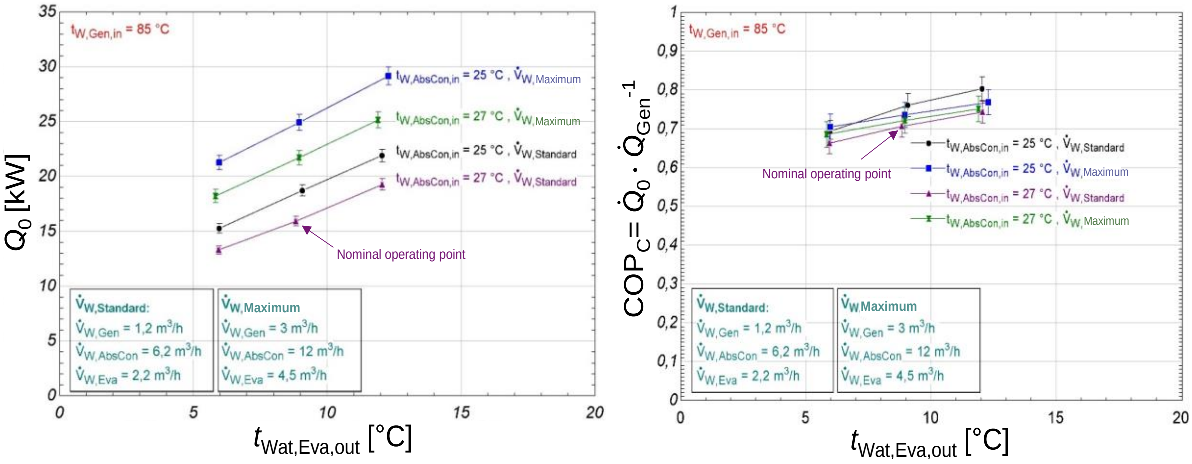

Figure 13. Variation of water temperatures: heat sink inlet (tWat,AbsCon,in), low-temperature heat source outlet (tWat,Eva,out) and variation volume flows in the water circuits of a H2O/LiBr-ACH (($\dot{Q}_0$ =15 kW) (adapted from Wernhart 2019)

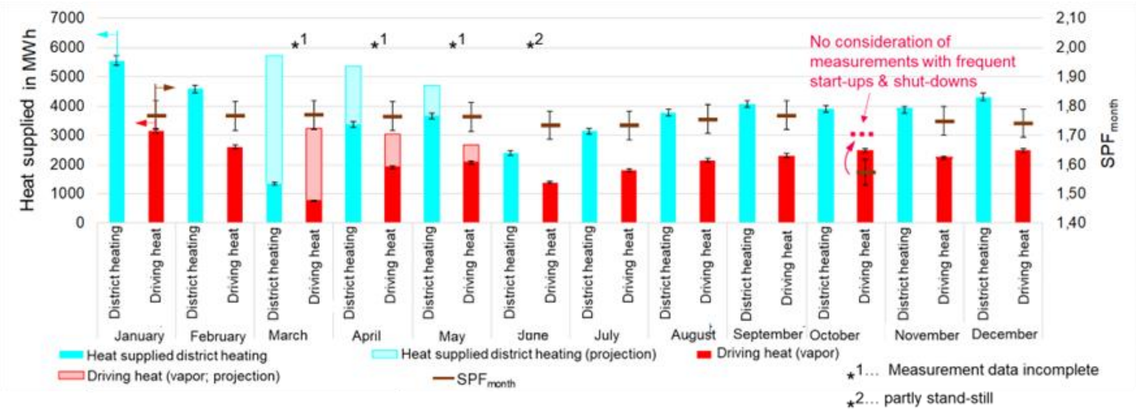

Figure 14. Monthly heat supplied and SPF of a H2O/LiBr- AHP ($\dot{Q}_h$=8 MW) (adapted from Wagner et al., 2021, Wagner et al. 2022)

Figure 13 shows that a decrease of tWat,AbsCon,in results in an increase of evaporator capacity as well as increase of COP_C which is a consequence of lower solution temperatures and lower condensation pressures. An increase of water volume flows results in an increase of evaporator capacity but a decrease of COP_C. An increase of tWat,Eva,out results in higher capacities and COP_C which is due to higher evaporation pressures. However, COP_C remains quite constant at the shown variation of operating conditions and changes slightly only.

These examples show that the investigated AHP and ACH enable rather constant efficiencies at (slightly) changing operating parameters and therefore enable flexible operation (load variation) at rather constant efficiencies.

5.2.2.3 Temperatures

AHP and ACH enable high temperature “lifts” between low-temperature heat source and heat sink, but “suffer” from limitations due to “high” saturation pressures when using NH3 as refrigerant crystallization of water below 0 °C when being used as refrigerant crystallization of lithium bromide in the solution at certain operating conditions**.**These limitations can result in a reduced flexibility which shall be explained using Figure 12. It shows how the crystallization zone of lithium bromide limits the temperature flexibility of H2O/LiBr-AHP. In the example shown, an increase of the high temperature heat source inlet from 90 °C to 115 °C in “cooling mode” at the given temperatures and temperature differences in the heat exchangers would result in crystallization of LiBr in the solution. The same accounts for decreasing the heat sink outlet (e. g. by increasing the water volume flow) temperature from 90 °C to 75 °C. Therefore, operating conditions which might occur during operation have to be examined during design. If there is a risk of crystallisation adaptions of the AHP / ACH cycles or control should be considered (e. g. “manual” dilution of solution at high LiBr mass fractions in the absorber using water injection).

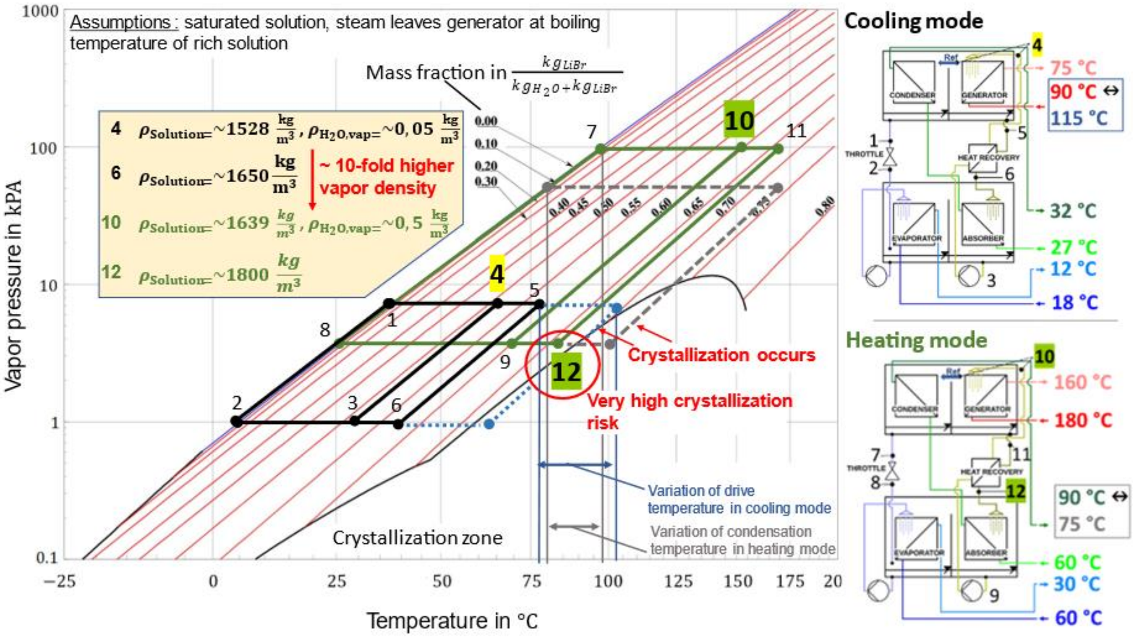

Figure 15. Variation of temperatures in a H2O/LiBr absorption heat pumping process shown in a Dühring diagram (adapted from M. Conde Engineering GmbH 2014)

5.2.3 Booster heat pumps in combination with water tank in low temperature grids

As part of the EnergyLab Nordhavn – Smart components project, a heat booster substation for multi-family buildings supplied by ultra-low temperature district heating was developed, tested and demonstrated (Thorsen et al., 2019). Ultra-low temperature district heating is defined as district heating at supply temperatures below the level required to provide domestic hot water to the building. The heat booster substation comprises of two heat pumps. The booster heat pump lifts the temperature of the ultra-low temperature district heating supply stream from 45°C to above 60°C in the condenser to provide domestic hot water to the building. The heat for the evaporator is taken from the district heating forward, too, and cooled down from 45°C to 30°C. The domestic hot water is stored in two accumulation tanks. The smaller heat pump heats the recirculated domestic hot water within the building to achieve short waiting times for hot water and thereby a high comfort level.

The integration with the two accumulating tanks allows operating the booster heat pump flexibly. For this purpose, an automatic tank charging scheduling algorithm was developed taking electricity price signals and the forecasted domestic hot water demand for the coming 24h into account. The flexible operation is based on shifting the operation of the heat pump to hours with low electricity and district heating prices. This is possible, as the heat pump only needs to operate during few hours of the day to provide the required amount of hot water. Ramping times of the heat pump where therefore not reported, as they are not decisive for the type of flexible operation.

The domestic hot water was provided at 55°C to the customers, the average domestic hot water production per day during the first year of operation was 1.700l/day. The share of the electric energy consumption for the provision of domestic hot water was found to be 14%, the remaining 86% were provided from district heating. The algorithm minimizes the operational cost.

The load shifting potential was found to be 7kWh/day electric and 67kWh/day heating for a 22-flat building. Corresponding to a possible change in power uptake of 3kW and of district heating utilization of 30kW. Further, the system has the potential to shift the load from the district heating grid to the electric grid and vices versa by varying the evaporation temperature. The potential for fuel shift was however found to be small with only 2kWh electric per day.

Several feasibility studies have been conducted for this case, and it was found that the concept is not competitive to low-temperature district heating (allowing for direct supply of domestic hot water) under the current energy price structure. It may only be competitive under very special boundary conditions. Efficient buildings, low heat demand densities and low district heating prices (due to exploitation of low-temperature heat sources) favour this solution (Meesenburg, Ommen, Thorsen, et al., 2020).

6 Communication protocols

In the SLAV project (Lindahl et al, 2023) a number of communication methods was identified for communication between aggregator and the individual heat pump, and a literature study was conducted with the focus on getting a high-level overview of available communication protocols suitable for demand response from heat pumps. The communication standards evaluated was mainly higher-level protocols, also referred to as communication middleware, that include application parameters and/or data models. The evaluated communication protocols are summarized in Table 2~~Table 2~~:

Table 2. Evaluated communication protocols in (Lindahl et al, 2023)

1	EEBus
2	EFI/S2
3	IEC 61850
4	IEEE 2030.5
5	OpenADR
6	PowerMatcher
7	SG Ready

Since the focus on the study was on large scale control of heat pumps for electrical grid flexibility, protocols mainly intended for, e.g., electric vehicle charging and building automation was not part of the scope. Therefore, protocols like, OCPP, OSCP, ISO 15118, KNX, Modbus, Z-Wave, and Zigbee was not included in the evaluation. Some of them are evaluated in a report by TKI Urban Energy about In-Home Energy Flexibility Protocols (TKI Urban Energy, 2020).

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. A benefit using Energy Management Systems (EMS) for flexibility services from heat pumps is that they 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. Another trend that has been seen for several of the evaluated 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 (Zuber et al, 2022).

The SLAV project concludes that recommendation of a specific communication standard among the ones evaluated is not easy, but states that some seems more suitable than others. OpenADR and IEEE 2030.5 are two US-based standards that have large 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 individually as further work is needed to recommend any of them before the others.

7 Discussion

The focus in this report is flexibility delivered by heat pumps to the power system. There are several potential flexibility markets identified, either for implicit- (voluntary adjustment of electric load due to e.g. variation in electricity price) or explicit services (get paid to adjust the electricity load as a service). The market for explicit flexibility puts technical demands on the heat pumps regarding activation time, duration and possibilities to measure the flexibility delivered. While implicit flexibility is a voluntary adjustment of the electric load for the end user to decrease the electricity costs. These services are in general easier to plan for, 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.

The duration of the flexibility service from heat pumps increases with larger storage volumes and higher thermal inertia. Here, it is a benefit for heat pumps connected to thermal grids due to the many times higher inertia of the system. Thereby the heat pumps can be switched off for longer periods without any notable impact on the system and, in the end, the comfort for the end consumers. But flexibility is all about moving electric loads in time. Sooner or later, the heat pump needs to run harder to catch up with postponed heat production if no other heat production can cover up for the lost heat production. Here, heat pumps in thermal grids many times have an advantage compared to stand-alone heat pumps in buildings as there are alternative heat production available. But other barriers like high power fees or a limited heat source can force the heat pumps to operate in a certain way that limits a flexible operation.

To use many small units aggregated as a flexibility resource is new compared to what historically has been used for balancing services, when these 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. 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 partly different. One example is the activation time, where the local markets have no function for frequency control and the activation could thus be slower or scheduled in advance. If the heat pump operation can be planned it is likely that the heat pumps can deliver flexibility with a lower risk of poor comfort.

Thera are different way to control smaller aggregated heat pumps in single family buildings for delivering explicit flexibility. Either the heat pumps are connected and controlled separately with focus on the heat pump only, or they are controlled via an Energy Management System (EMS) controlling several energy related units in the building. More and more buildings are investing in solar-PV, electric cars, and home batteries. An EMS gives the possibility to control all equipment together and eventually also measure the flexibility delivered, on the other hand the system gets more complex, and the cost risk increases as additional equipment dedicated for the control is needed. Here it comes down to the economic potential for delivering flexibility and the benefits with a central EMS. Delivering flexibility as a service risk to lead to additional investment costs, lower efficiency of the heat pump and lower comfort for the end user. Thereby the end user needs to be compensated, probably with revenues for the delivered flexibility but potentially with other benefits.

Standardization is important when it comes to communication with the heat pump, to have the communication standardized will make it easier for the parties involved. The aggregators will better know what is possible to achieve and how to control their heat pump pool and the heat pump manufacturers will know what to implement in the heat pumps control systems. In the longer run an international standard would be optimal, avoiding developing different solutions in different countries.

In the summer of 2023, the EU commission released the final draft of “Code of Conduct on energy management related interoperability of Energy Smart Appliances (V.1.0)” (DG ENER, 2023). 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 should “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.

It has been shown that heat pumps are relatively slow to change speed when the compressor is running but also starting a compressor to a predefined power consumption is slow compared to the demands for several of the TSOs ancillary services. It takes several minutes in both cases. But, the auxiliary resistive heater for heat pumps in buildings 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. Using 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. Similarly, a potential way forward to decrease the activation time for heat pumps in thermal grids can be to operate them in combination with an electric boiler. The boiler has the technical ability to react and change the electric load fast. In the next step, the heat pump can step in and adjust its power consumption, and the boiler can be phased out to avoid a decrease in efficiency.

8 Conclusions

- The ongoing electrification of society increases the demand for electricity and puts pressure on the existing grid infrastructure. The need for flexibility to balance variations in electricity production is foreseen to increase to achieve a resilient and efficient power system. Flexibility can also help to reduce problems with bottlenecks and shortage of capacity in the electricity grids.
- Heat pumps are sector coupling units and can support the power system by connecting the electricity sector with the heating sector. Thereby, heat pumps can provide flexibility to the electric power system by exploitation of storage capacities and thermal inertia available in the heating sector.
- The term “flexibility” is wide and can be divided in different ways.
  - With focus on the time frame flexibility can be divided into short- mid- and long-term flexibility. Where Short-term flexibility can provide balancing services with a short duration or be used to balance hourly fluctuations within a day. Mid-term flexibility can balance daily fluctuations within a week or weekly fluctuations within a month. Long-term flexibility can balance monthly fluctuations within a year.
  - Flexibility can also be divided into implicit- and explicit flexibility, where 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 flexible power use as a service.
- Several potential markets for flexibility have been identified, but for heat pumps many of the markets are relatively new. It varies how mature the markets are, but also what possibilities heat pumps have to fulfill the technical requirements set to contribute to the market.
- Important aspects for heat pumps to fulfill to participate as a flexible resource is defined by their technical constraints. Important aspects are the activation time needed and the duration of the flexible resource. The duration is influenced by other factors like the thermal inertia and storage size. Other technical constraints can be the possibilities to measure changes in electric load with high accuracy.
- How to communicate with heat pumps related to demand response is an important aspect, especially for small, aggregated heat pumps. Today there is no standardized communication method suitable for demand response from heat pumps, but several promising alternatives exist. OpenADR and IEEE 2030.5 are two US-based standards that have large potential for enabling demand response from heat pumps. Interesting European alternatives are EEBus and EFI/S2. There are also several building automation protocols, and solutions that are built upon them, that are evolving and can potentially be used for demand response from heat pumps.

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