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On heat pumps in smart grids: A review

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ABSTRACT

This paper investigates heat pump systems in smart grids, focussing on fields of application and control approaches that have emerged in academic literature. Based on a review of published literature technical aspects of heat pump flexibility, fields of application and control approaches are structured and discussed. Three main categories of applications using heat pumps in a smart grid context have been identified: First stable and economic operation of power grids, second the integration of renewable energy sources and third operation under variable electricity prices. In all fields heat pumps - when controlled in an appropriate manner - can help easing the transition to a decentralized energy system accompanied by a higher share of prosumers and renewable energy sources. Predictive controls are successfully used in the majority of studies, often assuming idealized conditions. Topics for future research have been identified including: a transfer of control approaches from simulation to the field, a detailed techno-economic analysis of heat pump systems under smart grid operation, and the design of heat pump systems in order to increase flexibility are among the future research topics suggested.

1. Introduction

Heat pumps (HP) are a wellknown technology for heating and cooling of residential buildings. From 2010 to 2015 approximately 800.000 electrically driven heat pump units have been sold in the European Union (EU21) per year [1] adding up to more than 7.5 million units. Thus, HPs play an increasing role in the heating sector. In electrically driven heat pumps, electricity is used to lift low exergetic heat to a higher temperature and consequently higher exergy level by running a vapour compression cycle. The heat is taken from sources like ambient air, water or ground. Heat pumps have been known as a low CO_2 emission technology for heat generation in the residential sector. Heat pump coefficient of performance (COP) and the CO_2 emissions of electricity generation determine the emissions during the operation phase of the heat pump.

1.1. Changes in the energy system and the role of heat pumps

Over the recent years three main developments that affect the role heat pumps in the energy system are observed.

First, due to progress in heat pump development [2] COPs of heat pumps are increasing. An evaluation of over 800 heat pumps at nominal conditions listed in reference [3] shows that COP values for market available heat pump units lie in the range of 3.2 to 4.5 for air source heat pumps (ASHP) and between 4.2 and 5.2 for ground source heat pumps (GSHP) for testing conditions according to EN 14511.[1]

A second trend besides growing COP values is the growth of renewable electricity (RE) generation from wind and photovoltaic (PV) plants. On the level of individual households this results in the emergence of prosumers, consuming and producing electricity at different points in time [4,5]. In 2015 more than 32% of the annual electricity demand in Germany is met by renewable sources [6]. On the long run the commitment to reduce the use of coal-fired power plants, as decided at the Paris Climate Change Conference 2015 (COP21[2]), will hopefully lead to lower CO_2 emissions for electricity generation and thus most likely for heat pump operation. In a simulation and optimization study, which investigates different pathways to a renewable German energy system [7–9], it was found that heat pumps can play a major role for de-carbonization of the heating sector. For the Danish case it is shown in reference [10] that district heating schemes with combined heat and power plant (CHP) and individual residential heat pumps offer the best solution for transforming the residential heat sector towards reduced CO_2 emissions. Reference [11] highlights the CO_2 emissions reduction potential of air source heat pumps in an

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[1] T_{Air}=2°C, T_{Water}=35°C;T_{Brine}=0°C, T_{Water}=35°C.
[2] (FCCC/CP/2015/L.9/Rev.1)

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Fig. 1. Wordcloud of the 50 most frequent words in paper titles when querying for "heat pump", "smart grid" at Reuters Web of Science.

exploratory simulation for the U.K. in a 2050 scenario.

With increasing generation of electricity from wind and PV new challenges arise in the power sector. Traditionally electricity generation would follow the demand. This is changing towards a system where increasing shares of the demand will be constantly adjusted to follow a fluctuating electricity generation. This leads to an increased need for flexibility on the demand side [12,13] and the need for storage capacity [14] to guarantee the balance of electricity demand and generation.

A third major development over the recent decade is the increased availability of small and relatively performant computing capacities, progress in algorithm design and the further spread of wireless communication networks with sufficient bandwidth to exchange measured data or control signals. The vision of the internet of things [15], where devices of all kinds are connected and help solving problems or increasing comfort of humans has emerged and partly became reality. In the field of energy, particularly in the power system, the concept of a smart grid has emerged.

But what is a smart grid exactly and what roles will heat pumps play in it? There is no clear answer to these questions, yet. The interpretations of a smart grid, the definition of its system boundaries and possible applications of heat pumps are diverse. This diversity in research interests and interpretations is illustrated by Fig. 1 showing the 50 most frequent words appearing in the title of scientific articles on a query of Reuters Web of Science using "heat pump" and "smart grid". The topic of heat pumps in smart grids is of high relevance and considerable knowledge has been built over the recent years. From 2007 to 2015 the topic of heat pumps in smart grid has come into the focus of research. For this period a total of 121 publications were listed on Reuters Web of Science[3] shown in Fig. 2.

1.2. Aim of study

The aim of this study is to provide a structured overview of the current discussion on heat pumps in a smart grid context with focus on residential applications. The study aims at providing new researchers with a quick start on the topic and experienced researchers with a summary of findings, structure and guidance for future research. Two main subcategories are analysed in further detail:

1. Applications of heat pumps in a smart grid context.
2. Control schemes used for these applications.

Heat pump technology in a smart grid context deserves a detailed and separate analysis on its own since it is a key technology linking the electric and the thermal energy sector. Furthermore, heat pumps show technology specific characteristics, explained in Section 2.2, that need to be considered when discussing their use to provide flexibility to the

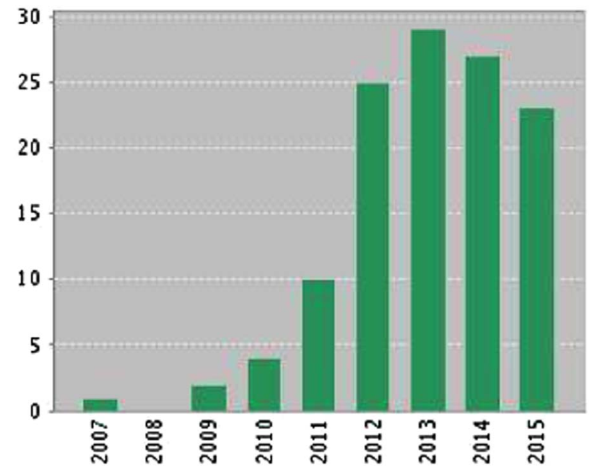

Fig. 2. Number of publications appearing on Reuters Web of Science querying for "smart grid" refined by "heat pump" (16/1/2016).

power system.

For this review over 240 studies presented at international conferences, in peer reviewed journals or as academic theses were analysed and the most interesting and relevant ones (in the authors opinion) were selected. In Section 2 concepts and system definitions related to heat pump systems in a smart grid as well as technical aspects regarding heat pump flexibility are discussed. The main applications of heat pumps in a smart grid context are presented in Section 3. The concepts and ideas used for control are presented in Section 4. The paper concludes in Section 5 with a recommendation for further research.

2. Heat pumps in a smart grid context

As a first step, important concepts and aspects concerning smart grids, heat pump systems and technical aspects regarding the flexibility of heat pumps shall be discussed.

2.1. The idea of a smart grid

The term "smart grids" found in academic literature is used in many ways and is used differently by different authors depending on the parts of the energy system that are considered. As an example the German grid agency defines smart grid in a way that only parts of the actual power grid are considered. In this definition the target of a smart grid is to optimally use the existing line capacity, manage congestions and improve safety. The benefits of a smart grid following this definition are mainly for the grid operator. Savings are achieved by decreasing the need for additional line and transformer capacity. A clear distinction is made between capacity and energy. Devices used to match generation and demand with the target of optimal power plant use and dispatch are seen in the context of energy and are not part of the core smart grid as such [16].

A similar but less strict line of argumentation is followed by the US department of energy [17], which excludes devices such as wind turbines, plug-in hybrid electric vehicles and solar arrays from the smart grid. With this definition only control and communication devices that provide the possibility to integrate and intelligently control distributed generation and consumption devices are seen as smart grid components.

A wider perspective is taken in reference [18] where the vision of a smart grid is defined as: "*… an electric grid able to deliver electricity in a controlled, smart way from points of generation to consumers that are considered as an integral part of the SG since they can modify their purchasing patterns and behaviour according to the received information, incentives and disincentives…*". The focus on consumer

[3] Accessed 16/1/2016 querying for "smart grid" refined by "heat pump".

flexibility is a central point of demand response and demand side management (DSM) [5,12,19–24] as well as decentralized energy management [25,26] approaches.

A wider, more holistic argumentation is stated in reference [27], where it is suggested to extend the focus of a smart electric grid towards a whole energy system approach including not only electric demand and generation but as well the heat and transportation sector.

All of the recent literature has in common that the challenges of integrating fluctuating renewable energy generation are tackled with a set of distributed controllable devices. This reaches from pure power line components as stated in reference [16] over heat generation units [27] all the way to demand side measures where operation of individual household appliances [28,29] or even persons' electric consumption behaviour is changed [30–32].

The main motivations for a smart grid, as stated in academic literature, are:

1. Minimum cost for installation and operation of the electric grid.
2. Stable operation of the electric grid within the allowed boundaries for frequency, voltage and transmission capacity.
3. Optimal use of the generation resources mostly targeting minimum CO_2 emissions or minimum cost.

In the context of a smart grid, heat pumps are seen as part of the demand side that can be actively managed to support the realization of a smart grid [12,33–42]. Coupling heat pumps to thermal storage or actively using buildings' thermal inertia offers the possibility to decouple electricity consumption from heat demand, which brings flexibility in operation that can be used in a smart grid.

2.1.1. Time scales and the need for flexibility in the power system

The need for flexibility in the power system is frequently motivated by an increase in renewable energy [12,43] and the resulting need for an ability to react or plan ahead [18] for safe and efficient power system operation. A transition towards a renewable electricity sector means that all services that are nowadays provided by conventional power plants will have to be provided by other devices.

For an individual device the definition of flexibility provided by Eurelectric [43] highlights the important properties as seen from the electric point of view:

"On an individual level flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterise flexibility include the amount of power modulation, the duration, the rate of change, the response time, the location etc."

Fig. 3 shows the time-wise characteristics of selected fields and mechanisms in the power system, where flexibility of the demand side might be used to create benefits. The mechanisms used to enable flexibility change with the service in the power system that is to be provided [12,18,44]. Depending on the speed needed for reaction

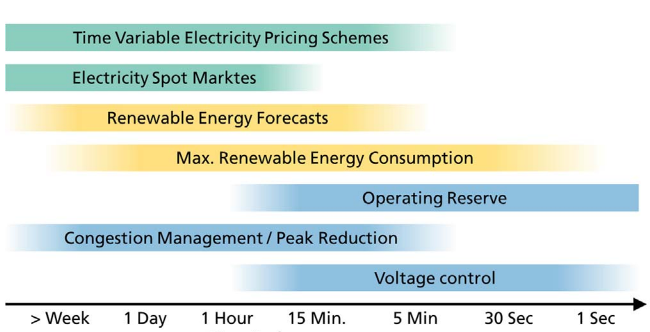

Fig. 3. Time scales of selected areas and applications in the power system.

different ways are used to activate flexibility. Direct activation signals are used to provide operating reserve. For primary reserve those are based on direct measurements of the grid frequency on-site; real time signals are sent to the devices for spinning and non-spinning reserve. Another way to activate flexibility is the use of prices. Those are with decreasing dynamics: Real time pricing, day ahead pricing and time of use tariffs [18].

The potential of heat pumps to provide flexibility to the power system depends on the case of application and the characteristics of the HP system.

2.2. Heat pump systems

A brief description of the most important features considering residential heat pump systems with respect to smart gird applications is given in the following. For more detailed information on HP technology and different applications refer to references [2,45–49].

2.2.1. Heat pumps in brief

Heat pumps are used to provide heat using thermal energy from a heat source and additional energy needed for compression. The energy needed for compression depends on the compression principle. In this paper the focus is on electrically driven, vapour compression heat pumps.

A basic vapour compression heat pump cycle comprises two heat exchangers, one acting as an evaporator and another as a condenser, a compressor, and an expansion device. These four components, together with the working fluid enable the pumping of heat from the low temperature renewable heat source such as ambient air, ground, lake or sea water to higher temperature useful for space heating and/or domestic hot water.

In such heat pumps a stream of liquid refrigerant is evaporated at low pressure using the heat source. The refrigerant vapour is compressed, leading to a temperature increase. This compressed refrigerant stream is condensed at high pressure and thus high temperature. The resulting heat is transferred to the heat sink. The now liquid refrigerant is expanded to the low pressure level and the cycle goes on.

Depending on the source and sink temperatures only little additional energy is needed for the compression process. For compression in residential applications typically a compressor, driven by an electric motor is used. The coefficient of performance COP of a heat pump is defined as the ratio of usable heat and the needed electricity for this.

$$COP = \frac{\dot{Q}_{use}}{P_{el}} \tag{1}$$

Depending on the system boundaries the usable heat $\dot{Q}_{use}$ and the electrical energy necessary P_{el} include different components, such as compressor, fans and auxiliary systems [50]. The characteristics of COP can be explained using a simple Carnot model as found in thermodynamic textbooks like [51]:

$$COP \approx \eta \cdot \frac{T_c}{T_c - T_e} \tag{2}$$

In this simplified model all additional losses and deviations from the Carnot process are summarised in the efficiency η.

It becomes visible that the temperature lift from evaporator to condenser T_e,T_c has a major impact on efficiency. The condenser and evaporator temperature determine the pressure difference that needs to be overcome by the compressor. Increasing the temperature lift leads to reduction of heat pump efficiency. The sink temperature depends on the temperature level in the heating distribution system which might be radiator or floor heating. The performance of the heat exchangers and the current thermal output influence the temperature of evaporation and condensation.

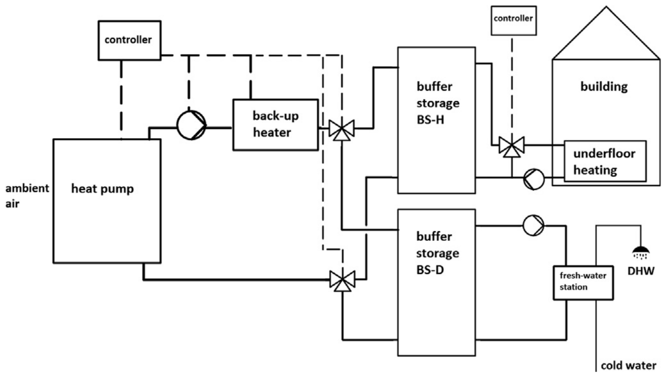

Fig. 4. Exemplary layout of a residential HP system [42].

2.2.2. Building level integration

An exemplary layout of a heat pump system is shown in Fig. 4. Air is used as heat source and water is used for the sink side. The system consists of the heat pump unit, a thermal storage tank for domestic hot water and a storage tank to buffer space heating demand. Floor heating is used as heating distribution system. An electric heater is used as an auxiliary heater to cover peak demand. Valves and pumps are needed for operation of the hydronic circuits.

Generally a residential heat pump system can be characterized by the type of heat source and sink, the technical features of the subsystems such as compressor type, refrigerant cycle properties and controls, and the heating system of the building. Fig. 5 shows the main distinctive features of residential heat pump systems.

The type of heat source and sink are important when characterizing heat pumps. The source and sink temperatures directly influence the unit efficiency as an increased temperature difference between source and sink leads to a lower heat pump COP. Hence the COP changes during the course of the year. As seasonal fluctuation in ambient temperature are usually higher than those of the soil or ground water, air as heat source leads to stronger seasonal changes in COP compared to ground as a heat source. Furthermore using air as heat source, frosting of the evaporator can occur and additional energy is needed for defrosting.

In residential buildings, the type of heat sink is linked to the type of heating distribution and storage system. Water is used for radiator or floor heating systems and the preparation of domestic hot water (DHW), whereas air is mostly used in ventilation and heat recovery applications. The temperatures that need to be provided by the heat pump differ depending on the requirements of the heat sink. Depending on the building physics commonly the highest temperatures are needed for the preparation of DHW (up to 65 °C) followed by radiator heating (up to 55 °C), ventilation (up to 40 °C) and floor heating (up to 35 °C) [52].

The type of storage used and the way it is integrated into the building energy system plays an important role when considering heat pumps for DSM applications. Water, phase change material or the building thermal inertia is frequently used as thermal storage material.

When water is used for heating distribution, this offers the possibility to easily store heat in tanks or to thermally activate building parts, which is done in reference [34,53–64]. When using building as storage, the buildings' wall or ground temperature and consequently the indoor temperature change when heat is stored. Hence, thermal comfort could change and this is an important point to be considered when actively using the building. Reference [65] shows that building physics play a major role in possible load advance with heat pumps. They conclude that for the U.K. building stock, heat pump blocking for 1.5 h is possible without violating indoor comfort . This time can be increased by adding buffer tanks and better insulation of the buildings. Reference [66] highlights that the amount and composition of the floor material impacts indoor comfort when load shifting is done with heat pumps. They suggest the use of PCM in building material to improve comfort and flexibility. A comparison of storage tank, considered as active storage, and the building mass, considered as passive storage is done in reference [67]. Heat pump flexibility is used to integrate wind power generation. The authors conclude that using building thermal mass as passive heat storage offers the most cost effective solution compared to heat accumulation tanks for the investigated case.

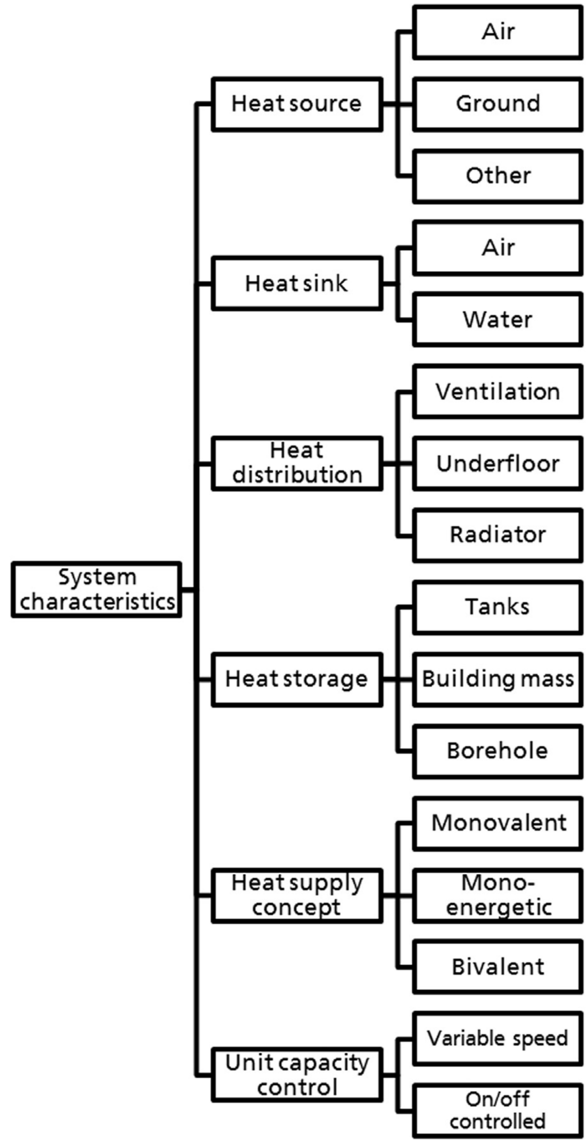

Fig. 5. Main distinctive features of residential heat pump systems.

Most of the heat pump systems in Europe are connected to a hydronic system and a thermal storage tank, which is reflected in references [35,37,40,68–90]. Thermal storage is used as space heating buffer and also for DHW. In Germany approx. 90% of the existing and 80% of the new built buildings are equipped with thermal storage tank when a heat pump is used [91]. As newer buildings are often well insulated and equipped with floor heating, with high thermal inertia sobuffer storage tanks are not always necessary. Using tanks for load shifting minimises the risk of high fluctuation of indoor temperature and thus comfort violations since the indoor set-points remain unchanged. This requires thermostats in the rooms and mixing valves in the supply and return pipes of the heat distribution system to keep the room temperature at the wanted level whilst increasing the temperature of the storage.

When ground source heat pumps are combined with renewable electricity such as solar PV and wind, there is a possibility to convert the renewable electricity to heat and store the heat seasonally in the borehole or a borehole field comprising several arrays of boreholes as shown in reference [92,93].

The annual performance of the heat pump systems is strongly influenced by how the heat pump capacity is regulated depending on the variable heat demand. Fixed speed heat pump units are operated in an on-off manner, whereas variable speed heat pumps allow a continuous regulation of the compressor speed over large parts of the operation range. This allows a control of the thermal output or the electric demand. For applications in Swedish single family houses it is shown in reference [94] that variable speed heat pumps can but do not necessarily improve system efficiency. For smart grid application the possibility to increase or decrease electric consumption offers higher operational flexibility which is for example used in order to improve power quality [72,95] or to increase local PV self-consumption [78,87]. Reference [96] demonstrated the concept of rapidly adjusting compressor speed to provide ancillary services on a lab scale.

The choice of refrigerant and the properties of the thermodynamic cycle influence the allowed temperature range of operation, part load characteristics and heat pump efficiency (for further reading see reference [2,45]).

Depending on the type of heating system, additional heat sources can be used together with the heat pump. If the entire heat demand is supplied by the heat pump, the system is referred to as monovalent system. Furthermore an additional heat source such as an electric heater (mono-energetic system) or a fossil fired boiler (bi-valent system) can be used to cover demand peaks. The type and use of the auxiliary heater influences system seasonal performance factor (SPF) and CO_2 emissions during operation.

2.2.3. Consideration on flexibility of heat pump systems

The potential flexibility that can be provided by heat pumps for smart grid purposes is influenced by different factors. In reference [65,76,97] a structured assessment of the load shift problem with heat pumps is described and extended as following.

First of all appropriate controls and communication interfaces between the heat pump unit, the building energy management system and the power system or an external body are required. If these are given, the potential flexibility is mainly determined by the thermal demand, the heat pump size, the storage size, the dynamic system properties and the flexibility requirements from the power system. Fig. 6 depicts the main factors influencing heat pump flexibility.

The thermal demand and its profile over time determines the maximum amount of energy that can be shifted within a given time period. In residential applications thermal demand is the sum of space heating load and the demand for domestic hot water (DHW). Depending on the building type, the location and the occupants behaviour, the energy demand varies during the day and year.

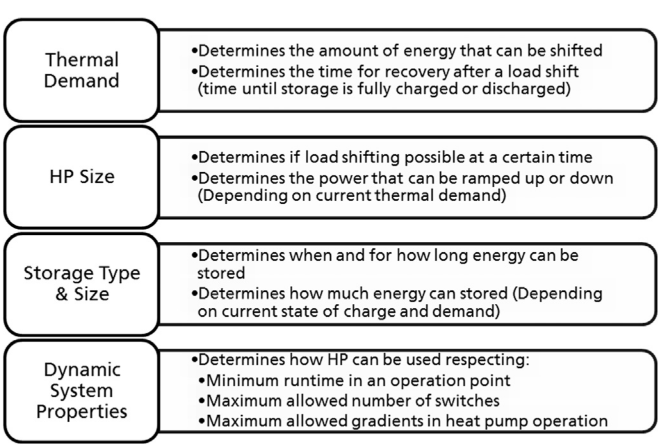

Fig. 6. Important points that influence flexible operation of heat pumps systems.

The heat pump capacity limits the possibility to increase or decrease HP's electric consumption by switching on or off, or by ramping the heat pump capacity up or down. The difference between the actual heat demand and the heat production of the heat pump unit determines the change in energy content of the storage. If the heat pump capacity is equal or smaller than the current heat demand the only flexibility option is reducing heat production of the heat pump, given that the storage is not empty. In case that thermal capacity of the heat pump exceeds thermal demand, HP thermal output can be increased to charge the storage. Since COP and maximum thermal capacity are dependent on source and sink temperatures, the available flexibility is not constant during the course of the year. Falling outdoor temperatures usually requires higher temperatures in the heating circuit to transfer the needed heat to the building, which leads to higher sink temperatures and hence reduced COP and reduced maximum HP capacity. This leads to reduced flexibility in times of high heat demand [76].

The type and capacity of the thermal storage determines how much energy can be shifted over a certain period of time. For water tanks, the maximum allowed temperature in the tank is limited by the maximum possible temperature of the heat pump and the safety issues. As a consequence, usable tank capacity decreases with decreasing ambient temperatures as the minimum required tank temperature increases. For building activation, indoor comfort is the most critical point. Building thermal mass, solar and internal gains of the building and influence the available storage capacity over the course need to be considered.

The amount of energy that can be shifted with a given storage capacity depends on the charging and discharging frequencies. The charging and discharging is determined by the flexibility requirements from the power system, the thermal load profile and the applied control strategy. This determines the number of charge and discharge cycles per day. A high number of cycles result in an intensive use of the storage and a higher amount of shifted energy compared to slow infrequent charging and discharging of the storage.

Finally the dynamic properties of the heat pump unit are important for flexibility. The speed of response is limited by the maximum allowed change rate of compressor speed and thus power consumption over a certain time. A minimum run and pause-time requirement as implemented in most heat pumps further decreases flexibility. Since frequent switching events reduce the lifetime of the heat pump this should be avoided, which further reduces heat pump flexibility.

3. Applications of heat pumps in a smart grid

Integration into a smart grid will change the way heat pumps are used. This leads to new requirements for HP control and design. In fact, some applications in a smart grid might be more suitable than others due to the technological characteristics of heat pumps.

Over the recent years different smart grid applications and control approaches for HPs have been covered by a number of scientific research projects and publications. The fields of application and conditions under which the HPs operate vary significantly from study to study. Nonetheless, they can be categorized in three main domains (see Fig. 7):

- Provision of ancillary services for the power grid, sometimes referred as grid-friendly operation.
- Facilitate the integration of renewable electricity on building, distribution grid and power system level.
- Operation of heat pumps under variable electricity prices.

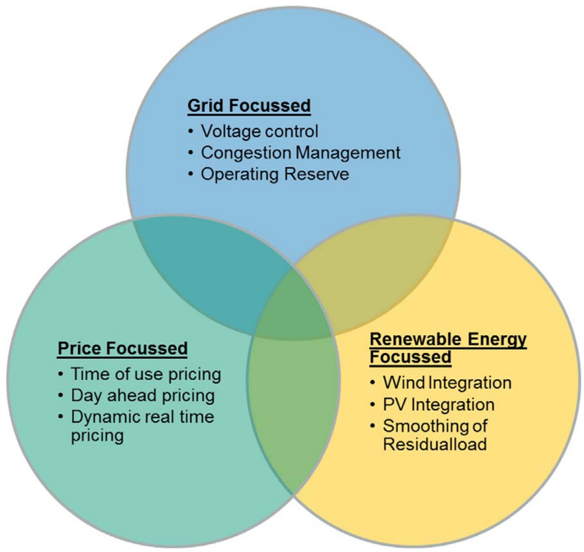

Fig. 7. Main fields of applications with heat pumps in a smart grid context, regarding the use-cases presented in academic literature.

Clearly these applications overlap and are partly mutually dependent. However, most studies focus primarily on one of these aspects. An overview over the studies, their key findings and references is given in Table 1.

3.1. Grid focussed

In the category of grid focussed applications, heat pump operation is aimed at providing ancillary services to the grid to allow a stable and cost efficient operation of the electric grid. The list of ancillary services according to the references [98–100] contains:

- Voltage control
- Congestion management
- Provision of spinning and non-spinning reserve

In **voltage control applications** the heat pump is employed in the electric distribution grid to guarantee that the voltage is within the allowed limits [72,95,101]. Essentially, this means reducing HP's active power demand in times of local under-voltage and increasing it in times of over-voltage. Too high values for local voltage in distribution grids may occur when PV installations are present and feeding in electricity [95,101]. Problems with too low voltage values are caused by high demands and can be caused by heat pumps itself [95,102]. Reducing and coordinating heat pumps' active power demand in such situations helps to stabilize local voltage. The References [72,95,101] use a combination of simplified heat pump system models to calculate the power demand at the buildings grid connection point and a simulation of the electric network to study the impact on local voltage. The results show that HPs can help overcoming over-voltage problems caused by PV but the applicability is limited by the seasonal mismatch of heat demand and PV production [72,95,101,103]. Power consumption of a variable speed heat pump can be adjusted in reference [95] according to local voltage conditions. Voltage stabilisation is achieved using a droop control, which adjusts compressor speed proportionally to the level of voltage violation. A piecewise linear control characteristic is implemented depending on heat pumps actual working point.

The provision of reactive power with heat pumps for voltage control is not discussed although theoretically possible using the inverter.

An application closely related to local voltage control is **congestion management** in the distribution grid to avoid limitations in the transformer and line capacity. In this context, heat pumps are operated to avoid transformer overloading [40,104] thereby helping to reduce or postpone investments for grid reinforcement [41,102,104]. However it has been shown that increasing the number of heat pumps in a distribution grid can possibly lead to higher transformer loadings and lower voltage levels [95,102]. To reduce transformer loading heat pumps can be switched depending on the state of the transformer as done in reference [40]. Operation can be planned to avoid simultaneity of load peaks on household andgrid level, which is discussed in reference [41] as one strategy. Furthermore, voltage and transformer loading problems can be prevented by a an optimised planning of HP operation. Nonetheless, in most studies a real-time control strategy is used for the HP to react to unforeseen events [40,72,73,104] and sometimes combined with day-ahead planning to avoid operation during critical periods [105,106]. The response to problems in transformer loading or local voltage is done by switching on heat pumps when voltage levels are below a certain threshold or vice versa [40,101]. For this case minimum unit run times of the heat pumps should be considered [101].

In the field of grid focused applications the **reduction of peaks** in load and feed-in plays an important role. The general set-up of these studies involves a) putting the system boundary at the grid connection point of the individual household and trying to reduce individual load peaks or b) using an aggregated load profile (usually on a national level) as a signal for load shifting and trying to reduce load peaks on this level. Target of operation is a) to avoid peaks (positive or negative) in the household load profile or b) to shift the load of the heat pumps to hours of low aggregate loads [23,33,36,39,42,59,74–77,81–83,107–111]. Shifting is typically achieved by planning operation on a day-ahead basis.

Potential benefits of peak reduction on an aggregate level involve lower electricity generation costs (merit order effect), less need for peak generation and reserve power plants and less need for transmission capacity. The generation of renewable electricity can lead to negative load peaks (valley) on aggregate and individual level. Reducing these peaks (valley filling) at individual level could lead to decreased costs for grid connection depending on the applied electricity pricing scheme. When demand side management is done to counteract feed-in peaks from renewables, this leads to an increased capacity of the electric grid to integrate renewable electricity generation, especially on the local distribution grid level (in the case of negative peaks caused by a feed-in surplus from renewable energy sources).

To balance electricity generation and demand, and ensure a stable frequency in the electric grid **spinning and non-spinning reserve** capacities are available to the transmission system operator (TSO). The reserve capacity are generation units or electric consumers that can be regulated upwards and downwards on demand. The time scales for regulation vary between a few seconds (primary reserve), to a few minutes (secondary reserve) up to more than ten minutes (tertiary reserve). Although operation of small responsive loads [112,113] like heat pumps on the reserve markets is heavily discussed in review articles on demand side management, flexibility and smart grid [12,18,24], the examples concerning heat pumps on that field are limited [70,100,101,105,114–121]. In most countries the organisation of reserve provision is done using market mechanisms to decide which units will be used. To participate in the reserve markets a minimum unit or pool size is needed in most countries (5 MW for Germany, 10 MW for northern European countries). Hence using heat pumps in the reserve markets leads to the challenge of operating a large number of small units. This includes:

- Predicting the flexibility of a heat pump pool in a way that it can be traded in the reserve markets.
- Planning of bidding strategy and scheduling of the pool.
- Control of a large pool after a reserve power call has been received.

The studies on reserve power with heat pumps consequently put the focus on three aspects: First, forecasting the flexibility of a pool of heat

Table 1
Summary of the main applications and the commonly selected approaches and reported results.

Applications		Target	Findings	References
Grid	Voltage Control	• Keep voltage in tolerance band • Reduce critical hours • Reduce grid reinforcement	• Significant reduction of voltage problems with appropriate controls • If HP is not controlled properly, could lead to voltage problems • Limited beneficial effects of storage increase	[40,72,73,95,101,102,105,106,143]
	Congestion Management	• Keep transformer load within tolerance • Reduce peaks	• Critical situations in the distribution grid appear mainly in summer (PV) or cold winter (HP) • Controls can help reduce load peaks in most cases but not always • HP can help reduce grid problems induced by PV, but potential is limited • Potential of HP for grid services shows strong seasonal dependency • Grid reinforcement due to increased HP penetration can be avoided or limited with appropriate controls	[33,39–41,81,83,104,107,108,143–148]
	Operating Reserve	• Providing reserve power	• Pools of heat pumps are able to operate on the reserve market • Focus of studies on development and demonstration of control strategies • A bidding and a reference tracking strategy is proposed as controls	[70,101,105,114–121]
RE	Wind Integration	• Increase wind consumption • Decrease fluctuations and peaks • Reduced need for peak power plants based on flexible HP operation	• Mostly focus on aggregated load profile • Reduce carbon emissions • Reduced imbalances • Correlation of wind availability and space heating demand (northern/central Europe)	[76,84,86,97,108,127,129,149–151]
	PV Integration	• Increase self-consumption rate • Reduce feed-in peaks • Reduce voltage problems • Reduce carbon emissions	• Mostly focus on individual household • Increased self-consumption through heat pumps • Reduced PV-feedin peaks at noon • Seasonal discrepancy between PV production and heat demand limits self-consumption • Variable speed HP increase self-consumption for small PV sizes • Limited impact of increased storage size on self-consumption • Efficiency losses reported	[26,37,38,58,71,74,75,77–79,84–90,111,131,132,146,149,152,153]
	Residual Load	• Smooth load curve • Reduce peaks	• Significant reduction of peaks and valley filling achieved • Reduction of power gradients • Reduced cost of el. generation,	[34,76,82,83,90,151]
Price	Variable Electricity Prices	• Minimise annual cost of energy	• Most studies focus on decentralized control/scheduling algorithms • Total electricity purchase cost reduced • Positive and negative impact on efficiency reported • Significant load shifting achieved through price signals	[23,36,37,54,56,57,62,64,66,68–70,77,79–81,85,108,110,120,123,124,126,136,138,139,142,150,154–158]

pumps [70,122,123]. Second, the calculation of a bidding strategy and evaluation of market attractiveness [115,121,124,125]. Third, controls of a pool of heat pump for participating in the reserve markets [114,116,118,124,126,120].

In references [117,125] forecasting the heat demand and electric demand of a heat pump pool is done using a lumped model. To supply the electricity at lowest price an optimized operation schedule of the pool is calculated on a day-ahead base. This schedule is adjusted intra-day if needed. If economically attractive, participation on the reserve markets is done. A control approach focusing on trajectory tracking of a pool of heat pumps, as needed in case of reserve power calls for the pool, is performed in references [114,118,120,124,126]. A heuristic strategy based on a sorting algorithm or priority stacks of available devices is used for unit dispatching and is reported to work for a heat pump portfolio of 10,000 units. In this approach the most suitable units are successively turned on or off to reach the wanted power output. The approach is successfully demonstrated in a field test with 54 heat pumps [116].

3.2. Renewable energy focussed

The main targets of heat pump operation in renewable energy focussed papers are an increased utilization rate of renewable electricity, a reduction of feed-in peaks and smoothing of the residual load curve. Special attention is paid to the **integration of wind and PV** electricity as the two main fast growing sources of fluctuating renewable electricity generation.

The references [84,127] show that the integration of **wind** power on building level can be supported by heat pumps and the required electricity from the grid can be reduced up to 95%. Reference [84] highlights the benefits of variable speed heat pumps for this case as they are able to constantly adjust electricity consumption. However since wind power plants are mainly installed in capacities above 1 MW, utilization of of the generated electricity has to be coordinated between several heat pumps. For this purpose heat pump systems may receive an external signal (like prices or current wind power production) to adjust their operation. Electricity generation from wind, the resulting negative peaks and fluctuations are highest during winter season as references [76,128] show for Denmark and Germany. This corresponds well with the heat demand and the seasonal variation in load shifting capacity of heat pumps [54,73,76,97]. Reference [129] concludes that even without adjusted controls the electricity demand of heat pumps matches the availability of electricity generated by wind power in Denmark. Furthermore the references [129,130] and reference [36] show that on an aggregate level heat pumps, operated in an optimal way, can be used to increase the absorption of wind power in the power system while at the same time reducing the need for peak capacity and thus costs.

The integration of **PV** is discussed mainly on two levels: First, on the level of individual households, where self-consumption is the focus of most studies, and second on the level of the electric distribution grid, where a reduction of feed-in peaks is the focus.

In many countries PV electricity generated locally has become cheaper than the electricity buying price for households and self-consumption has become an economically viable option. In this application which is presented in references [26,37,71,75,77,78,84,85,88–90,131–134] heat pumps are used to increase the self-consumption rate of locally generated PV. The self-consumption rate is the share of on-site consumed PV electricity with respect to the total PV generation over the course of the year.

Increasing PV self-consumption is achieved by shifting heat pump operation to hours where PV electricity generation exceeds household electricity consumption. If information about PV generation and demands are known ahead of time HP operation can be planned ahead. If only real-time measurements are available HP operation is triggered when PV feed-in exceeds a threshold. In the references [87,135] compressor speed of a variable speed heat pump is adjusted real time to minimise interaction with the power grid.

The achievable self-consumption rate varies depending on the size of the PV plant, the thermal and electric demand of the household, the size of the thermal storage and the used controls of the heat pumps. Self-consumption rates from 30% up to over 65% are reported [71,87,89,135]. A limiting factor for self-consumption with residential heat pumps is the seasonal mismatch between PV generation and space heating demand. During summer time PV electricity generation exceeds HP electric demand and the opposite occurs during winter times given central European climate and a reasonably sized PV installation.

In reference [87] for German climate and building conditions, self-consumption rates could be increased by up to 10% when adding a heat pump to a single family house with PV. In reference [78] it is shown that adjusting controls for variable speed heat pumps can further increase self-consumption by around 7%. In reference [87] the use of variable speed heat pumps leads to up to 14% higher self-consumption rates compared to on-off systems, depending on the building energy standard (higher for older buildings). The advantages of variable speed heat pumps decrease with increasing PV size. In this case the benefits of modulation decrease as electricity surplus is sufficient to power the on-off heat pump. An option to further increase PV self-consumption is to allow higher storage temperatures when the HP is operated with PV electricity. Increased self-consumption might come at the cost of decreased system efficiency though. Depending on the control approach, the temperatures of the storage tank might be kept on an unnecessary high temperature level already early in the day or even for several days in a row if controls mainly focus on the maximisation of PV self-consumption. Predictive controls can be used to only store the heat needed for the coming period, thereby minimising losses whilst maximising self-consumption. The benefits of increased thermal storage to increase PV self-consumption seem limited [38,74,75,78,135] as storage losses and additional investment costs quickly overcompensate additional self-consumption gains. A decisive parameter for the potential benefit of storage is the frequency of sunny and cloudy days and the structure of thermal demand.

Solar fraction is another parameter that is frequently used when PV heat-pump applications are discussed. The solar fraction is the annual share of the heat demand that can be supplied using heat generated with PV electricity. For the German case values of about 25% up to 40% are reported in the references [77,87].

On the level of the electric distribution grid, the goal of operation is to reduce feed-in peaks caused by PV. As feed-in of multiple PV units occurs locally, approximately at the same time, reducing the feed-in peak is needed to allow stable operation of the distribution grid and to increase the tolerance towards integrating PV into the power system. The strategies for this are discussed in Section 3.1. A reduction of peaks up to 30–55% is reported in the references [74,75,89].

3.3. Price focussed

Operation under time variable electricity prices is the third major category of studies. Clearly, prices are a vehicle to incentivise a certain electricity consumption behaviour. Prices are used to convey information about critical events, capacity limits, predictable load and generation situations and congestions or simply to reflect the real-time or day-ahead events like surplus renewable energy generation. Variable electricity prices are closely linked to the grid and renewable energy focussed applications, and are considered to be a central component of the smart grid. Different pricing schemes are applied in studies concerning heat pumps, which makes it hard comparing numbers on cost savings. Besides the level and the ratio of high to low prices the main difference between different pricing schemes lies in their timely characteristics. **Time of use** (TOU) prices such as classical high-low tariff schemes as used in the references

[33,69,86,136,137] might be static over a long period (up to many years), whereas dynamic prices as used in the references [23,36–38,56,57,59,64,77,82,104,115,116,119,120,124,135,138,139] might change at daily (**day-ahead pricing**) or even shorter intervals (**real-time-pricing**). A frequently used price signal are the day-ahead electricity spot price or a price that is based on it. When prices are known ahead of time, heat pump operation can be planned using heuristics or optimal control methods, which are discussed in Section 4.3.2 and used among others in the references [37,57,69,77,137,140]. For more information on market design and prices see reference [141].

The references [74,77] state that operating heat pumps with day-ahead electricity spot prices of the European Power Exchange EPEX, leads to a shift of heat pump operation towards night time when costs are low. In reference [77] it is shown for an ASHP that operation along time variable prices might lead to reduced HP efficiency due to higher storage and lower ambient temperatures during operation and increased part load ratios. The fact that lowering operational costs might not lead to higher efficiency is also stated in reference [142] where 8% lower electricity costs but 2% higher electricity demands are reported. In reference [82] even up to 19% higher electricity consumption is reported due to load shifting.

Furthermore, it is hard to quantify the benefits of changed operation as the cost savings that can be achieved strongly depend on the price assumptions of the individual study and the extend of idealisation in the assumptions. Reported savings reaching from 7% [57] up to around 35% [56]. Structure and volatility of prices, the quality of forecasts and a information about the system are decisive parameters influencing the results.

Changing operation in order to minimise costs might not only lead to increased energy consumption but also to indoor comfort deterioration as highlighted in the references [57,140] by showing the pareto curves for comfort violations vs. economic savings.

4. Controls

Along with new applications, different approaches for the integration and control of heat pumps in a smart grid context have emerged and are briefly introduced in the following. Many of the control approaches have been enabled by the emergence of small, affordable and sufficiently powerful computation and communication technology, new communication protocols and tailored algorithms over the recent years.

4.1. Tasks and targets

In the previous section it has been highlighted that the main cases of applications considered for heat pumps in a smart grid context are the provision of services to the electric grid, facilitating the integration of renewable electricity generation into the power system and operation under time variable electricity prices. The role heat pumps will play in the power system will also influence the way heat pumps are operated and controlled. The main control task of the heat pump, the supply of thermal energy to meet the comfort requirements, will be extended when integrating the heat pump into the power system. This results in two tasks required from future heat pump controllers:

1. Planing and scheduling (mostly day-ahead) of the heat pump operation ahead of time as a reaction to a forecast or broadcasted signal (e.g. day-ahead prices)
2. Change of operation as a reaction to a real-time signal

The control approach of the heat pump and storage is selected depending on the application. For all applications controls should avoid a violation of user comfort requirements, while maximizing utility. The objectives are to achieve the thermal comfort of the building occupants at:

a) Minimum cost of operation
b) Maximum efficiency of the system
c) Maximum self-consumption
d) Maximum benefits for the power system (as stated in the previous section)

Often it is possible or required to target multiple objectives simultaneously. In the remaining Section the main concepts as found in heat pump related work are briefly discussed. The focus is on providing an overview of the most important concepts and findings with respect to the application of heat pumps in a smart grid context. A comprehensive review on advanced control measures and techniques applied in buildings can be found in reference [159], where the focus is on comfort criteria and building supply with a high share of renewable energy.

4.2. Hierarchy and level of integration

In reference [141], it is highlighted that energy markets' regulatory requirements and the time scales as shown in Fig. 6 strongly influence the choice of controls and integration approach. For the control of heat pump systems in a smart grid context, three boundary levels and resulting control tasks exist:

1. Power system level: This includes integration and control of individual buildings or entire heating networks, (renewable) electricity generation and consumption devices in the context of electricity grids and markets.
2. Building level: This includes control of the heat pump, thermal storages, heating distribution systems, indoor temperature, on-site renewable energy sources as solar PV and solar thermal
3. Heat pump unit level: This includes the control of the refrigerant cycleincluding fans, valves and compressor. A good introduction to this topic is provided by the references [45,160].

In a smart grid the different systems have to interact. This can be implemented in an open loop way, where the high level controller sends requests or set-points to the low level system, without having state feedback. In a closed loop implementation feedback is provided from the lower to the higher control level. The higher control level might receive information about the outputs and states of the controlled system, which it uses to adjust the control signals. Control hierarchy as assumed in most heat pump related articles is mostly hierarchically organized (cascaded). The exception to this are agent or negotiation based control approaches, where individual actions are coordinated in a decentralized way using market places or other game theoretic negotiation approaches (for further reading see references [161–164]).

In a hierarchically organized control approach, as depicted in Fig. 8, a central instance sends signals like prices, grid state or switching orders (direct load control) to the building energy management system which coordinates the different devices (or just the heat pump) in the building. A central question is where operation decisions are made. In case of centrally controlled virtual power plants, a high level control instance generates operation schedules for each device and submits those to the field units in the form of switching orders, thus the degree of freedom for the field units is limited. The challenge for the high level is to determine control decisions that maximise overall utility and are technically feasible and economically reasonable for the lower systems. Contrarily, if prices are transmitted to the field devices, they have the freedom and challenge to autonomously manage their operation. In

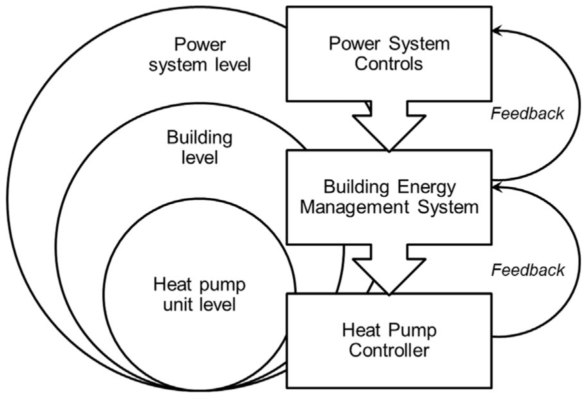

Fig. 8. Control hierarchy and levels of integration.

this case the challenge for the high level controller is to anticipate the reaction of the subsystems to the price signal.

According to the autonomy level of the building energy management system, based on reference [161], three categories can be defined with corresponding signals:

- Passive systems (direct control): The main control desicions are done at the higher control level. Direct set values are transmitted from the power system (e.g. an aggregator) to the field device, which tries to follow.
- Passive intelligent systems (indirect control): A cost signal is transmitted from the higher control level and the field device tries to optimise operation within the given cost structure.
- Active systems (agent based control): All entities are seen as individual agents seeking to maximise an individual or joint utility function. Control action of all entities is negotiated interactively, so that the common and individual goals of operation are achieved [107,110,119,149,151].

In all cases the low level controls have a certain minimum autonomy to guarantee that the heat pump unit is operated within the allowed range and user thermal comfort is not sacrificed.

4.3. Classification of approaches

Control approaches used at the building level are closely linked to the application and the top level control approach taken. For passive intelligent systems the two major categories are predictive control methods and non-predictive methods. For non-predictive methods, the key distinction is how control action is derived from the current system state. Predictive methods can be categorized by the predicted values, the prediction methods and the way the scheduling task is solved. Since no prediction is perfect, the treatment of uncertainties can play an important role.

4.3.1. Non-predictive methods

Non-predictive methods are the way most heat pumps are controlled today. Real-time or averaged sensor values of e.g. temperature sensors, PV electricity generation, frequency or voltage in the electric grid, and price information are used to calculate a control decision for the heat pump at every time step. Such methods are mainly used if predictions are not available or do not offer any additional useful information. Sometimes it is also possible that the costs of design and implementation of predictive methods exceed the benefits of improved controls. The calculation of the control signal is done using classical control theory, rule-based control (if-then) or predefined schedules and programs.

One example of non-predictive **rule-based** controls is providing “fast” services to the power grid for stabilisation of voltage or frequency as shown in the references [40,72,73,95,101]. In those studies the heat pump power is regulated up- or downwards given a certain condition in the power grid. As such critical conditions are not known beforehand and require fast response, rule-based non-predictive methods are the appropriate solution (Fig. 9).

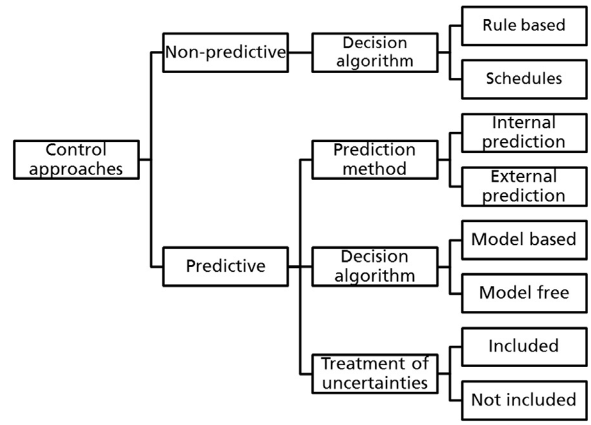

Fig. 9. Applied control strategies for heat pumps in a smart grid context. Only passive intelligent systems are considered.

A further example of rule-based controls is the case of PV self-consumption [71,75,78,84,87,89,111,131,153]. Heat pump operation is started when PV production exceeds a certain value or compressor speed is increased when electricity is fed into the grid. In reference [78] the limitations of non predictive methods are visible. When PV self-consumption maximising controls are applied, the storage is charged to use as much PV electricity as possible by the heat pump. The future thermal demand or the availability of PV electricity on the following day are not included in the calculation of heat pump operation. This leads to high storage temperatures and avoidable losses over a long period as more heat is stored than actually needed for the next day. However, as intended, PV self-consumption has been increased by 7% compared to a control without appropriate expert rules.

A further example of non-predictive methods are time **schedules**, as used today when a static time of use tariff structure is applied or grid congestions are to be avoided. In such a case heat pump operation is blocked during high price or high load hours.

Today non-predictive methods are applied in the majority of building energy management systems. A strong point of non-predictive rule-based controls is that the design of rules can be relatively simple and the controls still show good performance [37,75]. Further computation of the control actions does not require a lot of resources and rules can be robust. Sometimes rule-based controls are the only way to quickly response to critical conditions in the grid, such as voltage or frequency violations.

On the other hand, it is hardly possible with expert rules that do not take prediction into account to achieve an optimal result. Overheating of the storage, comfort violations and loss of efficiency can be the result. Furthermore, when conditions such as pricing structure, demand pattern or comfort requirement change frequently, designing appropriate rules can be challenging. In order to improve the performance of controls, predictions can be used.

4.3.2. Predictive methods

As aforementioned, operating a heat pump in a smart grid context implies some sort of external signal to be given. If this information is provided ahead in time, heat pump operation can be scheduled accordingly. Given the current state of the system, two main tasks arise:

1. Predicting the values of importance for operation (e.g. prices, PV generation, thermal demand).

2. Finding an operation schedule that satisfies the demand at minimum "cost" and respects the physical limitations of the system and the comfort requirements of the occupants.

The task of **prediction** can be divided to predicting external signals, that mostly influence cost of operation, and predicting demand to which operation is subjected to. For external signals, like prices, weather, PV and wind generation, forecasts can often be obtained at least a day-ahead from third party providers. Day-ahead electricity prices may come directly from the spot markets. Thus, the challenge for planning heat pump operation is mostly in predicting the buildings energy demand for space heating and domestic hot water.

Prediction methods differ depending on which information is used in order to predict the demand. Internal methods use historic measurements to learn or recognize patterns and predict the future of a value from its past. Persistence methods (e.g. yesterday-is-today), statistical methods such as auto regressive and moving average methods, AR(I)MA, artificial neural networks and generalized mixture models or clustering methods are examples for internal methods. The benefit of using internal methods for prediction is that no external information, such as weather forecasts, is needed for running a predictive controller, which makes the system autonomous and saves costs.

External methods use additional data for prediction, such as temperature or irradiation forecasts. Those can be used for predicting thermal demand of the building or the prediction of available PV electricity. For this purpose, regression methods, AR(I)MA-X, neural networks or system identification based on reduced physical models are frequently used. For more information on forecasting, see references [165–167] for statistical methods, reference [168] for an overview and reference [169] for artificial intelligence methods.

The type of **decision algorithm** is used to further categorize the control methods. Given a forecast for demand and costs, an operation schedule for the heat pump system has to be calculated and a control signal has to be applied to the system. This is usually done in a receding horizon way. A control schedule is planned for a given prediction time span (prediction horizon) and only the first steps of the scheduled actions are applied to the system (control horizon). After that, a new prediction is made and a new schedule based on the current system state and prediction is calculated. The task to be done is to find the best feasible control trajectory over the whole prediction horizon given the predictions and the current system state.

The methods used to solve this task are categorized by reference [79] into model based and model free methods. Model based methods, referred to as model predictive controls (MPC), use a representation of the physical system to be controlled for finding an optimal control trajectory. The type of model (black box, grey box or white box i.e. physical) and the mathematical formulation determine the effort for modelling and the type of the resulting optimization problem (optimal control problem). The type of the resulting optimization problem determines the class of solvers to be used. The parts of the building energy system that are commonly included in the model are heat pump, storage (building thermal mass or water tanks) and sometimes heating distribution system. A heat pump system shows non-linear, hybrid (i.e. a mix of contentious and discrete) system characteristics, which are treated differently to be used in optimization. In classic model predictive controls, linear or convex quadratic problems are favoured in terms of computational effort over non-linear non-convex formulations. Linear MPC is used in the references [56,64], convexified approaches are presented in the references [57,69,77,137]. In those cases, computational performance is prioritised over model detail. In non-linear approaches, the non-linearities of the system are represented more accurately as presented in the references [157,170] where shooting methods and interior point optimization are used for the solution and in reference [37] where dynamic programming is used for the solution of the optimal control problem. In the references [26,37,56,57,62,64,68,69,77,79,80,85,123,124,136,138,150,155,157,-158] model predictive control has been used successfully with heat pumps. Especially cases with variable electricity prices show cost savings up to 35%. However, the assumptions often include perfect predictions and no mismatch between the optimization model and the controlled entity. As a benchmark, mostly simple rule-based controllers are used.

A benefit of using MPC for building controls is the ability to include forecasts (like price and weather) in the calculation of the controls. The possibility to handle constraints of the system (like maximum HP capacity), the ability to track multiple objectives (such as comfort and cost) and the flexibility towards changing boundary conditions (such as prices) make MPC an interesting control option [171]. Especially when system inertia is high (as it is the case when controlling a thermal storage or building's indoor temperature) using MPC offers benefits over classical controls. It is shown that MPC improves efficiency, comfort and especially economic performance significantly compared to the used rule-based controllers.

The downside of model predictive controls is clearly that the problem formulation can be challenging and that identification procedures might be needed to adjust the model parameters [69]. Furthermore, the computational effort for solving the resulting optimization problem is higher than in rule based approaches, leading to higher requirements for the controller hardware. Moreover, the need of forecasts and optimization tools on the controller increases the complexity of the task and leads to increased technical requirements for field devices. Building a model representation of the controlled system might be non-trivial, time consuming, and costly.

In order to account for **uncertainty** due to imperfect predictions, stochastic control methods are used [140,154,158,172]. Those methods are based on the insight that forecasts will never be perfect, thus uncertainty is already included in finding the best control trajectory. This is done in the references [154,158] by considering different scenarios, adding them to the optimization problem and solving a larger optimization problem. It is shown that the scenario based method mostly outperforms classical MPC approaches, but at the cost of increased complexity in modelling, scenario generation and computation. In [140,172] a combination of stochastic programming and optimal controls is used to account for uncertainty in weather predictions. A safety margin is added to the constraints of the optimal control problem so that comfort requirements are fulfilled with a certain probability, given the uncertainty of the forecasts. It is shown in the references [140,172] that stochastic MPC outperform classical MPC approaches and rule based controls for the given cases.

Model-free predictive methods avoid the complexity of modelling and solving an optimal control problem. This is done using heuristics or rules to derive a control trajectory with respect to forecasts of price and demand. In such predictive rule-based decision strategies, decisions are based on prior engineering knowledge (expert systems). This has been successfully applied in the references [37,41,60,104,126,139,142]. If designed carefully, such rules might be a good compromise between MPC and non-predictive methods, being computationally inexpensive but still using the available information and forecasts. However, the solution might not be optimal and rules might not be flexible enough to cover all possible scenarios.

Further artificial intelligence techniques like reinforcement learning where the control action is learned and improved from previous tries are discussed in reference [63] for building temperature control but have not been demonstrated with heat pumps so far.

Table 2 lists and compares the different control approaches used to control buildings and heat pump systems for the case of indirect control signals (e.g. price).

5. Conclusion and recommended future research

In this study the use of heat pumps in a smart grid context was

Table 2
Overview of frequently used control approaches for heat pump systems.

Type	Pros	Cons	References
Rule based	• Mostly simple to implement and design • Computationally cheap • No external information needed	• Mostly inflexible rules adjusted to the use-case • A-priori expert knowledge needed	[33,38,40,53,54,71–73,75,78,82,84,87,89,90,101,111,116,118,131,133,134,153]
Model-free predictive control	• Uses information from predictions • Compromise between complexity and performance • Computationally cheap • Better performance compared to simple rule-based controls	• Mostly static adjusted to the use case • A-priori expert knowledge needed	[41,60,74,104,106,114,117,126,139,142]
Model based predictive control	• Uses information from predictions • Optimal or close to optimal solutions possible • Flexible towards changes in boundary conditions (like pricing structure) • Constraints handling possible • Mostly superior performance compared to rule-based controls	• Complex in design • Modelling effort • Computational requirements • Prediction errors • Modelling errors • Robustness	[23,26,34,36,37,39,55–59,61,62,64,67–70,76,77,79–81,83,85,86,93,102,105,106,108,115,120,123,124,129,136–138,143–147,150,154,155,157,158,173–176]
Stochastic Predictive Controls	• Treats errors in prediction • mostly better results than non-stochastic MPC • Robustness	• Complex in design • Can be computationally expensive	[36,145,154,158,175]

analysed and discussed. The term smart gird is used in various ways depending on the authors' perspectives and focus of the study. The majority of applications with residential heat pumps in a smart grid context are motivated by the provision of services to the electric grid, a maximisation of the use of renewable electricity or the operation under variable prices. It has been highlighted that those fields of applications are inherently linked together.

5.1. Conclusion

Heat pumps are considered to be a major technology to provide flexibility to the power system meanwhile providing efficient heating and cooling solutions to residential buildings. The technology is supported by increasing efficiency, the deployment of computing and communication technology and increased renewable electricity generation. In order to successfully integrate heat pumps in a smart grid, it is critical to have a holistic view on the energy systems affected. Analysing the smart grid barely from the electric perspective will lead to missing how heat pump system efficiency and indoor comfort will be affected by potential changes in heat pump control. Oppositely, if the focus is only on heat pump efficiency without considering the characteristics and expectations needed in the future electric system, this will lead to considerable costs and waste of resources in the power system. Hence, a holistic perspective is required to analyse, design and operate the future energy system.

The investigated studies show that heat pumps can be used to ease the transition towards a renewable interconnected energy system. It is highlighted that altered heat pump operation might come at the cost of efficiency. High storage temperatures, operation far from optimum compressor speed or frequent switching of the heat pump units.

The potential flexibility of heat pump systems, which should be considered already in the planning phase, is mainly dependent on the building physics and the resulting thermal demand profile, heat pump and storage type and size with respect to the demand, and the control strategy applied.

Predictive and non-predictive control approaches have been presented for heat pumps in a smart grid context. The choice of controls is strongly connected to the application and integration approach. On the level of individual buildings, model predictive control approaches have been found to outperform non predictive approaches in terms of achieving control goals such as maximising thermal comfort and minimising operation costs. However, those come at the cost of additional complexity, needing expertise in design and computational resources. Predictive rule-based approaches can be a promising compromise between complexity and effectiveness of controls.

5.2. Recommendation for future research

The research over the recent years has contributed with simulations, prototypes and field tests towards integrating heat pumps in smart grids. The concept of a smart grid integration of heat pumps can thus be considered as proven. However to enable a large scale integration of heat pumps into the power system, further research should focus on application topics in three levels.

The first level is the integration and management of heat pumps in the power system. Here the following points should be addressed:

1. The use of a large number of heat pumps in a pool: Here the development of scalable control concepts and knowledge about the flexibility of a heat pump pool in contrast to single entities should be

in the focus.
2. Development of business cases to build the foundation for integrating heat pumps in smart grids.
3. A techno-economic analysis of heat pumps when operating on different electricity markets such as day-ahead, intra-day and the reserve markets. .

The second level is the integration and management of heat pumps in buildings energy systems. Here the following points should be addressed:

1. The design of optimal flexible systems for a given application, should be addressed in a more clear and structured way. This includes recommendations for sizing heat pumps, storage, the layout of building energy systems and the choice of control approach.
2. The impact of different control approaches and smart grid applications on system cost and efficiency needs to be investigated further. A focus should be on the practical relevance and feasibility of many suggested solutions.
3. Model predictive control is used in many studies for operating heat pumps in a smart grid context. Although benefits are well known, implementation rate in the field is low. A comprehensive study about strength, weakness and opportunities especially when compared to expert systems should be conducted to give advice to system engineers and researchers to improve MPC for practical use.

The third level is the heat pump unit itself. Here the focus should be on the impact of smart grid use on the heat pump units and address the following points:

1. The use of variable speed compressors enables a continuous regulation of power consumption. This option should be further investigated with respect to possible benefits for smart grid applications.
2. Many studies consider a heat pump as a black box which can be easily used for smart grid purposes. However, this can strongly influence the performance of heat pump cycle and system. Therefore the design of the whole heat pump system should be investigated with respect to be optimally adapted to the requirements from the electric system.
3. Minimum run and pause times and ramping rate constraints are examples for limitations to consider when integrating heat pumps to a smart grid. Finding and improving such smart grid bottlenecks in heat pump component and circuit design can improve flexibility characteristics and lifetime of a heat pump unit.

We conclude that heat pumps have the potential to be a central part of an efficient, renewable and interconnected energy system, but there is still some work to be done.

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