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Price-Optimized heat pump operation considering LV distribution grid constraints

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- Where I have consulted the published work of others, this is always clearly attributed.
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Abstract

Department of Electrical Engineering and Computer Science

Energy Management and Power System Operation

Master of Science

Price-Optimized heat pump operation considering LV distribution grid constraints

by Niklas Bjarne Hoffmann

Rising usage of heat pumps (HPs) for heating in buildings can overload low-voltage (LV) distribution grids, threatening grid stability. The German Federal Grid Agency proposed solutions based on § 14a EnWG with reactive measures from the DSO to address overloading by reducing the power to a minimum of 4.2 kW. This study proposes a preventive control strategy for HPs integrated with Home Energy Management Systems (HEMS). The objective is to minimize household electricity costs while preventing overloading through time-dependent power reductions. Unlike most existing solutions, this approach proactively reduces HP power consumption based on predicted grid load. Simulations were conducted using a combination of tools (pandapower, microSCOPE, pandaprosumer) to evaluate the effectiveness of the proposed control strategy. The simulations compared scenarios with and without the control strategy, considering different HP sizes, thermal storage sizes, and sensitivity analysis. The results demonstrate the functionality of the preventive control strategy in reducing transformer overloading. However, the effectiveness is limited during long periods with particularly low temperatures. Also, it is influenced by factors such as HP size relative to building heat load and thermal storage capacity. Further research is needed to generalize the findings and include more factors.

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Chapter 1

Introduction

1.1 Motivation

In 2022, 27.8 % of the final energy consumption in Germany was used to provide heat in buildings and 5.1 % to produce hot water. Residential households used 82.7 % of their energy for heating and hot water, with about one in two using natural gas and one in four using oil [1].

The Bundes-Klimaschutzgesetz defines objectives to meet the national climate protection targets in compliance with European goals. In comparison to 1990, the emission of greenhouse gases has to be reduced by 65 % by the year 2030 and by 88 % by 2040. In 2045, net greenhouse gas neutrality should be reached, whereby the usage of carbon-free electricity is of overriding public interest [2].

According to the Gebäudeenergiegesetz (GEG) from 2024, every newly installed heating system must run on at least 65 % renewable energy from the start of 2024 with some transitional rules for existing buildings. In cities with more than 100,000 inhabitants, the heating system has to run on at least 65 % no later than the end of July 2026, and in cities with up to 100,000 inhabitants two years later. Furthermore, municipalities must carry out heat planning to determine if district heating or decentralized heating systems should be used in the future [3]. The aim of the Wärmeplanungsgesetz (WPG) is to make a significant contribution to converting the generation of space heating and hot water to renewable energies in an economical, cost-efficient, and greenhouse gas-neutral way. As a result of the heat planning, there should be a plan for how buildings can be supplied with heat via district heating or decentralized via hydrogen network, biomass boiler, or heat pump (HP) [4].

Heat pumps that use electricity to generate usable heat out of ambient heat are considered carbon neutral according to the GEG [3]. The electricity in Germany is currently 51.8 % produced from renewable sources, and the share of renewable sources doubled in the last 10 years. Also, the amount of heat pumps is increasing, and in 2022, 1.7 million HP are used to generate heat [5]. With the rising amount of heat pumps and share of renewable energy for electricity production, the CO_2 emissions can be reduced and provide a cheaper solution than other alternatives like hydrogen or biogas, but this goes along with a higher load on the power grid [6]–[8].

Electricity suppliers must offer dynamic prices to their consumers if they have more than 100,000 customers on the 31^{st} of December in the previous year. This obligation applies to every electricity supplier from 1 January 2025, according to § 41a EnWG (2) [9].

With the increasing number of households using a home energy management system (HEMS) that optimizes a household's energy usage, a new way of electric energy consumption is emerging. A HEMS can be used to shift electricity usage in time, utilizing cheaper electricity prices if time-dependent or flexible electricity tariffs are used. Another use case is to improve the utilization efficiency of household appliances, on-site energy sources, or energy conservation. Therefore, HEMS is crucial to household demand-side management and smart grids. Usually, heating, ventilation, air conditioning, electric water heaters, and refrigerators account for most energy consumption and can be controlled. [10], [11]

Asare-Bediako et al. show that an existing LV distribution grid is unsuitable for high penetration of HP and EVs. With an adoption rate of 100 %, the peak load could be three times as high compared to the existing situation [7]. Based on a Dutch LV grid, Damianakis et al. demonstrate that HPs provoke a higher impact with their frequent use, while EVs provoke a longer-lasting violation due to their charging periods [8]. Also, the increasing adoption of uncoordinated HEMS and new consumers, such as HPs and EVs, can impose capacity problems on the LV distribution grid. The consequence is grid congestion where the power flow through grid assets such as cables, transformers, etc., is higher than their rated capacity and voltage limit violations [11].

Normally, power grid capacity issues have been resolved by reinforcing the assets with high investments to resolve the relatively short peak demand [11], [12]. This thesis proposes a solution to increase the adoption of HPs without or delayed power grid reinforcement.

1.2 Research Objectives and Contribution

Based on the resolution from the German Federal Grid Agency concerning § 14a EnWG, which is described in detail in Chapter 2.1 the research objective is to create a preventive control that avoids the overloading of the grid by reducing the power of HPs. The primary requirement is to minimize household electricity costs, with the secondary goal of preventing or at least reducing grid overloading. To achieve this, assumptions should be realistic, and the solution should be practically implementable. The German Federal Grid Agency's resolution aims to reduce the power of controllable consumption devices to prevent hazards or disruptions to the power grids safety or reliability due to asset overloading. The proposed solution should eliminate the need for intervention.

To study the effect of controllable consumption devices using the example of HP, which is controlled by an HEMS a simulation is used. This connection, focusing on the LV grid, has been little studied to date. First, the theoretical background of the proposed changes, the controls of controllable consumption devices, the functionality of heat pumps and HEMS, and demand-side management are thoroughly studied. Next, the connection and iteration between the pandapower, pandaprosumer, and microSCOPE as well as the goals plus constraints are developed.

Simulations are used to demonstrate the challenges of uncontrolled consumption devices with flexible electricity prices and a price-optimizing HEMS in contrast to fixed prices. For the simulation, a suitable LV grid and period are utilized. To prevent the overloading of the grid, a preventive control is developed. If the loading of the transformer is over the threshold, the permissible power consumption in the corresponding times is reduced as much as necessary. Therefore, the control is a time-dependent power reduction. To evaluate the time-dependent power reduction, simulations are conducted with and without different dimensions of HPs and thermal storage.

In Chapter 2, the proposed changes of the § 14a EnWG from the German Federal Grid Agency are described. Furthermore, the functionality of heat pumps, controls of controllable consumption devices, HEMS, and demand side management are described. In Chapter 3, the connection between the simulation modules and their underlying goals and constraints, as well as use cases and their sensitivity regarding different flexibility capabilities based on their storage and HP sizes are described. The simulation modules are described in Chapter 4. The results are shown and discussed in Chapter 5. Finally, in Chapter 6, the findings are summarized, and an outlook for further research and development is given.

Chapter 2

State of the Art

In this Chapter, the state-of-the art and new § 14a EnWG and their interpretation from the German Federal Grid Agency are described. Thereafter, heat pumps as heating systems and their behavior is depicted, before controls of controllable consumption devices such as heat pumps are described. This follows an explanation of home energy management systems and demand side management, which are needed and used to realize the new § 14a EnWG and research objective.

2.1 § 14 a EnWG

To reach the goals described in Section 1.1 the Bundesregierung wants to reach a stock of 15 Million EVs by 2030 [13] and an addition of 500 000 HPs per year [14]. The addition of EVs and HPs means additional power from the LV grid with a high simultaneity factor, with the consequence of necessary power grid reinforcement. However, integration is not possible in the near future without overloading the grid due to the lack of grid reinforcement, and a total grid reinforcement is deemed too expensive. To prevent delays when connecting HPs and EV charging stations due to the grid operator's calculated potential grid bottlenecks, a control instrument to reduce the power is introduced [15].

Consumers have to register their new heat pump with the local distribution system operator (DSO) and get approval if the rated power is greater than 12 kVA according to the NAV § 19 [16]. Also, consumers can receive grid fee reductions if they have controllable consumption devices (e.g. HP and heating element) and grant the DSO the ability to reduce the power. In § 14a EnWG grants the German Federal Grid Agency the right to specify the rules [9].

In the determination procedure, the German Federal Grid Agency specified that the DSO could only control the power of the controllable consumption devices behind the grid connection point (HP and heating element, EV, etc.). The control, designed solely to eliminate hazards or faults caused by equipment overloads, impermissible voltage values, or limit violations in the affected grid area, should only be used reactively to prevent hazards or disruptions to the safety or reliability of the grid. Likewise, the control cannot be used to prevent problems at the higher grid levels. The threshold for participation is an electric power of 4.2 kW or greater. If the power has to be reduced, 4.2 kW is also the minimum to which the load over the grid connection point can be reduced. If, for example, a PV plant produces enough power, the controllable consumption devices don't need to reduce their power. It is inadmissible to always reduce the power to 4.2 kW because reductions may only be made to the extent necessary. HP or air conditioners (ACs) with more than 11 kW have their minimum at 40 % of rated power. If the devices are staggered, the minimum power is calculated by multiplying 4.2 kW with a simultaneity factor. The next lowest must be chosen if the controllable consumption devices cannot reduce to the required power. The grid is monitored to determine when and how much the power of the controllable consumption devices has to be reduced according to the grid status [15].

To determine the grid status, a state-of-the-art real-time measurement of the specific part of the grid has to be conducted. This procedure is similar to the existing grid state estimation at higher grid levels. In combination with individual technical parameters of the affected grid, the DSO can determine if a grid-oriented control of the controllable consumption devices is necessary. The German Federal Grid Agency assumes that if 15 % of all grid connection points are measured, or 7 % in combination with measurements at the transformers, then the status of the grid can be determined, at least temporarily. The measured values should have a resolution of one minute or less and must be sent from the smart meter to the DSO. Additionally, data can be used regarding the topology, electrical behavior of the assets, grid connection points, and systems behind them in connection with historical data. Based on the measurements and information the DSO has to determine by how much the power of each controllable appliance (e.g. HP) has to be reduced to prevent the hazard. A safety surcharge can be added to address uncertainties, such as the number of running appliances or IT problems when

sending the control command. If the power has to be reduced, all controllable consumption devices must have the same relieving effect on the grid. The reduction should be an ultima ratio and last only as long as necessary. The reduction can be undone in steps to prevent a return to the initial state [15].

Apart from exceptions such as HPs and ACs, which are used for commercial purposes (process heating or cooling), every controllable consumption device has to participate. In return, the DSO cannot delay or reject due to a lack of grid capacity. The obligation of the DSO to optimize, expand, and reinforce the grid continues to exist [15].

2.2 Heat Pumps

Heat pumps are devices that generate heat by using mechanical work to move heat from a colder location to a hotter one. They work in principle as a reversed heat engine. An HP uses a refrigerant liquid to transport the heat by using the physical properties of evaporation and condensation. The mechanical work is required because otherwise the second law of thermodynamics is violated [17]. HPs exist as four main components: a compressor unit, an internal heat exchanger, an expansion valve, and an external heat exchanger. The compressor is used to compress the refrigerant, which increases the pressure and, crucially, the heat. An internal heat exchanger transfers heat to the home (usually water, which is used to distribute heat). The expansion valve reduces the pressure, and the temperature of the refrigerant drops below the ambient temperature. An external heat exchanger is used to absorb the ambient heat. ACs or refrigerators can use the reversed process to provide cold [18], [19]. In Figure 2.1, a schematic HP system is shown, which uses air as a source of heat and electricity for its mechanical work. Besides air source heat pumps (ASHPs), which use air as a heat source, ground source or geothermal heat pumps (GSHPs) are mainly used in residential dwellings [18], [20]. ASHPs are divided into air-to-air and air-to-water systems and can be identified by the external ground or wall-mounted unit [18].

The efficiency of HP is determined by comparing the amount of generated heat to the amount of energy that is needed. It is measured by the Coefficient of Performance (COP), which is the ratio of heat output to the electrical power needed

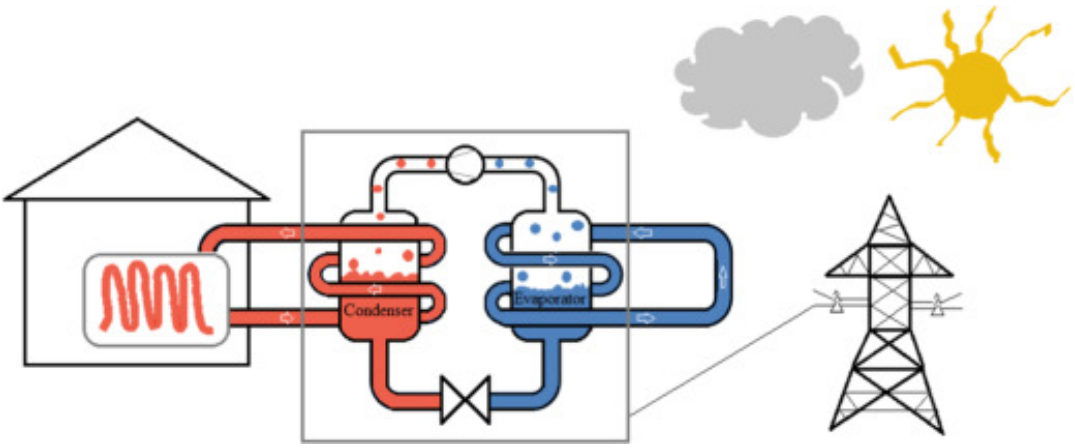

FIGURE 2.1: Schematic HP system diagram [19]

by the HP. COP and, therefore, the efficiency of HPs decreases with the temperature of the source [17]. To better compare and measure the efficiency of the HP on an annual basis, the Seasonal Performance Factor (SPF) is used. Whereas COP is a steady state-state measurement, SPF depends on location and climate. Furthermore, SPF can include the production and consumption of the heating rod, the refrigerant circulation, the external heat exchanger fan, and defrosting [18].

Because ASHPs use the ambient air as a heat source, the temperature greatly affects their efficiency [17]. During the electrification of home heating, it is anticipated that air-to-water systems will play a large role by retrofitting existing water-based heating systems [19], [21]. In [6] it is shown that ASHPs could be the cheapest solution with the lowest carbon footprint next to district heating if investment and operating costs are considered. Air-to-water ASHPs can provide heating and/or hot water [18]. An exemplary hydraulic system of an air-to-water ASHP, which is used to generate heat and hot water, can be found in Figure 2.2.

Ground source or geothermal heat pumps (GSHPs) extract and reinject water from ground sources and use the heat from the water if they are open-loop systems. Close-loop or ground-coupled systems extract heat from soil or rock through underground pipes. The pipes can be laid vertically or horizontally. The latter requires a large area and can delay vegetation. The higher investment costs usually are canceled out by stable and moderate heat sources (5-10 °C) compared to ASHPs [18].

HPs are usually not designed to provide the peak demand. The reason is that by

undersizing capital, costs can be reduced and utilization increased. To produce enough heat during peak demand, a backup heater is used; usually an electric heating rod [18], [22].

Different forms of energy can produce mechanical work, but due to the dominance of electric HP, which uses Air as its source and water to transfer heat throughout the house, only this kind be discussed in the following [20], [23].

Most ASHPs in Europe have thermal storage, in which water is used to store energy for later heating or cooling. Most of the water storage is sensible heat storage, where the temperature rises or falls, although different materials and physical effects can be used [23], [24]. Stratified tanks, which store water at different temperatures and volumes in a single tank, are widely used and are designed to prevent mixing. Water stratification occurs naturally since colder water, being denser, sinks or remains at the bottom, while hot water rises or stays at the top [24].

Thermal storages are used in combination with ASHPs to store energy for later use as part of load management to improve the efficiency by optimizing runtimes and to take advantage of cheaper tariffs or self-generated electricity, thereby increasing the cost-efficiency [24], [25]. The shifting potential depends on the size of the storage and possible constraints, such as a certain temperature range [26]. In combination with surface heating the thermal storage of the heat could be separated from the hot water because of the different temperature requirements. For example, underfloor heating needs around 35 °C, and hot water must be at least 60 °C for hygiene reasons. Therefore, a separation of generation and storage could make sense [22]. In [25] it could be shown that a small water storage tank of 0.06 m^3 reduces the start-stop loss of ASHP from 12.5 to 0.8 %. Likewise, the energy-saving can be increased from 13.3 % to 18 % by operating during high-temperature periods and with a 1 m^3 to 4 m^3 storage. Higher ambient temperature alone causes a saving between 1 % and 6.8 %. On the other hand, the size of the ASHP has little effect on energy saving; therefore, the investment cost plays a bigger role. While the energy saving is largely dependent on the ambient temperature and required heat, the frequent start-stop of the compressor can reduce its lifespan [27].

HPs can provide ancillary services to the grid: voltage control, congestion management, and provision of spinning and non-spinning reserves, whereby the latter is not addressed at the LV-distribution grid. Overvoltages in distribution grids can be caused by high PV feed-in and avoided by increasing the active power. Problems with low voltage are caused by high demand, and reducing the active power minimises them [23]. Congestion management is similar to voltage control but is used to avoid or reduce transformer loading instead of line overloading. Due to this, power grid reinforcement can be delayed or postponed [23], [28]. Most studies use a real-time strategy to deal with unforeseen events or day-ahead planning to avoid operation during critical periods by switching the HP on or off. Another grid-focused subject is the reduction of peaks at the household or national level. The goal is to shift on a day-ahead basis to avoid positive or negative peaks [23].

Besides optimizing the operation of ASHPs with storage, the storage can also be used to separate the production and usage of heat and therefore shift the energy usage in time. The flexibility can be used to avoid or reduce load and feed-in for the benefit of the grid [23].

The interaction between PV, battery storage, and HP can also affect the grid but is not part of this thesis.

In Figure 2.2 an exemplary hydraulic system of an ASHP is shown, where there is one storage for domestic hot water and one as a buffer for the floor heating.

Most basic HP have just the option to either switch on and off with a fix-speed to control their output. Thermal storage could be used to balance production and usage and reduce start-ups and shut-downs because they always run at full power [18], [22]. More advanced HPs feature two-stage or two compressors (around 2/3 power) to reduce on-off cycles [30]. HP with inverter-driven compressor can modulate the compressor speed to match the desired output [18], [22]. Especially with ASHPs the inverter technology prevails in contrast to the on and off fix-speed HPs [21], [22].

As already described HPs have a heating rod as backup during peak demand. With ASHPs, the heating rod is also needed during low ambient temperatures since the output decreases with falling temperatures and has to completely take over at around -15 to -25 °C [18]. Another problem with ASHPs during cold

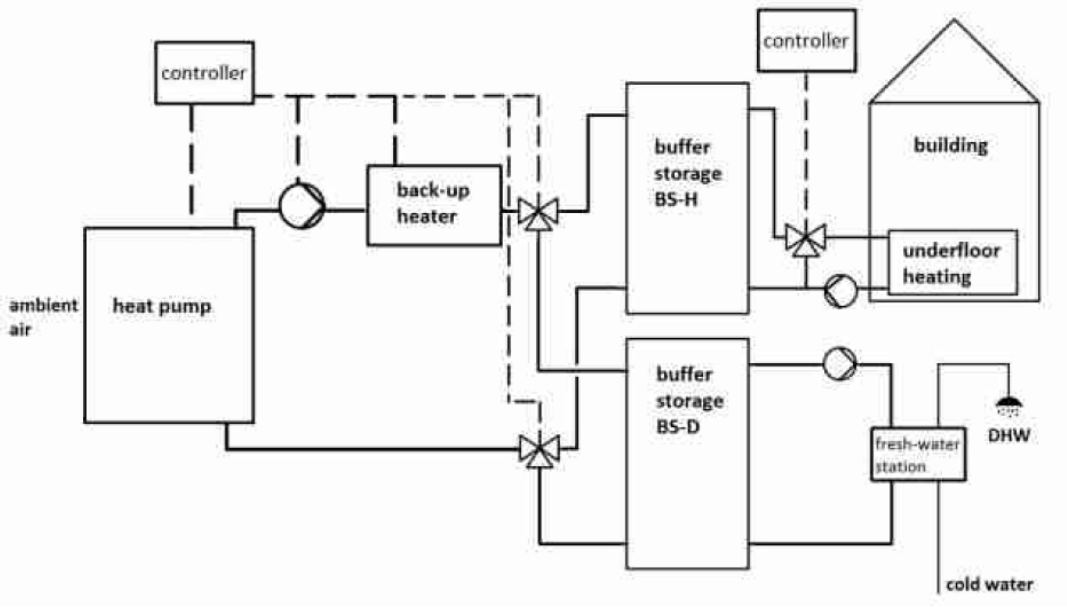

FIGURE 2.2: Hydraulic scheme of the exemplary heat pump system in residential house [29]

temperatures is the freezing of the heat exchanger, which occurs because the air that leaves the heat exchanger is below the freezing temperature of the humidity. The freezing hinders the function of the heat exchanger, so defrosting cycles are used by reversing the flow of the refrigerant, drawing heat from the storage or heating rod [18], [22]. These effects occur during a period with high heating demand from the domestic dwellings, low ambient temperature, and therefore corresponding impact on the power grid thus the demand-side management potential of ASHPs is reduced [28]

2.3 Controls

Until 2024 gird operators had the possibility, according to the revised § 14a EnWG, to use HP to relieve the power grid by controlling them. In contrast to the revised paragraph and its specification from the German Federal Grid Agency HPs could be turned off based on fixed times or congestion in upper grid levels. The fixed times were controlled by a timer and the control of the HP was done by various technologies such as smart meters, control boxes, and ripple control [31].

Ripple control is a technology that uses the grid as a transmission path and sends the control command, like a telegram with pulse sequences on a specific frequency and amplitude that is superimposed on the grid frequency. A receiver receives the command and controls the HP or controllable consumption devices if necessary accordingly [32], [33]. Disadvantageous is that the grid operator does not know if the command is received because it is a mono-directional communication [33].

The grid operator usually published the fixed times, which could be up to six hours per day and up to two hours per shut-off period after which an equal or longer time had to follow, where the HP could run. Therefore the HP and thermal storage could be designed accordingly [31], [34].

A smart meter is state-of-the-art and could be used for the implementation of § 14a EnWG. A smart meter (or advanced metering infrastructure) consists of a digital electricity meter and a communication unit [35]–[37]. In contrast to an analog Ferraris meter, which just measures the usage, a digital electricity meter can detect the actual period of use. The smart-meter-gateway (SMGW) has a secured port for communication between the consumer/producer, grid operator, and energy provider [36].

The German Federal Grid Agency does not specify the system that the grid operators should use to send commands to the controllable consumption devices. Another option for the consumer is to receive the reduction command via the energy management system (or HEMS), which could save separate control technology [15].

On the side of HPs and their control technology the label SG Ready is used to specify and identify devices that can be controlled to provide services for the power grid or to increase the self-consumption of PV. The HP has to have four operating states which are on/off time-based, energy efficient normal operation, increased operation for heat and hot water, and, definite command to run either just the compressor or the compressor plus electric heating element [38]. A potential disadvantage of the SG Ready label is that a potential necessary reduction of the electric power consumption in the sense of the § 14a EnWG, which is described in Section 2.1, can't be specified.

Besides commands from the grid operator variable electricity or grid cost can also function as signal since it is a economic incentive [10], [23].

2.4 HEMS

Home energy management systems are made possible by different technology among other things advanced metering infrastructure (AMI), bidirectional communication, smart home appliances, home area network (HAN), and home energy storage system (HESS) [10]. The AMI device enables the two-way communication between the DSO and consumer and therefore part of the smart grid [39]. The term Smart Grid is a concept introduced by the European Commission to propose a strategy for the development of future electricity networks. The electricity network of the future should be flexible, accessible, reliable, and economical while switching from a central carbon-based electricity generation to decentralized costumer-centric networks [40].

HEMS is a system that provides energy management services to monitor and manage electricity generation, storage, and consumption in smart houses. It uses economic incentives by changing electricity prices and optimizes self-consumption by demand-side management. Besides the described economic incentives other optimization goals such as residential energy conservation or utilization efficiency of household appliances can be pursued [41]. The information collection from the appliances, the monitoring and control with a smartphone or personal computer can be achieved over a home area network (HAN) [10]. In Figure 2.3 an exemplary HEMS is shown.

The main functionalities of an HEMS are monitoring, logging, control, management, and alarm. The monitoring allows the user to access real-time information about energy usage and can be displayed with other details about the operational modes and energy status of the appliances. Logging collects and saves the data on the energy usage of the appliances, generation of energy, and storage state. Based on this data future responses can be optimized. The control is split into direct control which is the control between the system and the appliances and the remote control from the user to change the behavior of the appliances. Management is the key functionality of the HEMS because it connects services such as home appliance management, renewable energy system management, energy

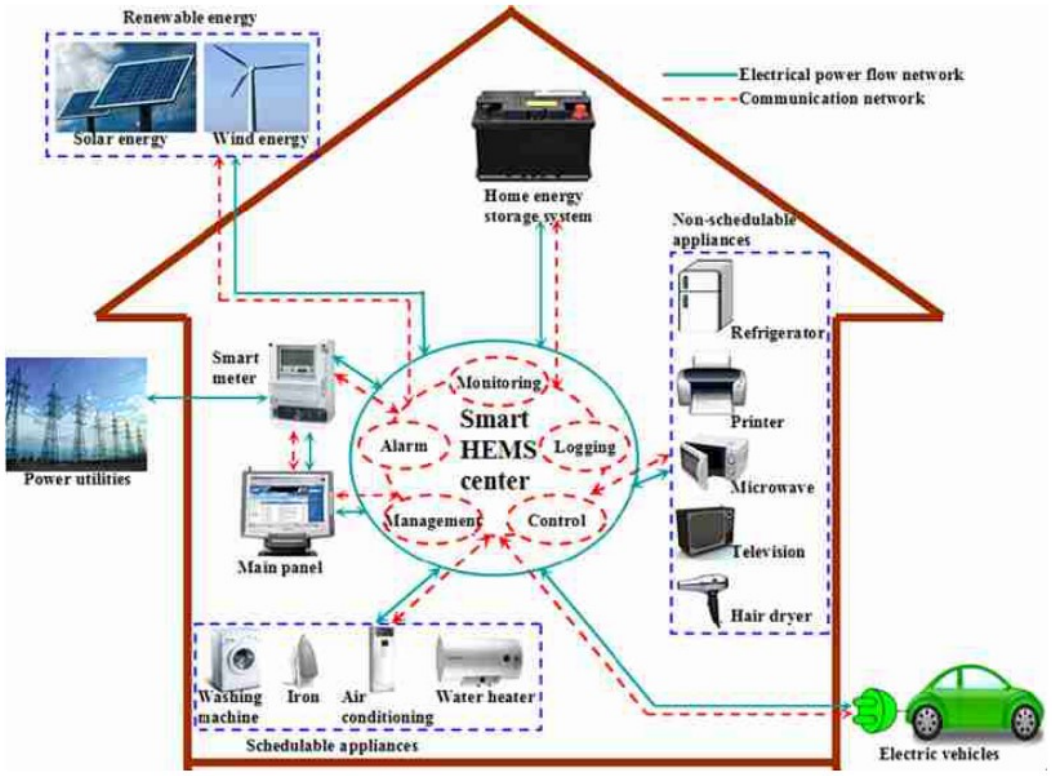

FIGURE 2.3: Overall architecture of a representative HEMS from [10]

storage management, battery management, and EV management. Alarms are used to inform the user about events such as unusual behavior. [10], [42]

Different technologies are used to exchange information between PV, EVs, household appliances, and equipment for communication inside the house. Household appliances can be separated into non-schedulable (TV, microwave, etc.) and schdulable (EV, washing machine, etc.) [10]. Smart meters, which are described in Section 2.3 are used to measure energy consumption and provide a two-way communication scheme between the consumer and power utilities (DSO) [10]. In Germany the smart meter is split into modern measuring equipment with a communication unit also called smart meter gateway [37]. The smart HEMS center is the core, where smart energy management is implemented. Furthermore, it receives, processes, and acts on the data/forecasts and/or human input (via human-machine interface) [10].

In [43] shows that dynamic residential demand response with multiple/ continuous iterations between the demand response provider (e.g. households), the demand response provider agent (responsible for maximizing profits with consideration of the power balance), and DSO (incorporates the constraints of the grid) outperforms technically and economically compared to static residential demand response, where the interaction is limited to one event.

In the last years, the smart home market and also the subsection of energy management systems is growing in Germany [44]. The results from [11] indicate that even if just half of HEMS participate overloading can be mitigated. Also voltage level can be improved if more HEMS participate.

2.5 Demand side management

Demand side management (DSM) is a tool to optimize the power system from generation to final use by changing the load profile [24]. After [26] demand side management of HPs or ACs can be categorized into energy efficiency, storage, and demand response. Energy efficiency entails among other things natural refrigerants, optimal design, and optimal control strategy which can reduce the energy demand. The term storage refers for instance to thermal energy storage which in combination with an HP are described in Section 2.2. Hereafter the demand response, which can improve renewable energy sources integration, cost reduction, and especially the provision of ancillary services is described.

As above mentioned in Section 2.2 HPs can provide ancillary services, which are frequency and voltage control, congestion management, and provision of spinning and non-spinning reserves [23]. Additionally, peak shaving of load to minimize grid cost and optimizing the load behind the grid connection point can be goals of demand side management [45]. To determine the flexibility several methods have been proposed [26]. Most widely used are the amount of power change, duration of the change, rate of change, response time, shifted load and maximal hours of load shifted, and recovery time [46]. The time-shifting of energy can be evaluated by comparing load curves with and without DSM [26].

As discussed in Section 2.4 household appliances can be separated into non-schedulable (lighting, basic refrigeration, and so forth also called base load or

residual load) and schedulable. The schedulable appliances can be further classified into interruptible and non-interruptible, where the interruptible gives more scheduling flexibility and DSM potential. An example of an interruptible household appliance is an EV or battery storage, whereas a non-interruptible could be a heat pump that has minimal run times [10], [47].

HPs have even at a low penetration rate a DSM potential and an impact on the weighted average transformer loading. The effects are limited by the storage size and could even show no effect at low temperature because the COP of the HP is low in conjunction with higher thermal energy demands from buildings which leads to a high power demand [28]. Besides HP other appliances can provide flexibility whereby the potential to increase the power is many times over than to decrease the power. Also, the flexibility potential varies over the day and weekday [48]

In [46] a pool of 284 HPs with their demand from heat and hot water is modeled to investigate their flexibility when the SG-Ready interface is used to control their load. Results show that the assessed flexibility is highly dependent on the ambient temperature and the use of an electric backup heater. Furthermore, SG-Ready provides more flexibility than switching HP off. Flexibility can be used to provide services to the grid.

Chapter 3

Methodology

In this chapter, the theoretical background of the connections between the mod-

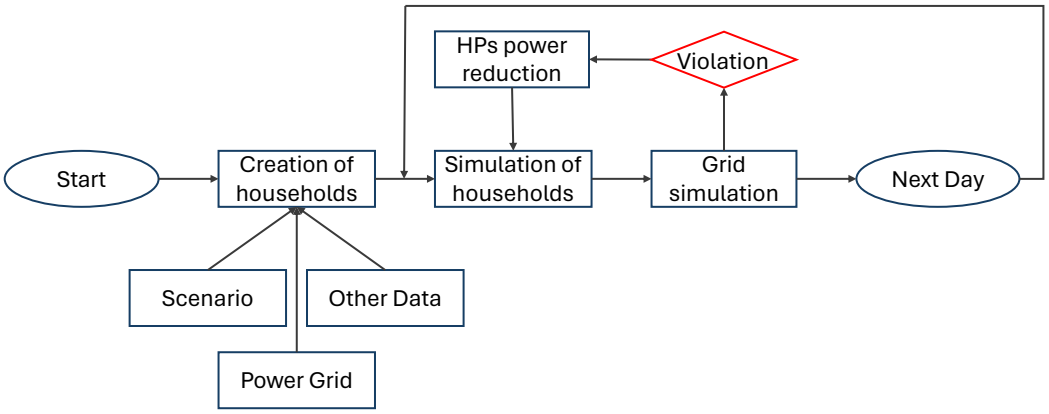

FIGURE 3.1: Visualization of the simulation as a flowchart with a power reduction for the HP

There are different modules to simulate the heat demand of buildings, optimize prices with heat generation from HPs, and calculate the grid's power flow, collectively referred to as modules. Figure 3.1 shows the simulation. After the first day, the households do not need to be recreated; only the SOCs of the heat and hot water storage need to be updated as explained in Section 4.4, which is not shown in Figure 3.1. The restrictions on the electric power consumption of the HPs are calculated if constraints are violated during the grid calculation. After that, the households are simulated again. The loops run a specified number of

times or until the grid violations are resolved. To reduce computing time, four random runs are used for this thesis. The comprehensive flowchart can be found in Appendix A.

3.1 Connection between the modules

To achieve the research objective, different simulations need to be conducted, and the simulation modules must be connected. The simulation is a bottom-up study; therefore, the energy demand of individual households for heating needs to be determined first. A heat pump is modeled for the simulation of heat and hot water generation, and with these results, a grid simulation is run.

To simulate the heat demand of the buildings, their boundaries first have to be defined. Inside temperatures are assumed to be fixed and are the same for every building, with 18 °C during the day and 15 °C at night. The boundaries of the building are based on the Institute for Housing and Environment – Institut Wohnen und Umwelt (IWU) building typology from [49], but with the exclusion of the oldest and newest buildings. Old buildings were not included since they are assumed to have undergone partly or fully energetic renovation. Single-family houses were used. Since the building typology presents the energy state at the construction, it is likely that they are not in their original state. New buildings are excluded since energy requirements have improved, and they require less heat and, therefore, have a smaller HP, which has a lower impact on the grid. IWU clusters buildings by letters from A to J. The following Table 3.1 shows the used buildings type, share in simulation, construction period, heated area, and useful heat per square meter and year (netto).

TABLE 3.1: Type of buildings used for the simulation

Typ	Share [%]	Periode [year]	Heated area [m²]	Transmission heat coefficient [W/m²K]	Useful heat (netto) [kWh/m²a]
D	13	1949 - 1957	101	1.35	312.5
E	21	1958 - 1968	110.2	1.07	303.2
F	21	1969 - 1978	157.5	0.9	223.6
G	11	1979 - 1983	196	0.98	149.3
H	18	1984 - 1994	136.6	0.72	173.7
I	16	1995 - 2001	110.8	0.55	134.9

The share of a particular building in Table 3.1 is based on the proportion in Germany. The heated area excludes unheated spaces such as unheated cellars, entrance areas, or others. The TABULA procedure from the IWU calculates the useful heat demand with reference climate data from Germany [49].

With the selection of buildings and their boundaries shown in Table 3.1, a space heating model based on DIN 4108-6 with additions from DIN EN 832 and DIN V 4701-10 is used. The detailed model is described in [50] and an overview is given in section 4.2.

While the heat demand is highly dependent on the ambient temperature, the demand for domestic hot water (DHW) and residual electricity is not. Therefore, the demand profiles don't need to be simulated based on the chosen year. The domestic hot water demand is simulated with the SynPRO Simulator, described in [51]. The modeling approach is based on combining behavioral and energy balance models and stochastic modeling. The domestic hot water demand is highly dependent on user behavior and time-dependent characteristics. Realistic and consistent load profiles are the result. For the generation of the domestic hot water demand, it is assumed that every house has two residents and an average socioeconomic status. The year for the simulation of domestic hot water demand is 2019. The resulting data has a resolution of 15 minutes. For the simulation, one out of 602 data series is randomly selected.

Time series of the residual electric demand was also created with the SynPRO Simulator and randomly selected during the simulation. The assumption is the same as with domestic hot water with the deviation, that as load type "apartment" was selected. In [52] the model is described, which uses a statistical approach and is calibrated for German households. Seasonal effects such as inhabitants' behavior change, pumps' operation, and lighting are included. The year for the simulation of residual electricity demand is 2019.

The ambient temperature data series is taken from historical data measured by the Deutsche Wetter Dienst (DWD). Kassel is chosen as a location. Because the time series has a resolution of one hour, it is linearly interpolated to fit the other time series, which has a resolution of 15 minutes.

The time series of the flexible electricity prices are from SMARD and are wholesale prices from the control zone Germany & Luxembourg. The time series has

a resolution of 15 minutes, which is the smallest resolution with price changes [53]. In addition, 0.2404 €/kWh are added to account for gird fees, taxes, and so on [54].

The necessary size of the HP depends on the building, historical temperature in the area, inhabitants and their behavior. A heat load calculation is usually done to determine the size of the HP. This calculates how much energy is needed at a specified temperature. These temperatures and how to calculate the heat load are taken from DIN/TS 12831-1 [55]. To simplify this thesis, the heat load is calculated by determining the heating needed at the standard ambient temperature for the specific building, excluding factors such as heating-up load. The thermal power is based on the heat load and varies depending on the scenario. To include the domestic hot water, 0.5 kW is added.

The simulation of household electricity use is price-optimized, but certain demands cannot be altered. These demands include residual electricity, domestic hot water, and heat. Flexibility is introduced through thermal storage for heat and domestic hot water. Each building has one thermal heat storage unit, with a minimum temperature of 25°C and a maximum temperature of 40°C. The domestic hot water storage has a minimum temperature of 35°C and a maximum temperature of 60°C. Both starting state-of-charges (SOCs) are 80 %. In Table 3.2 are the sizes of the storages, which depend on the heat storage on the electric power of the HP.

TABLE 3.2: Heat and Domestic Hot Water Storage sizes

	Heat [l/kW]	Domestic hot water [l]
Small	20	200
Medium	30	300
Large	40	400

The volumes from Table 3.2 are based on VDI standard 4645 for storage volumes with off-times. This standard recommends a storage volume of 30 to 40 liters per kilowatt electric power of the heat pump's shut-off time in hours [56].

The LV grid where the calculation should be run is from the synthetic grid database SimBench [57]. For this thesis ***1-LV-rural2–0-sw*** is used which is visualized in Figure 3.2. The number of loads determines how many buildings and therefore

households are connected to the grid. Based on the number of buildings, a certain percentage has HPs, which are randomly assigned. Therefore, these buildings produce their heat and domestic hot water with an HP. Any other building has another heating system that does not use electricity and, therefore, has just the residual electric load.

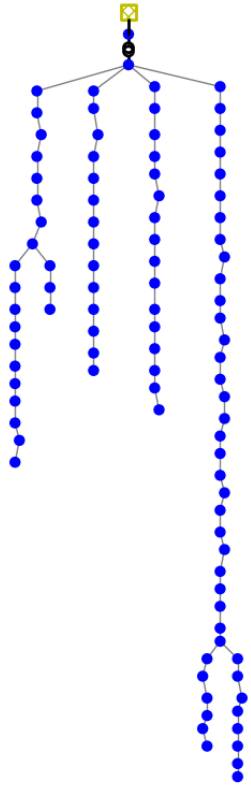

FIGURE 3.2: Visualization of the used grid

Heat demand, ambient temperature, domestic hot water demand, residual electric energy demand, electricity prices, size of HP and electric heating element, and other assumptions such as the sizes of storage and COP of the HPs are used as inputs for the optimization of the households. The simulation is done for two days and then given to the power grid calculation. The resulting load profile of each building is assigned to the respective grid connection point. The power flow calculation is run for the period to check if the constraints are violated. If this is not the case, the simulation advances to the next day with consideration

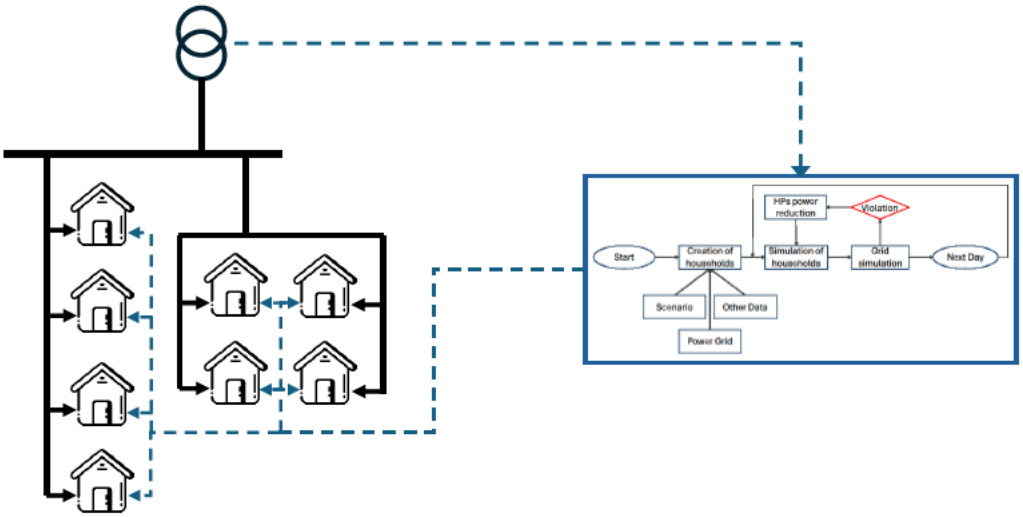

FIGURE 3.3: Visualization of the information flow from the transformer to the households

Before every simulation with the time-dependent power reduction, a price-optimized simulation is run. If no solution to the heat production can be found in the price-optimized simulation, the simulation stops entirely.

3.2 Scenarios

The parameters for the simulation are explained below. Two time periods in 2021 were selected, which represent interesting times for the weather and electricity prices.

- 20.01.2021 - 19.02.2021 a months period
- 18.12.2021 - 31.12.2021 two-weeks period

Shown in Figure 3.4 is the ambient temperature and price of the period with a duration of one month. Particularly cold temperatures characterize the period in the second half. The first half has more moderate temperatures. The cold temperature represents a particular challenge to the heat and DHW production with ASHP, as explained in Section 2.2. Therefore, it is likely the heating element needs to be used, which could have a high impact on the power grid since the cold temperature affects every household in the LV grid. The price is mostly just below 300€ per MWh, with a few dips below and above. Also, the daily fluctuations are visible. The medium ambient temperature is -0.73°C with a minimum of -16.6°C and a maximum of 9.5°C. The medium price is 291.18 €/MWh with a minimum of 236.56 €/MWh and a maximum of 377.11 €/MWh.

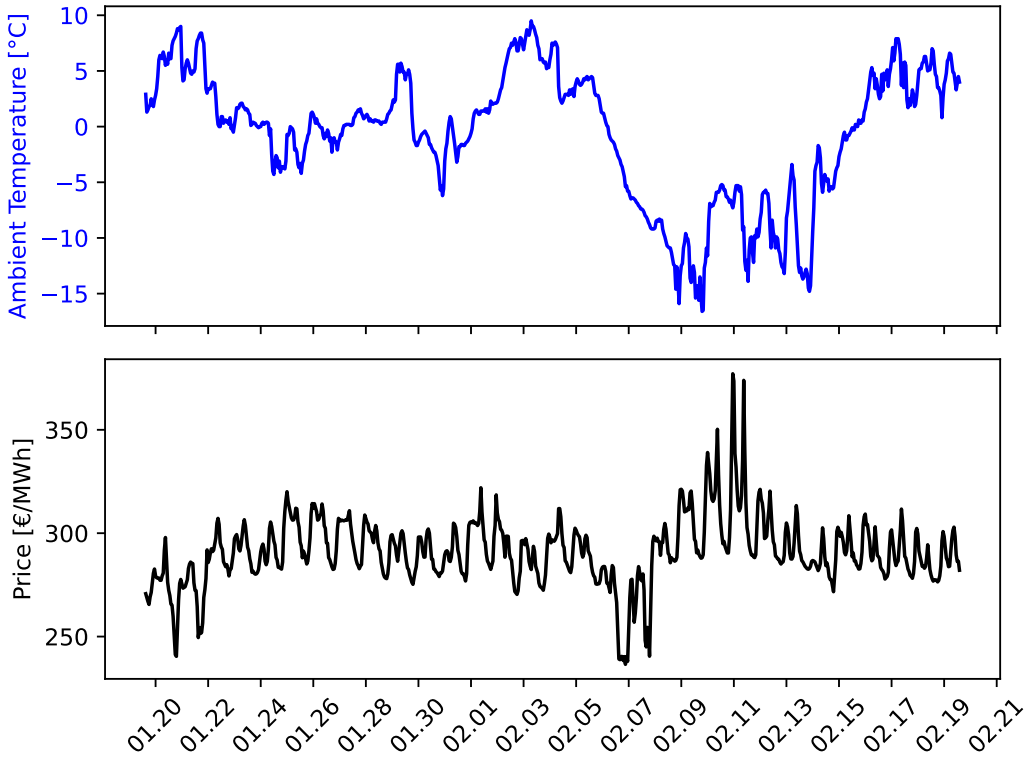

FIGURE 3.4: Ambient temperature and price below from 20.01.2021 to 19.02.2021

The second period of two weeks in Figure 3.5 has a drop in the temperature before it rises, falls, and rises again. This represents an interesting period to see the impact of cold and warmer temperatures on the ASHP power demand and, therefore, the power grid. The price is higher during the first temperature

drop compared to the second. On average, the price falls towards the end of the period. The medium ambient temperature is 2.27°C with a minimum of -8.5°C and a maximum of 13.1°C. The medium price is 449.04 €/MWh with a minimum of 240.34 €/MWh and a maximum of 860.40 €/MWh.

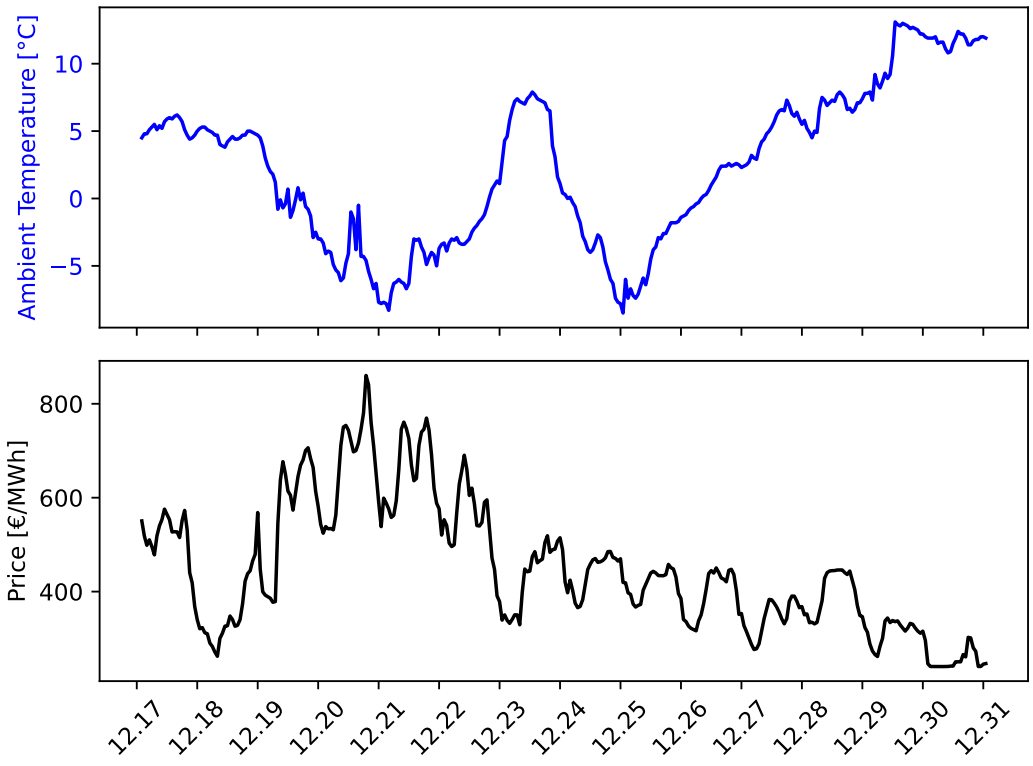

FIGURE 3.5: Ambient temperature and price below from 18.12.2021 to 31.12.2021

First, the two periods described above are simulated with a fixed price. The price of 32.63 Cents per kWh is an average for 2021 [54]. A fixed price is very common in Germany. It is interesting as the price of electricity plays an important role during the price-optimized simulation and can be considered a control signal as described in 2.3. The simulation with the fixed price is only run with medium-size storage and for the 70 %, 80 %, and 110 % size of HP in relation to the heating load.

With all use cases randomly, 40 % of households have an HP. As Figure 3.6 shows branching from this, the houses have three different sizes of HPs. The percentage refers to the thermal power of the HP compared to the calculated heat load at the

nt
.2

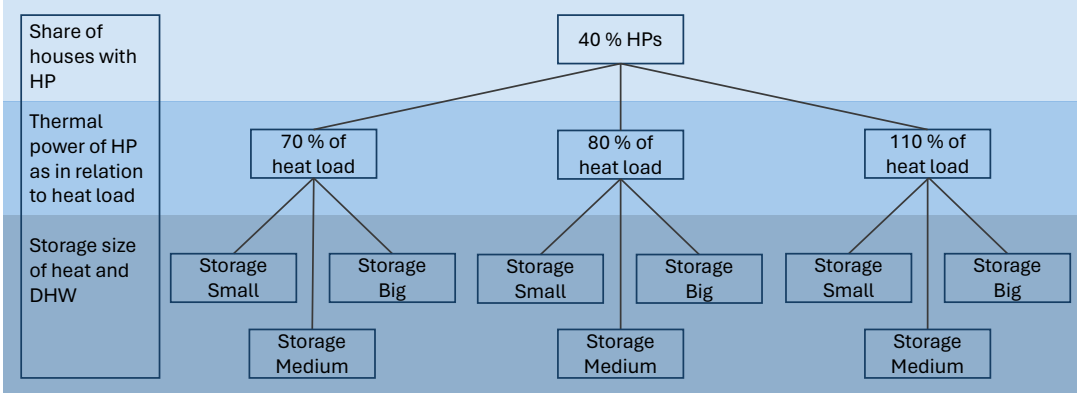

FIGURE 3.6: Visualization of the different Use Cases

A table with an overview of the described use cases can be found in Appendix A.

To evaluate the results of the time-dependent power reduction, the same period is simulated but without the time-dependent power reduction; therefore, it is only price-optimized. The price optimization is run first and is assumed to be state-of-the-art.

3.3 Goal and constraints

In the following, the simulation's goal and constraints are described, after which the comfort of the users and the power grid load are considered.

It is assumed that every household has an inverter HP with a smart meter so that the DSO can control them. Furthermore, the transformer is equipped with a digital measurement.

The goal of the simulation is to optimize the prices of heat and hot water. To achieve this, flexible prices are used in combination with storage. Hence, the times of the HP runs are optimized because all other parameters cannot be modified.

The secondary condition is to avoid or at least reduce overloading on the power grid. As the following describes, this conflicts with the goal. Therefore, overloading reduction is not always achieved.

Demand for heat, hot water, and residual electricity are always covered. If this is not possible, the simulation will be canceled. The different demands are described above in Section 3.1

Overloading of the grid is defined as transformer loading greater than 100 %. The analysis of the transformer feeders is oriented after the § 14a EnWG, which is described in Section 2.1 So if the power grid calculation reveals that for one day with the load profiles, the transformer loading surpasses 100 %, the algorithm attempts to prevent this by reducing the permissible power consumption of the HPs in these corresponding times. Therefore, it is a price optimization with the secondary condition of avoiding or reducing power grid overload.

Chapter 4

Simulation modules

In this chapter, the modules necessary to run the simulation are described. They are pandapower 4.1 for grid calculation, pandaprosumer 4.2 to calculate the heat demand of the buildings, microSCOPE 4.3 as optimization framework, and the database and interfaces between the modules 4.4.

In this chapter, the modules are described. The methodology and logical connections between the modules are described in Chapter 3.

4.1 pandapower

pandapower is a Python-based open-source tool for power system analysis [58]. The tool is aimed at automating static and quasi-static analysis and optimizing power systems. The main functionalities are power flow, optimal power flow, state estimation, topological graph searches, and short-circuit calculation, according to IEC 60909. The solver is based on PYPOWER and uses as default the Newton-Raphson method, but other methods can also be used [58].

pandapower uses an element-based model (EBM) to define the network. Each element is connected to one or multiple buses in this model and defined by its characteristic parameters. In comparison to the bus-branch model, this approach allows the definition of the networks with nameplate parameters like length and relative impedance instead of calculating the impedance for each branch and summed power injections for each bus [58].

A tabular data structure is used based on the Python library pandas [59]. Each element type is represented by a table that holds all parameters or results of an

analysis [58]. Pandas allows the storing of different data types to store electrical parameters in the same table as meta-data. All inherent pandas methods can be used in addition to the pandapower functionality [58], [59]. pandapower uses the same index for the parameters in the input and output table. The network is structured as a Python dictionary containing all the tables [58].

pandapower has a library where many different electric elements such as loads, static generators, lines, different kinds of transformers, and so forth are available, which are described in the documentation [58], [60].

Time series simulation can be used with load and feed-in profiles. A power flow is carried out in each time step, and it is possible to adapt, for example, the position of the tap-changer of a transformer if a certain constraint is violated [58]. With a controller called ConstControl, the power values of loads or static generators can be updated at each time step and element. The ConstControl gets the data from the Data Source and writes them onto the corresponding element before the power flow calculation. The Data Source is an object in which the data for the time series simulation is stored in a DataFrame [60].

The Output Writer is part of the time series simulation and can save the results of a time series simulation as a DataFrame or store them in a file. To specify the table and column of the results to be stored, they can be provided as arguments to the OutputWriter. [60]. Afterward, the results can be analyzed to adjust the time-dependent power reduction or evaluate the results.

The grid is taken from SimBench, which provides validated open-source datasets for power grid analysis. They are specific to Germany and offer different voltage levels and scenarios of renewable energy penetration [57], [61].

4.2 pandaprosumer

In [62] Python-based open-source tool pandaprosumer is introduced, which can be used to simulate prosumers for grid simulation and is described below. Its architecture and structure are based on pandapower and pandapipes, whereby the former is described in section 4.1. Pandaprosumer empowers users to conduct multi-energy grid planning operations by coupling different sectors. It allows the creation of dynamic and static time series that represent electric or heat demand

patterns. Since pandaprosumer is closely related to pandapower and pandapipes and borrows components from these, both tools must be installed to run it.

The three main elements of pandaprosumer are the components, controller strategies, and data classes. Similar to pandapower and pandapipes, the component information and time series are saved in a tabular structure. The tables are based on the Python library pandas [59].

The control strategies are built upon the controller architecture of pandapower and pandapipes and contain the logic of the technology. The complexity can range from a simple control loop to a mathematically optimized/AI system.

Compared to pandapower and pandapipes, pandaprosumer has additional data classes to describe the control strategies as interactions between the involved technologies. The pandaprosumer object contains all information about the controller, technologies, and time series.

There are two different processes for generating time series, but both create a pandaprosumer object. As in pandapower and pandapipes, a time series can be created by running controller loops in each time step. In a time-dependent simulation, the interactions of the different technologies can be depicted. The second option is to create the time series at once using the matrix calculation's performance power.

Time series are created using a bottom-up approach for categories including household (electric and heating demand), electric vehicles, heating systems, photovoltaic systems (PV), battery systems, and energy systems. Subsequently, only the heating demand, specifically space heating, as described in [50], is depicted.

The calculation of the space heating model is mainly based on the quasi-stationary approach of the DIN 4108-6 in combination with DIN V 4701-10 and DIN EN 832 [63]–[65]. The definition of different types of houses is based on the publication by the Institut Wohnen und Umwelt (IWU) [49]. In the publication, IWU clusters the non-homogeneous and strongly changed German housing stock. The possible energy efficiency improvements of the buildings are illustrated as variants [49]. To create a building, the following parameters need to be defined:

- Building geometry
- Overall heat transfer coefficient

- Adjacent buildings
- Heating system
- Modernization actions
- Residential behavior

In addition to the building parameters, the location, year, and outside temperature of a specified time period are necessary inputs for creating the time series.

Since the tool is only used to create static heat demand time series, only this procedure is described. The following steps are required to calculate the heat demand. First, the outside layer and the building volume are determined, along with the temperature correction factor, after which the heat loss can be calculated. The solar and internal heat gains are determined using the inside temperature and the monthly mean outside temperature, and the effective heat capacity is derived. The utilization factor is then calculated, and the heating degree days are determined. With these values, the heat demand of a building can be calculated—the utilization factor accounts for building dynamics with heat gains.

4.3 microScope

microScope is a tool from the Fraunhofer IEE to solve unit commitment problems of energy unit portfolios and is based on the optimization core $micro - core$ [66]. It is set up in Python and Pyomo and uses the commercial solver Gurobi [67]. For example, it can be used to solve a unit commitment problem of a hybrid power plant with a battery by considering the buying and selling of energy on the continuous intraday market to find a price-optimal solution [67].

In [66] Dörre et al. describe a simulation that comprises many microsystems, which are individual households. These microsystems consist of ten different combinations of PV, battery storage (BSS), electric vehicles (EVs), heat pumps (HP), and electrical household loads [66].

The electricity generation of the PV is represented over irradiation and ambient temperature in connection with different orientations and sizes of the modules. The BSS is used in combination with the PV to maximize the self-consumption

of the household. Moreover, the BSS provides positive and negative flexibility to the grid by charging or discharging and reducing or increasing its power [66].

The energy demand from the EV's driving profiles is combined with charging and the user's comfort needs. In addition, half of the EVs can charge bidirectionally, which provides flexibility. In contrast to the BSS, the flexibility of the EVs is limited by their absence and the user's comfort needs, such as a certain state of charge [66].

The energy demands of the heat pump and auxiliary heating systems are determined by the thermal load profile caused by heating and domestic hot water generation, which they must cover. Thermal load profiles cannot be generated by microSCOPE and must be provided for the simulation. The HP is supposed to cover the demand, except if the actual demand exceeds its capacity or negative flexibility is needed, a heating element is used. The ambient temperature determines the thermal load and the electricity load as air-to-water HPs are assumed. Flexibility can be provided by using the capacity of the hot water and heating buffer storage tank. To transfer the heat to the house, underfloor heating systems are used, which provide the benefit that due to their high inertia, a constant room temperature can be assumed even if the residents are absent [66].

The variations in household electric loads are simulated and must be met at each time interval. Electricity prices are based on the hourly day-ahead market [66].

Each household is considered a self-demand optimized microsystem for which the unit commitment problem (UCP) needs to be solved with consideration of the flexibility potential, which is calculated based on a mixed-integer linear program. The aim is to maximize profits while minimizing costs. The flexibility provision is not explicitly considered in the operation strategy but gives the household occupants an additional benefit. The technical and economic restrictions of energy production, consumption, and storage are considered in the UCP. The household microsystems that is the Home Energy Management System (HEMS) objective function maximizes the economic profits over the solution space. To solve this, microSCOPE is used [66].

In the following Figure 4.1, the modeled system with all its power units is visualized.

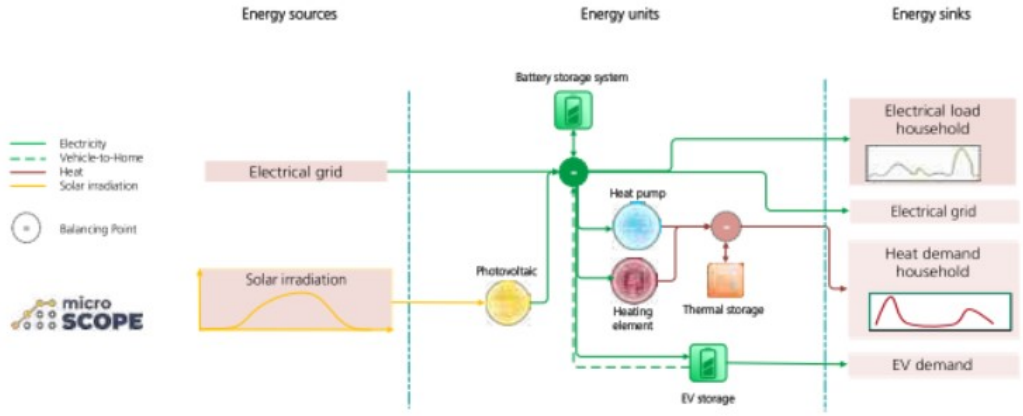

FIGURE 4.1: Visualization of the modeled system with all its power units

The electrical grid and solar irradiation in Figure 4.1 are considered external energy sources, whereby the latter is used to produce electricity with PV. The battery and thermal storage (plus half of EVs) can provide flexibility by storing energy for later use and balancing the demand, which is visualized with the balance points. The energy demands are represented by the energy sinks on the right side of the figure.

To configure such or similar models, an Excel-based configurator is used. Each row in a sheet is a potential microsystem if the scenario group matches. Besides general information about the system, the balancing reserve, PV, battery, combined heat and power unit, residual load, gird source/sink, EV and charging point, HP, heating element, heat, and domestic hot water load, and storage of heat and domestic hot water can be defined [68].

4.4 Interfaces between the modules and database

Figure 4.2 shows the origins of the time series data from price, weather, and so on and if they are created by a tool such as pandaprosumer for the heat demand or the household simulation from microSCOPE.

To connect the different modules databases and the Exel-based configurator of microSCOPE were used.

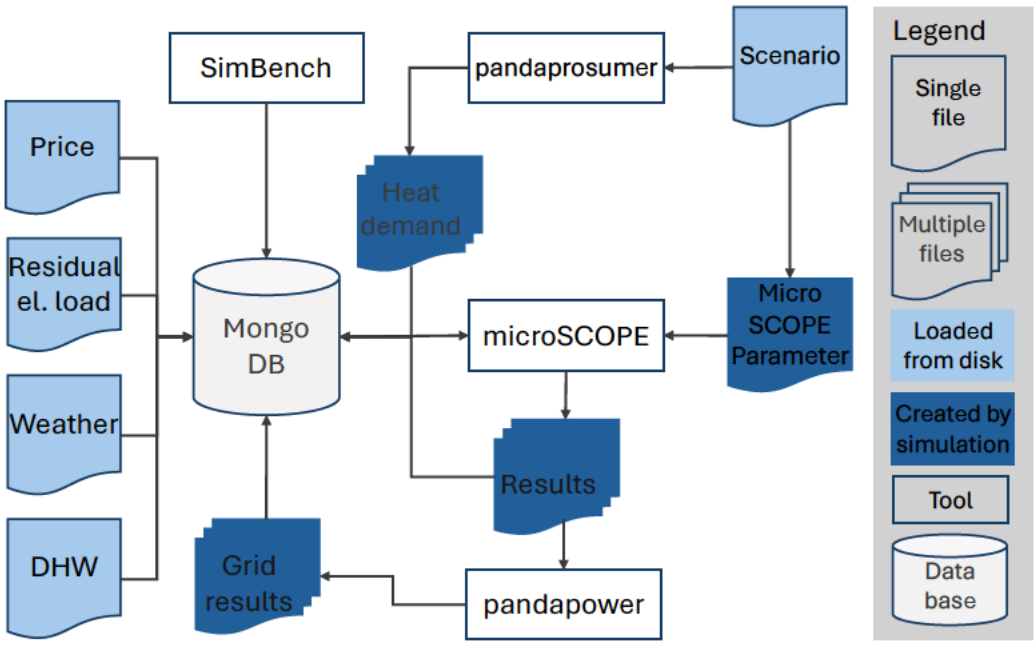

FIGURE 4.2: Visualization of the DB and files of the time series in connection with the tools

As a database, MongoDB is used. MongoDB is a distributed document database that is designed for ease of application development and scaling. It is built on a horizontal scale-out architecture and uses a flexible schema for storing data. Instead of storing data in tables of rows and columns like SQL databases, MongoDB stores data as documents described in BSON (similar to JSON), a binary representation of the data. These documents can have a hierarchical structure and can be stored in collections. MongoDB provides a great developer experience with drivers for major programming languages and offers features like indexing and validation [69], [70].

To connect and store the data in the MongoDB database, pandahub is used [71].

As described in Chapter 4.3 microSCOPE has an Excel-based configurator, which is used to define the simulated households. The process is automated because microSCOPE is used more than once during a simulation period. Also, the households' first definition is automated and based on the given scenario. An example of the parameters and how they are defined is shown in the following Table 4.1.

TABLE 4.1: Example storage input parameters

Quantity	**Unit**	**house1**
int		1
volume	liter	300
min_temp	°C	35
max_temp	°C	60
soc_initial	%	80
soc_final	%	

Table 4.1 is an excerpt from the rows of the house1 column of the microSCOPE configurator. The shown excerpt belongs to the domestic hot water storage. The volume is given in the scenario, and the rest of the data is based on a template. From each rolling period to the next, the initial SOC has to be changed. Since microSCOPE saves only the amount of energy in MWh, the SOC is calculated.

For the grid calculation, the time series of the energy usage of the households are saved as Hierarchical Data Format (HDF) files. HDF is an open-source file format designed to store and organize large amounts of data efficiently. HDF files can store various data types, including numerical arrays, text, images, and more, in a hierarchical structure. The advantages include the hierarchical structure to organize the data, support for large datasets, especially compared to Excel, efficiency while storing and accessing large datasets, and native support in pandas [72], [73].

These files are read with pandas, and the electricity consumption time series is brought into the necessary data format so that the grid calculation with pandapower can run. The results are saved into the MondoDB database.

Chapter 5

Results and Discussion

In this chapter, the results of the case studies are analyzed and discussed in Section 5.1. In section 5.2, the sensitivity analysis focuses on the houses' heat demand and their impact on the power grid. The results are shown and discussed mainly with the help of figures that present the transformer loading due to the grid calculation. First, an overview of the two periods and different use cases is given before selected use cases are analyzed in detail.

5.1 Case Studies

The two periods shown in Figure 3.5 for the two weeks and Figure 3.4 for the month present ambient temperature and price data, which are discussed separately. First, the shorter period of two weeks is examined. Figure 5.1 shows the sum of minutes over the transformer loading of 100 % in the period. This indicates how much impact the houses and their heat generation with HPs have on the grid. While the heat demands are the same, the use cases differ by the size of the heat and domestic hot water storage and the thermal and, therefore, electric power of the HPs.

The first row presents the simulation results with the fixed price. The second row shows the results with the flexible price without time-dependent power reduction. The last row displays the results with time-dependent power reduction. The first column shows the results for an HP size of 70 % of the heating load plus the added power for domestic hot water. Similarly, the second column shows an HP size of 80 %, and the last column shows an HP size of 110 %.

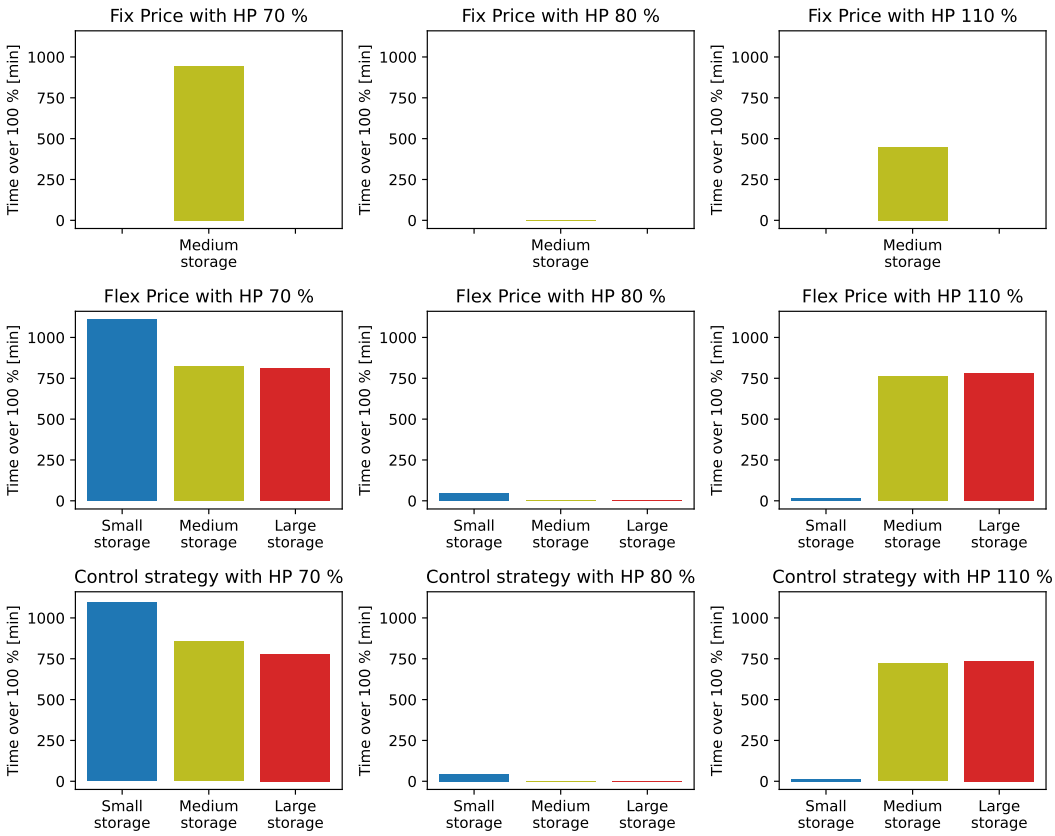

FIGURE 5.1: Minutes over the transformer loading of 100 % for the period of two-weeks

The absence of data for the fixed-price scenario in the first row of the small and large storage Figure 5.1 reflects its exclusion from the primary comparison with the time-dependent power reduction results. The other missing bars are explained by the fact that the transformer loading was never over 100 % during the grid simulation. Therefore, the sum of minutes is zero.

Across the fixed price, flexible price, and time-dependent power reduction control scenarios, the use case with HP sizes of 70 % spends the most time over the transformer limit of 100 %. Large storage generally results in less overloading within the same HP size, except for the oversized HPs at 110 %. It must be noted that the volume of the heat storage is dependent on the electric power of the HP, and therefore, it increases as well. Thus, simply increasing storage size does not result in decreased transformer loading if the electrical power of the HP also increases. This effect is studied in detail in Subsection 5.1.2.

Figure 5.2 shows the same plots as in Figure 5.1 but for the period of a month, as shown in Figure 3.4. Other than in Figure 5.1, the missing bars are caused by the inability to run the household simulations. This is likely due to the small storage for heat and domestic hot water, as the simulation with the medium-sized storage could run. The simulation and the reasons for its stoppage are explained in Section 3.1.

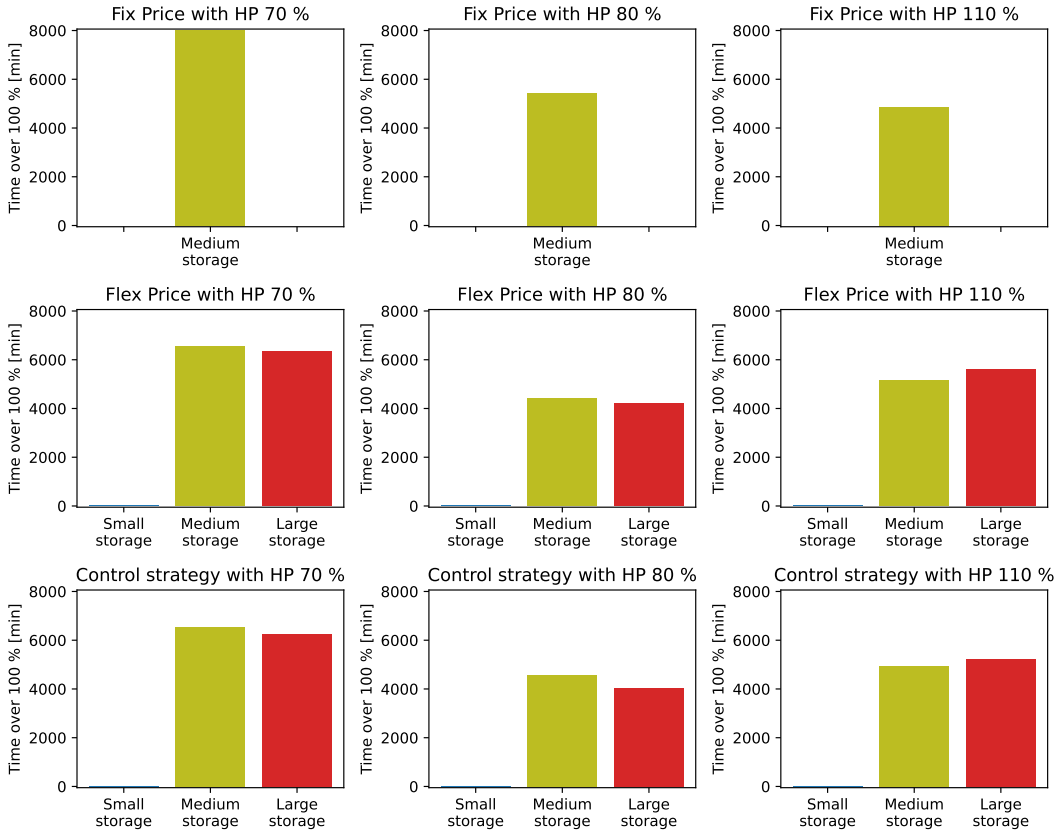

FIGURE 5.2: Minutes over the transformer loading of 100 % for the period of a month

The sum of the minutes over the transformer limit of 100 % is much greater with the period of a month since the temperature is lower and therefore the houses need more energy for heat. Additionally, as Section 2.2 explains, the HP has a worse efficiency. Similar to the results in Figure 5.1, the time over the transformer limit drops with increasing storage size to a certain point. With the HP size of 110 %, the effect reverses, and the time increases. It is noticeable that a larger storage at cold temperatures leads to the heat requirement being covered. From

this, it can be concluded that storage size plays a vital role in particularly cold temperatures.

5.1.1 Fixed Price

Figure 5.3 shows the price, ambient temperature, and the resulting transformer loading of the two-week period. The thermal power of the HP in relation to the heat load of the houses is 80 %.

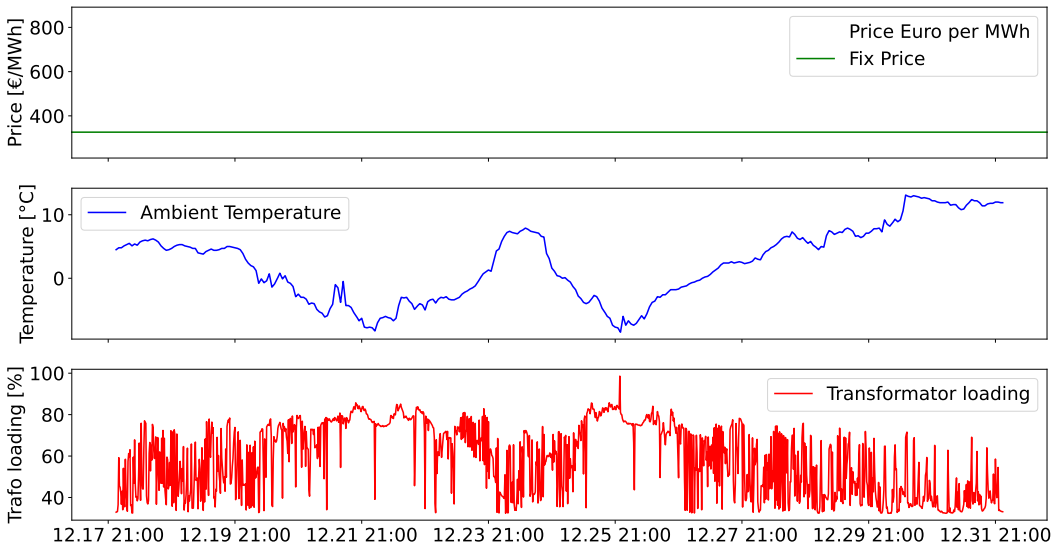

FIGURE 5.3: Price, temperature, and transformer loading for the two weeks medium storage and HP size 80 %

Figure 5.3 demonstrates that the continuous high transformer loading occurs during low ambient temperature. In particular, the highest spike appears as the ambient temperature is low. Since the HPs don't run always but only if necessary the transformer loading spikes at these times. Empty storage, in combination with the demand for heat or domestic hot water, can cause the running of HP. Because the price is fixed, the household cannot minimize the cost by shifting the heat production over time.

The following Figure 5.4 shows the same data but with the thermal power of the HP in relation to the heat load of the houses of 70 %.

The spikes in transformer loading during low temperatures are much more pronounced and higher in Figure 5.4. With the smaller HP, the heating element must

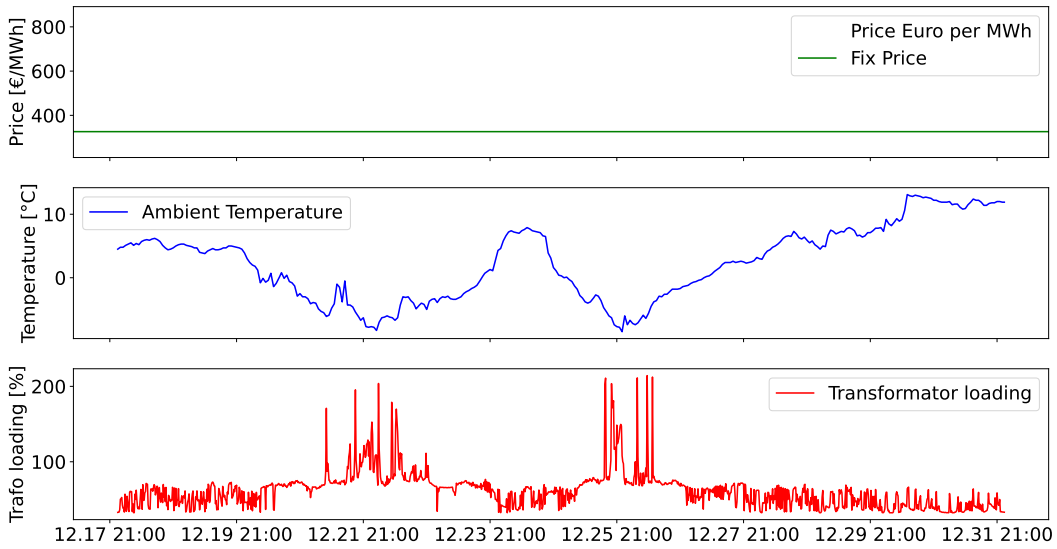

FIGURE 5.4: Price, temperature, and transformer loading for the two weeks medium storage and HP size 70 %

support heat generation to a greater extent during cold times, resulting in high electric power demand because the heating element does not use ambient heat. Additionally, the smaller storage means the HP and heating element must run more often, as less heat and domestic hot water are stored. For example, if the inhabitants consume hot water, it has a greater impact on the SOC of smaller storage systems compared to larger ones.

5.1.2 Control with Base Case as comparison

To analyze the impact on the transformer loading of the control with the time-dependent power reduction, it is compared to the use case with a flexible price.

Figure 5.5 shows the transformer overloading and the magnitude as the maximal value plotted of the two-week period with the time-dependent power reduction. As a comparison in Figure 5.6 is the same except without control and therefore just price optimized.

Figure 5.5 shows for the two-week period the magnitude of overloading as the maximal value during the overloading and their duration. The box with the HP in relation to the heat load of the houses of 70 % has the most times over the transformer loading of 100 %. At the same time, the medium-size storage has the

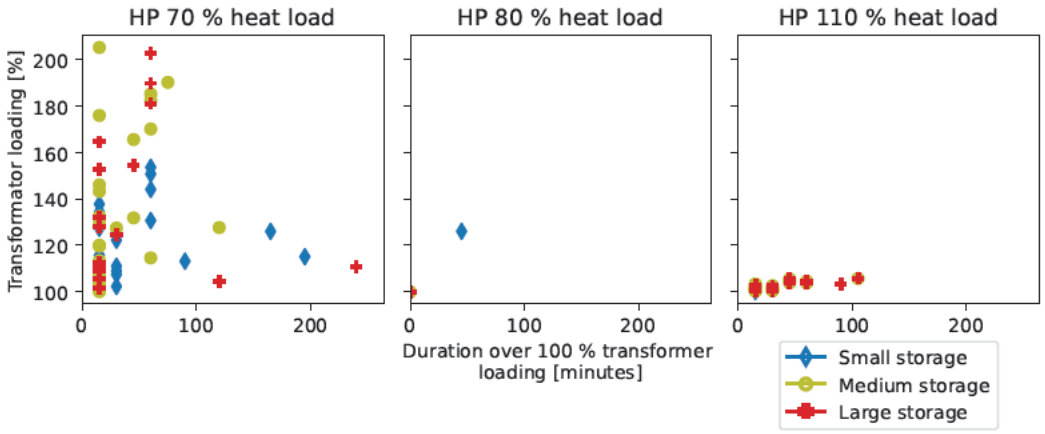

FIGURE 5.5: Visualization of the transformer overloading with its magnitude for the two-week period and control

highest transformer loading. The large storage has the longest overloading. The HP size of 80 % has next to no transformer overloading. In contrast, the 70 % HP size of 110 % has relatively low and short overloading.

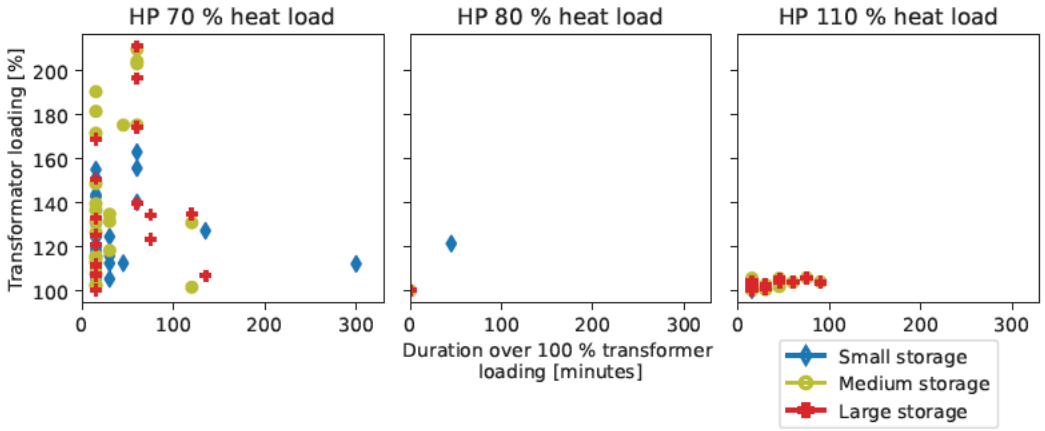

FIGURE 5.6: Visualization of the transformer overloading with its magnitude for the two-week period

Figure 5.6, which acts as a comparison without control, shows a similar pattern. But with the HP size of 70 %, the maximal overloading is higher, and the longest periods are longer. The HP sizes of 80 % and 110 % show results that look alike, with the difference that the time of the longest transformer overloading is shorter without the time-dependent power reduction.

For example, Figure 5.7 shows the price, ambient temperature, and the resulting transformer loading without and with the time-dependent power reduction of the HPs below.

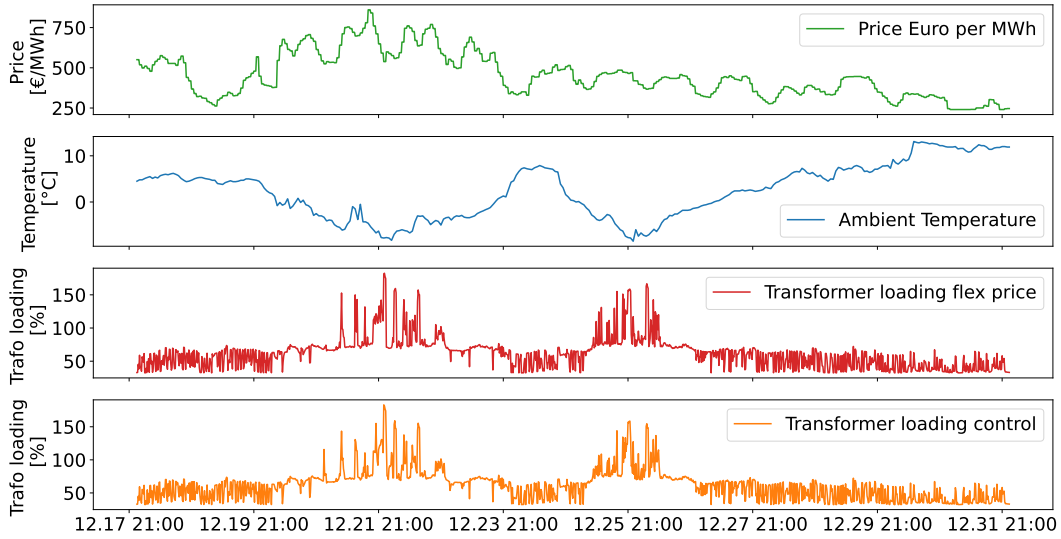

FIGURE 5.7: Display of price, temperature, and resulting transformer loading of the HP size 70 % and small storage's

Figure 5.7 shows that high transformer loading occurs often during cold ambient temperatures in combination with low prices. The spikes of the transformer are caused by the heating element use if demand for heat or domestic hot water exists, which cannot be covered by the HP or from storage.

For the two weeks, the ambient temperature and the sum of electrical power usage of the heating element and HP are shown in Figure 5.8. The power of heating elements are in the same plot but are independent of each other and are cumulative. During the cold temperatures, the electrical power of the HPs stays above 100 kW and does not fluctuate as it does with warmer temperatures, which is shown in 5.8. This does not mean that the HPs are too small for the houses but is intentional, as described in Section 2.2. Since the temperature is slightly higher for most of the heating period, the size of the HPs is optimized for these conditions, with the heating element used to produce additional heat at lower temperatures. Although this approach leads to more efficient heating, it puts additional stress on the power grid and transformer, as shown in Figure 5.7.

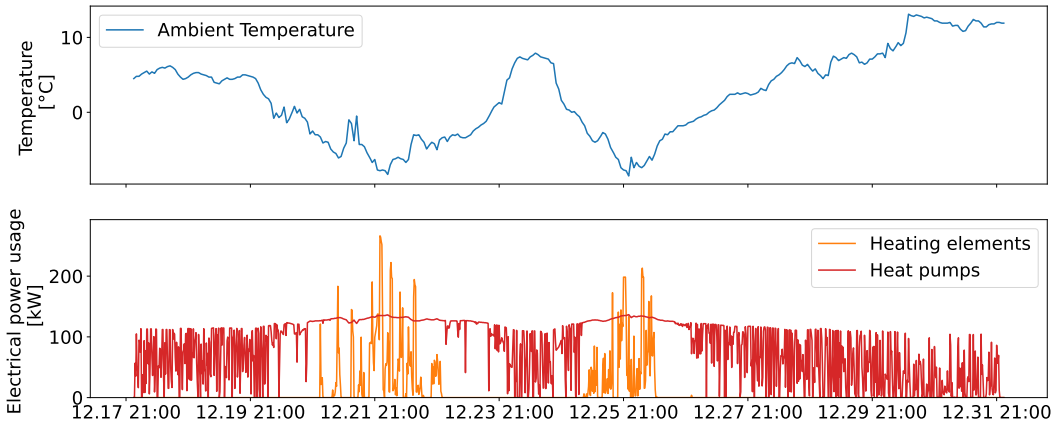

FIGURE 5.8: Visualization of temperature and total electrical power consumption of the heating elements and HPs

Since Figure 5.7 shows no obvious difference between the lines from the transformer loading, a zoomed-in annual duration line is used in Figure 5.9. The use case has the HP's size of 70 % in relation to the heat load of the houses and small storage. To create the annual duration line the values were sorted in descending order. Only values over and around 100 % transformer loading were used. Transformer loading can be reduced and the load is shifted to a time without overloading.

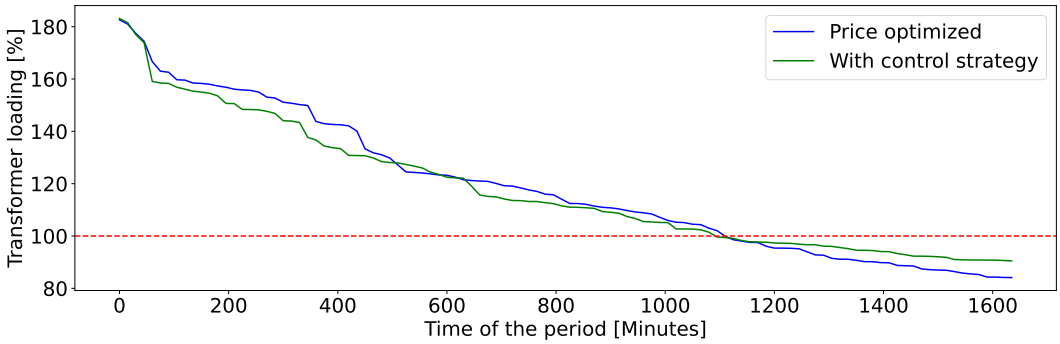

FIGURE 5.9: Annual duration line with a focus on the transformer loading greater than 100 % of the HP size 70 % and small storage's

As described at the beginning of this section, the length of one month is analyzed after the short two-week period. While the two-week period is characterized by two short times of low temperatures down to - 5 °C, the length of one month

begins similarly. During the second half, the temperature drops to - 15 °C, representing an extreme. In addition, the electricity price has spiked, as shown in Figure 3.4.

In Figure 5.10, the magnitude of the overload is shown as the maximum value during the overload and its duration for the two-week period. The results from the use cases with small storages are missing since the simulation could not run as described at the beginning of Section 5.1.

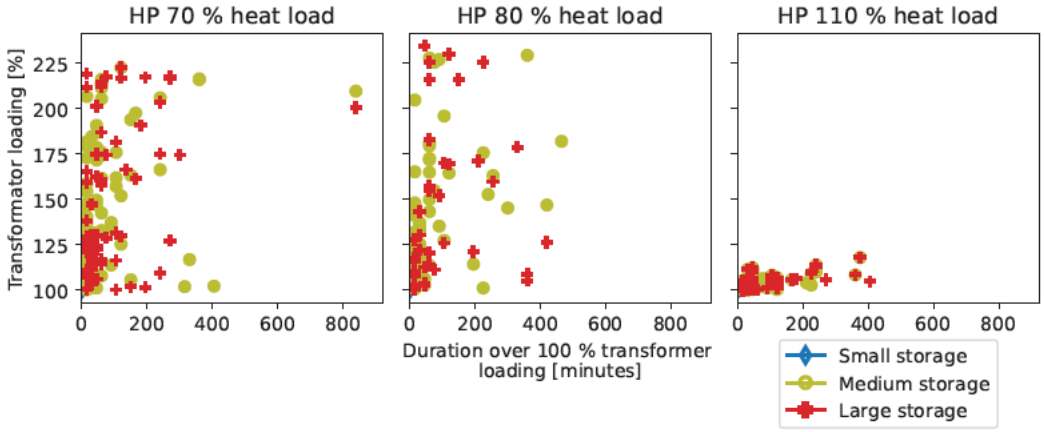

FIGURE 5.10: Visualization of the transformer overloading with its magnitude for the month period and control

Compared to the two-week period in Figure 5.5, much more overloading occurs, and it lasts longer as shown in Figure 5.10. Furthermore, the use cases 80 % size of the HP also have overloading, which is as high as those of the 70 % HP's size but doesn't last as long. The two use cases where the HP's size is 110 % of the heating load of the house have both transformer overloading. They are just over 100 % of transformer loading and therefore lower than that of the other HP's sizes. But the longest lasts equally as long as the longest of the 80 % HP's size with around 400 minutes.

Figure 5.11 is for comparison of the same visualization but without the control and, therefore, not the time-dependent power reduction of the HPs.

Since the difference is not obvious apart from the two high and long overloading periods in the use cases with the HP size of 70 %, which would suggest a worse performance with the time-dependent power reduction, selected use cases are

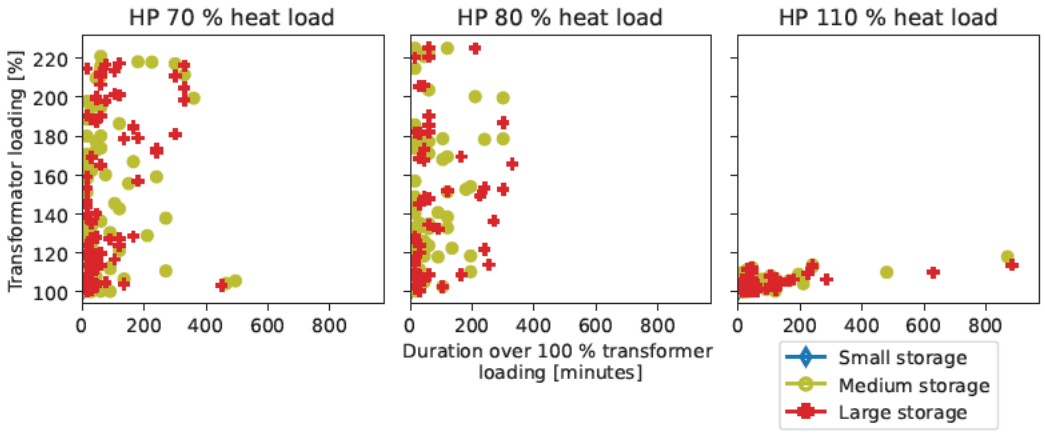

FIGURE 5.11: Visualization of the transformer overloading with its magnitude for the month period

analyzed further in the following. In contrast, the design of 110 % HP size has the longest overloading only half as long with the time-dependent power reduction.

Similar to Figure 5.9 but with a bigger HP and larger storage, the annual duration line for the HP size of 80 % and large storage is shown in Figure 5.12.

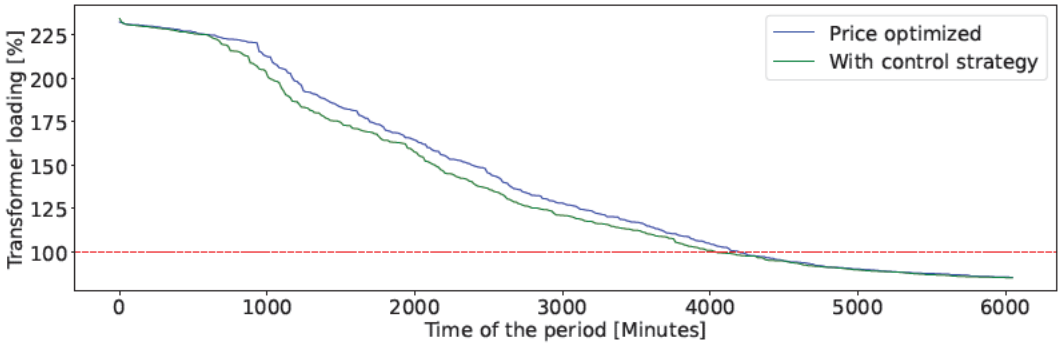

FIGURE 5.12: Annual duration line with a focus on the transformer loading greater than 100 % of the HP size 80 % and large storage's

The gap between the two lines in Figure 5.12 is the effect of the control and time-dependent power reduction. The effect does not improve with bigger HPs but is decreasing, as shown in Figure 5.13.

It should be noted that this period is characterized by extremely cold temperatures, which are below the standard ambient temperature described in 3.1. Therefore, the HPs can't provide enough heat without the heating element. Figure 5.14

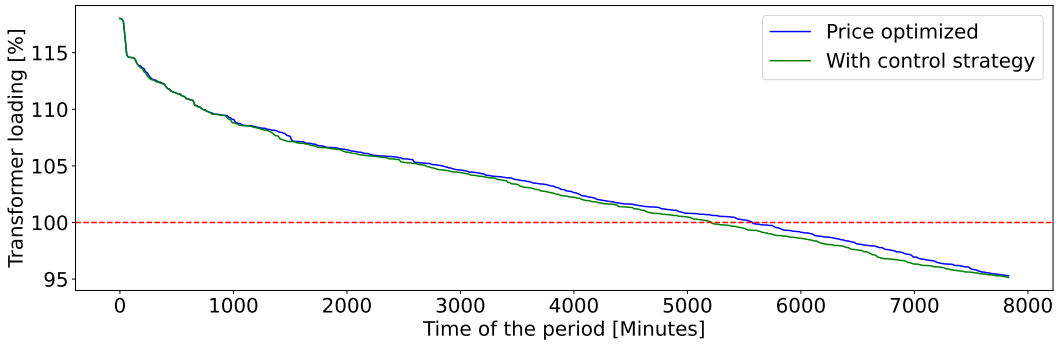

FIGURE 5.13: Annual duration line with a focus on the transformer loading greater than 100 % of the HP size 110 % and large storage's

shows the ambient temperature and the electrical power demand of the HPs and heating element.

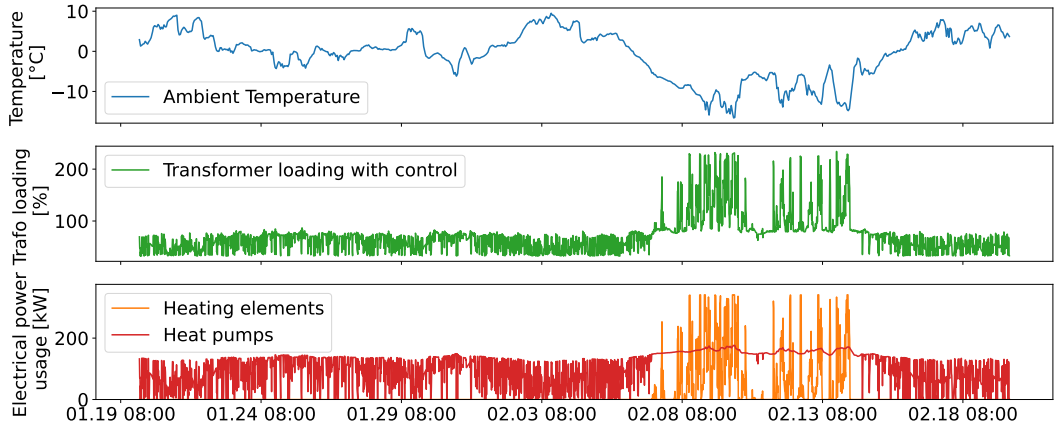

FIGURE 5.14: Visualization of temperature, transformer loading after time-dependent power reduction, and total electrical power consumption of the heating elements and HPs

Figure 5.14 shows that the overloading of the transformer is a result of the heating elements that are needed because the HPs can not generate enough heat at specific times.

To analyze the effects and impacts of the time-dependent power reduction, a period that is first characterized by low temperatures and later by a drop in the price is shown in Figure 5.15.

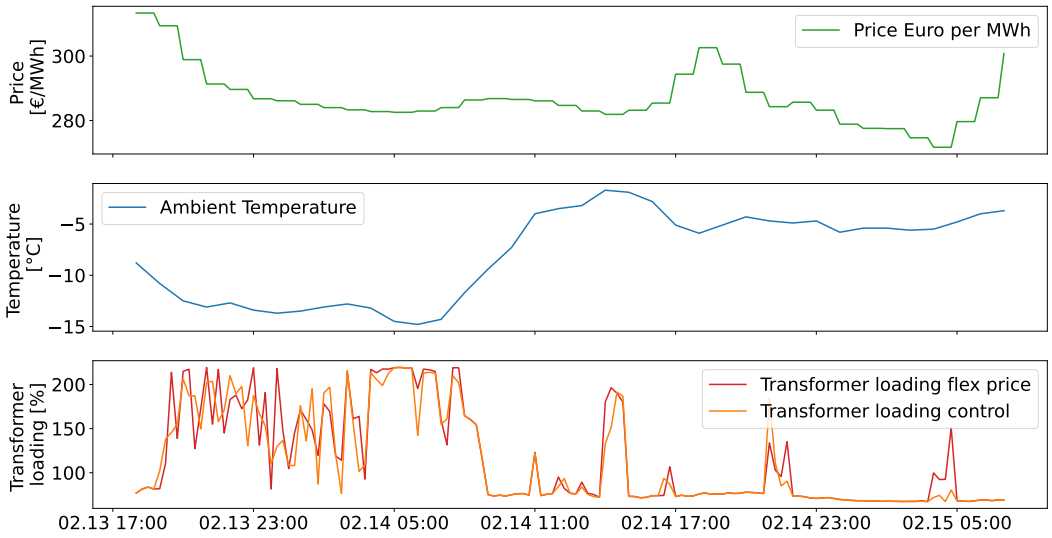

FIGURE 5.15: Zoom into the period from 02.13 17:30 until 02.15 13:00

Figure 5.15 shows that during cold temperatures, the control with the time-dependent power reduction can only reduce a few spikes by a small amount. The heat demand is so high because of the cold temperature, and the HPs can't produce enough heat for the heating element needed. Also, the simulation always tries to cover the energy demand and otherwise fails. This causes high electrical loads that cannot be shifted in time due to the high demand and low temperatures. The later standalone spikes, mainly caused by the price, can, in part, be reduced. The last spike in this period is primarily caused by the price and can be avoided with the time-dependent power reduction.

Additionally, only four loops with a one-day rolling time frame of two days are used for the optimization. This prevents possible shifts of energy usage over longer times.

5.2 Sensitivity analysis

To analyze the sensitivity of the results, simulations with slightly different parameters are carried out. To study the effect of the HP penetration, the simulation is run with a deviation of 5 %. The storage size is always medium, and the

period of a week and a month is analyzed. In Table 5.1 are all the parameters shown.

TABLE 5.1: Use cases to analyze the sensitivity of the HP penetration

Share of houses with HP	Period	Thermal power of HP as in relation to heat load	Storage size of heat and DHW
35%	Week	70%	Medium
		80%	Medium
		110%	Medium
	Month	70%	Medium
		80%	Medium
		110%	Medium
45%	Week	70%	Medium
		80%	Medium
		110%	Medium
	Month	70%	Medium
		80%	Medium
		110%	Medium

In addition to the use cases shown in Table 5.1, the use cases with the same storage size from previous investigations are also used. Therefore, in the following, the share of houses with HPs of 35 %, 40 %, and 45 % are compared.

The results are shown in Figure 5.16 for the shorter two-week period and in Figure 5.17 for the one-month period.

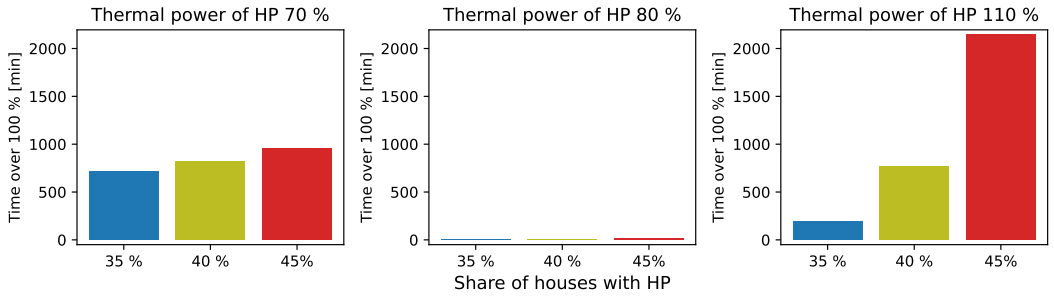

FIGURE 5.16: Comparison of different shares of houses with HPs for the period of two weeks

Figure 5.16 shows that with a higher share of houses with HPs in a grid, the time over the 100 % transformer loading is increasing. While the difference for thermal power of the HP of 70 % is not that great, the effects are much larger with

the higher HP thermal power of 110 % of the house heat load. Similar effects are shown in Figure 5.17, which suggests that if the HPs have too much power compared to the heat load of the houses, it has a negative effect on the grid.

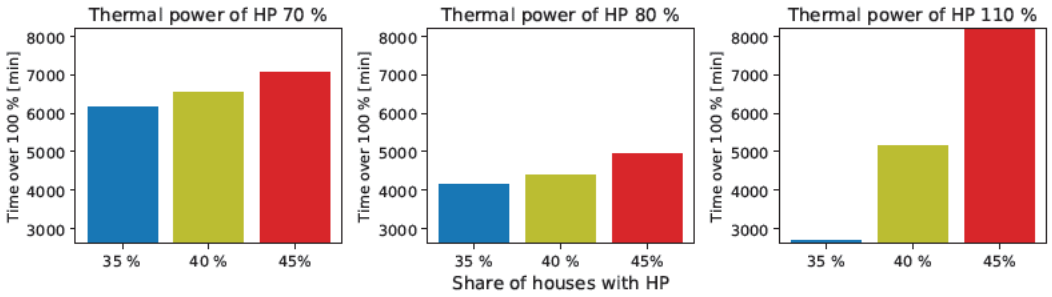

FIGURE 5.17: Comparison of different shares of houses with HPs for the period of a month

Figure 5.18 shows a scatter plot of the transformer overloading with its magnitude for the two-week period for a share of 35 %, 40 %, and 45 % of houses with HPs in the grid. This shows that the maximum transformer loading increases if more houses have an HP. As shown in Figure 5.16, the total time over the transformer loading of 100 % increases.

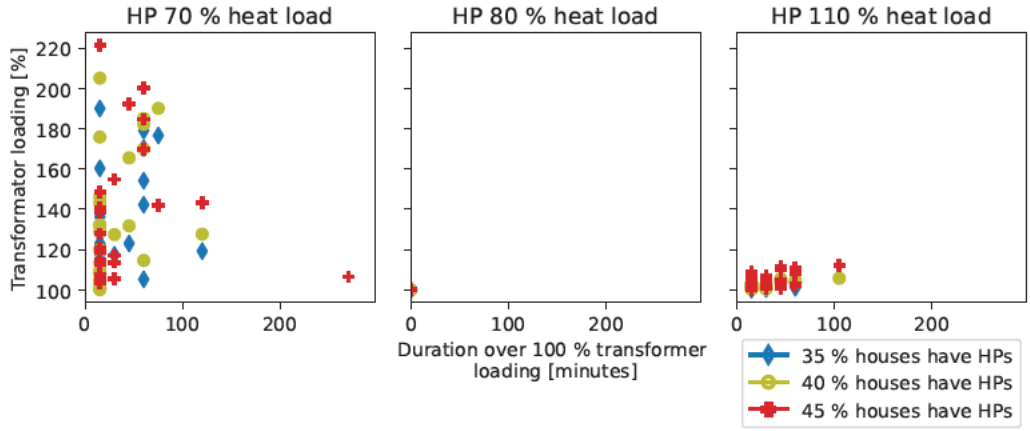

FIGURE 5.18: Visualization of the sensitivity of transformer overloading with its magnitude for the two-week period

Figure 5.19 shows the same plot as Figure 5.18 but for the longer period of a month.

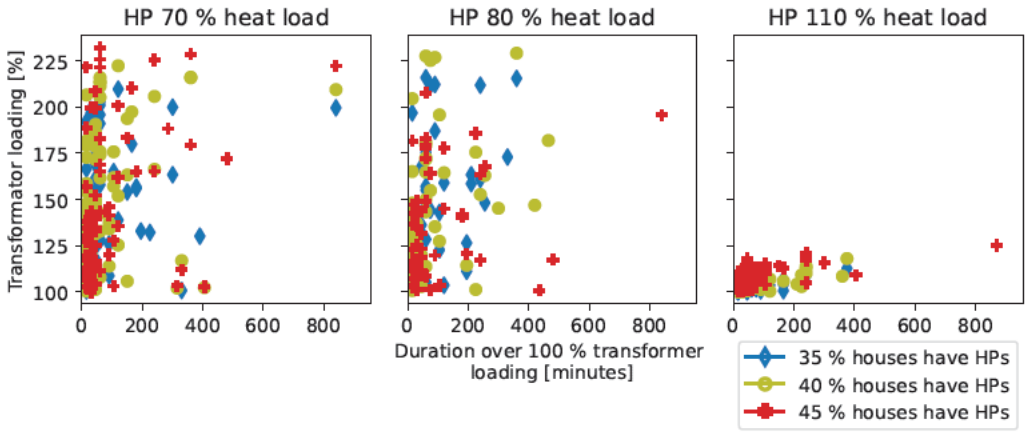

FIGURE 5.19: Visualization of the sensitivity of transformer overloading with its magnitude for the month period

As shown in Figure 5.18 Figure 5.19 shows for the thermal HP power of 70 % of the house heat load that the transformer loading is highest with the most HPs in the grid. With the HPs size of 80 % and 110 %, this is not the case.

5.2.1 Heat demand of houses

Since the heat demand of the houses and, therefore, the power of the HP to generate the heat is beside the amount of HP's, the biggest factor on the transformer loading, the effect of energy renovation is investigated. To analyze the impact of the heat demand on houses, it is assumed that every house built after 1979 has undergone some renovation. The randomly decided new distribution is now shown in Table 5.2.

On the left side in Table 5.2 are the new houses with their share of the total building stock and the heat load. The right side shows the same for houses used for all other use cases and described in 3.1. In general, newer buildings have a lower heat load, and an overall lower energy demand for heating can be assumed. While the energy demand depends largely on the usage for this study, the usage is assumed to be similar in each house. Even if new houses are more energy efficient, if they are larger, the heat load could be higher and also the energy demand over a year.

TABLE 5.2: Comparison of share and heat load of houses with and without energy refurbishment

With energy refurbishment			Original state		
Typ	Share [%]	House heat load [kW]	Typ	Share [%]	House heat load [kW]
G	16	9,30	D	13	12,14
H	23	7,82	E	21	13,50
I	21	4,61	F	21	12,41
J	18	3,82	G	11	9,30
K	14	4,80	H	18	7,82
L	8	3,38	I	16	4,61

Both distributions of houses are studied in the use case with the HP's size of 70 % of the heating load of the houses and medium-size storage. This use case was chosen since it had a long transformer overloading and produced results for a two-week and month-long period. The results are shown in Figure 5.20.

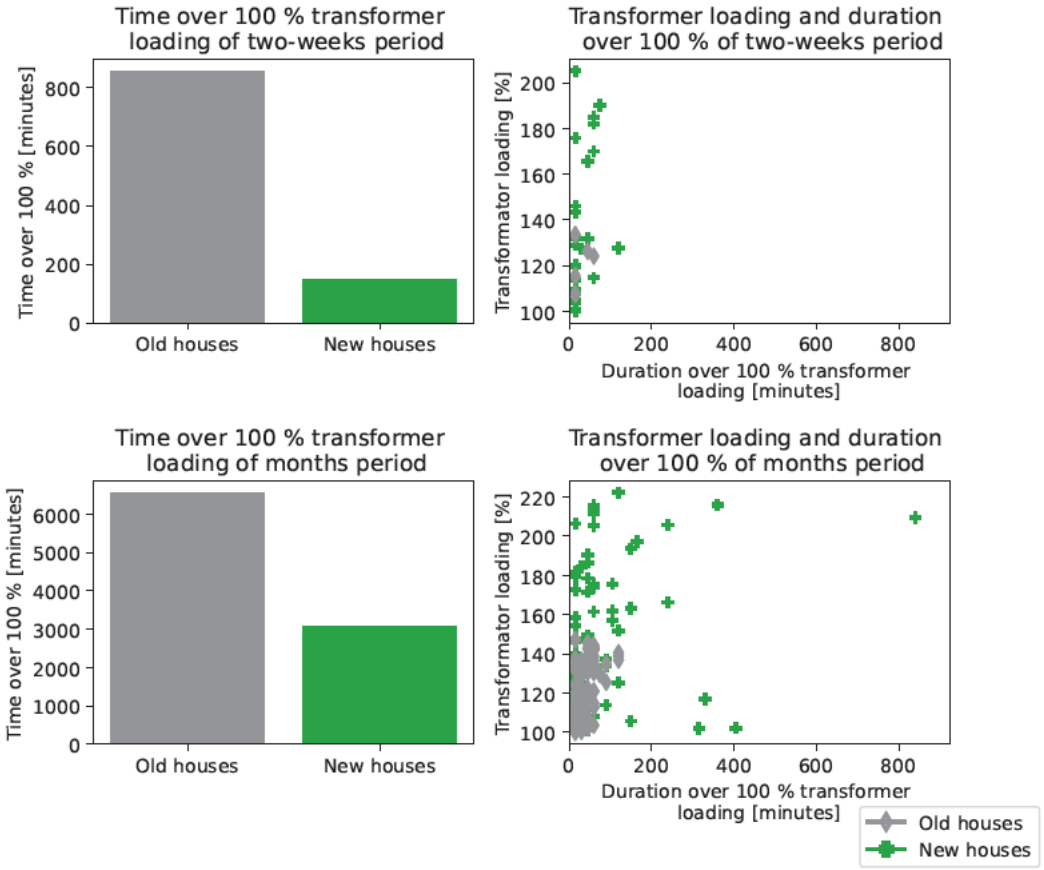

FIGURE 5.20: Visualization of the effect of new buildings on time over 100 % of transformer loading and its duration with magnitude

Figure 5.20 shows that the type of houses used for the simulation affects the resulting transformer loading. For a the period of a month, the time over 100 % of transformer loading is half of that compared with the old houses. The short period of two weeks in the first row shows an even bigger effect with a resulting time of one quarter compared to the initial case. The scatter plot in the second column shows that with new houses the duration and magnitude of the transformer overloading is not always lower. This is due to the low electrical power of the HP' since the time-dependent power reduction does not reduce below 4.2 kW. With many HPs with an electric power of around 4.2 kW, the impact on the power grid cannot be reduced by much.

The effects shown in 5.20 with the period of a month are not as great as the

shorter period since the temperatures are much lower and stay cold for longer. This reduces the possibility of shifting the load by the control with time-dependent power reduction.

In an exemplary grid where all households with HPs have a rated electric power of around 4.2 kW, the represented control and also § 14a would not work since a minimum of 4.2 kW is always guaranteed.

Chapter 6

Conclusion and Outlook

In this Chapter the conclusion of the results is given in Section 6.1 and then an outlook into further research in Section 6.2.

6.1 Conclusion

The study is based on the resolution from the German Federal Grid Agency concerning § 14a ENWG with the objective of creating a preventive control that avoids overloading the grid by reducing the power of HPs. The developed and implemented solution takes a proactive approach to grid management. It utilizes time-dependent power reductions to prevent overloading before it occurs. This differs from the German Federal Grid Agency's solution, which relies on reactive measures. It minimizes household electricity costs while also aiming to prevent or at least reduce the overloading of the transformer and, consequently, the power grid. A button-up simulation is used where a HEMS is simulated, which optimizes the heat and domestic hot water generation, incorporating flexible prices and time-dependent power reductions.

The results in 5.1.2 show that the time-dependent power reductions implemented by the control system are effective but have a limited impact. Since the energy demand must always be covered, the usage of heating elements is required during long periods of cold temperatures, which are responsible for the high spikes of the transformer loading. It can still reduce the transformer loading if the violation is introduced by a time period with a low price.

As shown, it does not reduce transformer overloading if the power of the HPs is either too low or too high compared to the building's heat load. The shortest

duration of transformer loading exceeding 100 % is achieved with heat pumps (HPs) that have a thermal power equal to 80 % of the house's heat load. While larger storage reduces the duration of transformer loading exceeding 100 % for the HP size of 70 % and 80 %, the effect reverses with larger HP sizes of 110 %.

As shown, the resulting individual energy need for heating depends largely on the type of house and whether the house is energetically renovated to reduce the energy demand. For an LV-grid, the share and the number of houses with HPs are decisive.

It must be noted that the findings also depend on the type of transformer and power grid, as transformer overloading is used to measure the overloading of the power grid. Moreover, line loading and voltage measurements are also crucial for decision-making in a real application. Therefore, the same power grid with a larger transformer might not experience overloading.

The control works best for grids with buildings with moderate energy efficiency and penetration of HPs with medium-sized storage. It could be shown that the negative effects of price-based strategies on the power grid can be reduced. However, these effects largely depend on the chosen types of houses, the size of HP and storage, and the specific power grid. Therefore, further research needs to be conducted to make general statements, or a specific grid with houses needs to be analysed to make accurate statements about it.

6.2 Outlook

Since not only heat generation in buildings but also transportation is going electric, future research should incorporate electric vehicle (EV) charging. Wall boxes are used to charge EVs at people's homes and can have an electric power greater than that of HPs. Since EVs often don't have to be charged immediately, they also provide greater flexibility. Also, they could support the grid with bidirectional charging, where the stored electricity is used in the household or fed into the grid. Therefore, EVs could play an even bigger role regarding § 14a EnWG to prevent hazards or disruptions to the power grid as described in 2.1. With its time-dependent power reduction, the proposed control could have a bigger effect on EVs than HPs.

Furthermore, electricity generation with photovoltaic (PV) systems and battery electric storage systems (BESS) and their interaction ought to be investigated. Since with PV or BESS, electric power can be generated or fed in behind the grid connection point, HPs or EVs can use more power than the DSO allows, according to § 14a EnWG. This could allow more flexibility, as electricity from PV or BESS can be used instead of the power from the grid. Additionally, with BESS, more electricity can be drawn from the grid when prices are low and stored for later use when prices are higher.

To address the different objectives, a multi-criteria optimization should be used instead of an optimization with constraints. This is particularly important because, in the simulation, the constraint was not enforced to always ensure user comfort. User comfort refers to maintaining the desired indoor temperature of the houses and meeting domestic hot water demand. For example, if the indoor temperature fluctuates, energy usage can be shifted more effectively over time to avoid grid overloading. Thereby, during longer periods with low temperatures, the usage of the heating element can be avoided, which has been shown to be a major cause of transformer overloading.

Further research should investigate various types of heat pumps (HPs) and other heating technologies, as the efficiency of air-source HPs decreases with lower temperatures, unlike ground-source HPs. Additionally, user behavior should be considered, as different users utilize their houses in diverse ways, such as heating only necessary rooms or using wood-burning fireplaces.

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Appendix A

Appendix

A.1 All Use Cases

Share of houses with HP	Periode	Thermal power of HP as in relation to heat load	Price	Storage size of heat and DHW
40%	Week	70%	Flexible	Small
				Medium
				Large
			Fix	Medium
		80%	Flexible	Small
				Medium
				Large
			Fix	Medium
		110%	Flexible	Small
				Medium
				Large
			Fix	Medium
	Month	70%	Flexible	Small
				Medium
				Large
			Fix	Medium
		80%	Flexible	Small
				Medium
				Large
			Fix	Medium
		110%	Flexible	Small
				Medium
				Large
			Fix	Medium

A.2 Flow chart of simulation

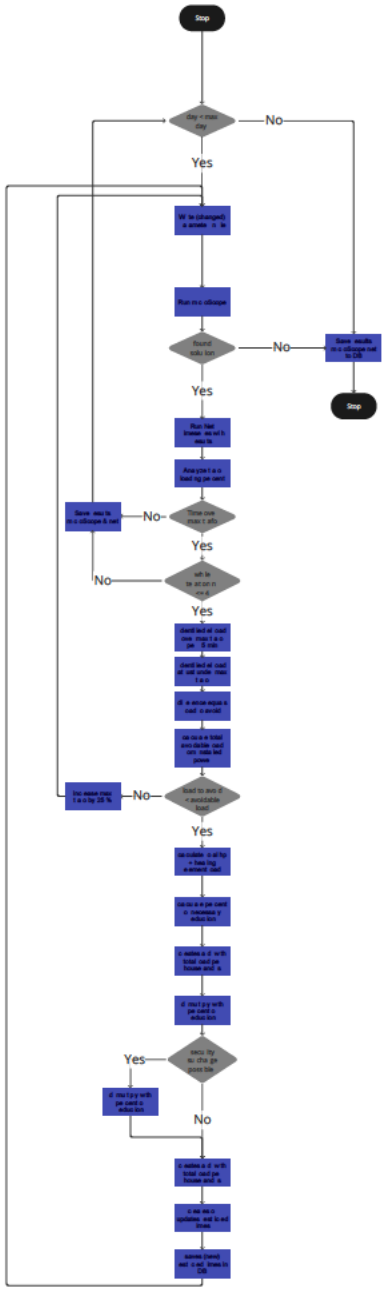

FIGURE A.1: Flowchart of the hole simulation