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Integrating Demand-Side Flexibility of Residential Heat Pumps for Smart and Sustainable Energy Consumption

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Abstract

As the global deployment of variable renewable energy sources like wind and solar power accelerates and offers a low-carbon option for the electricity sector, their inherent intermittency poses significant challenges to power system stability and reliability. To address this issue, this dissertation explores the critical role of demand-side flexibility through the use of residential heat pumps, which are highly efficient and contribute to the electrification of the heating sector.

The research focuses on three demand response programs to integrate heat pump flexibility: (1) leveraging real-time pricing in local energy markets, (2) providing ancillary services via home energy management systems, and (3) implementing direct load control with district energy management systems. The goals of this research are to assess the economic and environmental benefits of heat pump flexibility under market-based pricing, quantify the flexibility potential of heat pumps and evaluate the efficiency of district energy management systems in leveraging the flexibility.

Through comprehensive simulation studies, this research demonstrates that integrating local energy markets with heat pumps can reduce energy costs by up to 6.8% and increase self-consumption by up to 18.5% during transition periods. It also shows that heat pump flexibility within a household can be accurately quantified, taking into account technical constraints and user comfort. Additionally, the findings reveal that district energy management systems can effectively balance production and demand, resulting in lower energy costs and reduced CO_2 emissions.

These insights offer a significant advancement in understanding the role of residential heat pump flexibility in energy systems. They also provide valuable guidance for policymakers and researchers, suggesting diverse demand response programs as effective tools for maximizing the benefits of heat pump flexibility.

Zusammenfassung

Während sich der weltweite Einsatz variabler erneuerbarer Energiequellen wie Wind- und Solarenergie beschleunigt und eine kohlenstoffarme Option für den Stromsektor bietet, stellt ihre inhärente Volatilität erhebliche Herausforderungen für die Stabilität und Zuverlässigkeit von Stromsystemen dar. Um dies zu adressieren, untersucht diese Dissertation die kritische Rolle der Demand-Side-Flexibilität durch den Einsatz von Wohngebäude-Wärmepumpen, die für ihre hohe Effizienz bekannt sind und zur Elektrifizierung des Wärmesektors beitragen können.

Die Forschung konzentriert sich auf drei Demand-Response-Programme zur Integration der Flexibilität von Wärmepumpen: (1) Nutzung von Echtzeit-Preisen auf lokalen Energiemärkten, (2) Bereitstellung von Dienstleistungen über Heimenergiemanagementsysteme und (3) Implementierung von direkter Laststeuerung mit Quartierenergiemanagementsystemen. Die Ziele sind, die wirtschaftlichen und ökologischen Vorteile der Flexibilität von Wärmepumpen unter marktbasierten Preisen zu bewerten, das Flexibilitätspotenzial von Wärmepumpen zu quantifizieren und die Effizienz von Quartierenergiemanagementsystemen bei der Nutzung dieser Flexibilität zu evaluieren.

Durch umfassende Simulationsstudien zeigt diese Forschung, dass die Integration von lokalen Energiemärkten mit Wärmepumpen die Energiekosten um bis zu 6,8% senken und den Eigenverbrauch um bis zu 18,5% in Übergangszeiten erhöhen kann. Zudem wird gezeigt, dass die Flexibilität von Wärmepumpen innerhalb eines Haushalts genau quantifiziert werden kann, unter Berücksichtigung technischer Einschränkungen und Nutzerkomfort. Außerdem zeigen die Ergebnisse, dass Quartierenergiemanagementsysteme elektrische Produktion und Nachfrage effektiv ausgleichen können, was zu niedrigeren Energiekosten und reduzierten CO_2-Emissionen führt.

Diese Erkenntnisse bieten einen bedeutenden Fortschritt im Verständnis der Rolle der Flexibilität von Wohngebäude-Wärmepumpen in Energiesystemen. Sie bieten auch wertvolle Orientierungshilfen für politische Entscheidungsträger und Forscher und schlagen vielfältige Demand-Response-Programme als effektive Werkzeuge zur Maximierung der Vorteile der Flexibilität von Wärmepumpen vor.

Acknowledgements

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On a personal note, I owe immense gratitude to my wife, Yajie Wu. Her love, patience and understanding have been the bedrock of my resilience during challenging times. And to my family, who have always believed in me and supported my aspirations, I am forever grateful. Your unwavering love and encouragement have been a constant source of strength and inspiration.

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Contents

Chapter 1

Introduction

For decades, the German economy has relied on lignite and hard coal for energy. However, this heavy reliance on coal-fired power has resulted in significant pollution, imposing a considerable burden on the population. In order to get rid of coal, secure energy supply and reduce import dependence, Germany has made wind and solar energy the backbone of its energy transition. The development of renewable energy and energy independence has become a priority for German society [1]. Germany has formulated a series of goals and laws. According to the Renewable Energy Law, by 2030, the share of renewable energy should reach 65% in electricity consumption and 30% in total final energy consumption [2]. Moreover, electricity produced and consumed in Germany should be completely greenhouse gas neutral by 2045 [3].

1.1 Renewable energy and grid stability

To achieve the ambitious goal by 2045, the capacity of variable renewables such as wind and Photovoltaic (PV) has increased dramatically over the past decade in Germany (Fig. 1.1). Over the past decade, the production capacity of PV has grown to over three times its original size, while wind energy capacity has more than doubled. The increasing share of renewable energy sources is paramount in the low-carbon development of the electricity sector and fundamental to achieving a cleaner energy transition [4]. However, renewable energy integration into existing electricity systems is challenging. Unlike conventional energies, renewables are more diverse in space and time, varying on diurnal, seasonal, and interannual scales [5]. Since solar energy and wind energy are highly weather- and climate-sensitive, their higher penetration into the electricity mix increases the dependence on weather and climate [6]. This development raises many questions about how to safely and robustly plan and operate a power system when generation is often dominated by renewables that fluctuate rapidly over a short time period [7, 8].

First, the problem is raised by the inherent characteristics of renewable energy: intermittency and reliability concerns. Though Renewable Energy Sources (RESs) are inexhaustible in quantity, they are characterized with fluctuating sources as commonly observed in wind, tidal wave and solar power systems. In addition, many RESs like solar and wind are even intermittent and do not produce energy consistently. This variability poses a challenge for

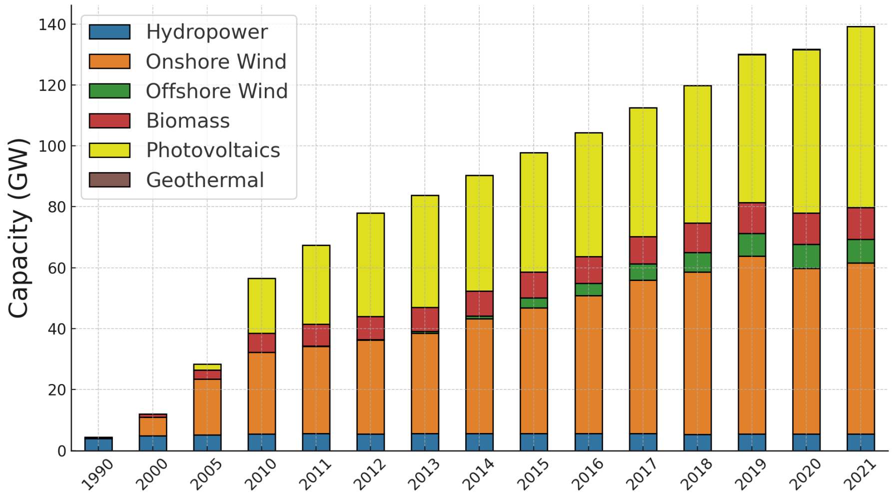


Figure 1.1: Installed power generation capacity based on renewables (1990-2021). Based on data from [9]

grid stability and requires the development of reliable energy storage solutions and smart grid technologies to balance supply and demand [10].

Second, integrating renewable energy into existing power grids is also challenging because it requires significant upgrades to infrastructure. This includes not only the physical grid but also the regulatory and management systems to efficiently distribute and manage the variable power supply [11].

To address these issues cost-effectively, tailored and innovative solutions are crucial. One such approach is demand-side flexibility, which allows for active participation from small consumers in managing energy demand.

1.2 Demand-side flexibility

The demand side has been traditionally considered relatively inelastic. However, thanks to an increasing number of flexible loads such as Electric Vehicles (EVs) and Heat Pumps (HPs) and emerging communication infrastructure, demand side is taken into account for solving the problems related to renewable energy integration, especially to defer costly investments on infrastructure [12]. Activities enabling demand-side flexibility are commonly referred to as Demand Response Programs (DRPs), which belongs to solutions under Demand-Side Management (DSM). DRPs, as one variant of load management approaches, are gaining more attention in power system operations recently, driven by the increasing interest in implementing the smart grid concept. DRPs involve customers altering their usual electricity consumption patterns in response to varying electricity prices or incentives, especially during high market prices or when system reliability is at risk. Facilitated by the advancement in smart grid and technologies such as intelligent Energy Management System (EMS) in end-user households and advanced metering infrastructure, DRPs have been adopted by Independent System Operators (ISOs) in leading countries around the world.

DRPs can leverage demand-side flexibility, the ability or potential of energy consumers to adjust their electricity usage in response to external signals. Demand-side flexibility is critical in fully utilizing the electricity generated from intermittent renewable sources, such as wind and solar power [13]. It also plays a significant role in balancing the power grid and relieving it during peak hours [14]. In addition, DRPs are necessary to ensure power quality in the network and meet the requirements of various entities, including system operators, energy consumers and suppliers [15]. Generally, there are two categories of DRPs that allow for demand-side flexibility provision: price-based and incentive-based programs and price-based programs [16]. The former is provided through electricity price signals, such as time-of-use or real-time pricing, where all consumers voluntarily adjust their energy consumption to the price fluctuation in the power market [17]. The latter is offered through demand bidding, ancillary services or curtailment contracts, where energy consumers are incentivized to change their energy consumption patterns by load reduction or shifting.

The utilization of DRPs aims to foster smart and sustainable energy consumption. This approach addresses the variability of renewable energy sources, facilitating greater integration of renewables into the energy mix and reducing the need for costly power grid enhancements.

In the context of this dissertation, energy consumption is considered smart and sustainable when it positively influences the following aspects on the demand-side:

1. **Energy balance**: Aligning electricity demand with energy supply conditions.
2. **User comfort**: Ensuring maximum comfort for consumers.
3. **Interconnectivity**: Coordinating different energy devices and systems for optimal energy flow and utilization.
4. **Renewable sources**: Prioritizing the use of renewable energy sources, such as wind and solar.
5. **Reduced environmental impacts**: Minimizing negative environmental effects, especially CO_2 emissions.
6. **Economic advantages**: Offering economic incentives to consumers to encourage grid-friendly behavior.
7. **Feasibility**: Considering the economic and practical viability of approaches such as investment costs and regulatory constraints.

These aspects should be considered for providing demand-side flexibility in energy systems.

1.3 Potential of residential heat pumps in providing flexibility

DRPs are primarily employed to shift loads that allow for time-variable operation. Among various flexible load options, residential HPs stand out due to their significant potential for flexibility. These devices are highly efficient and offer sector-coupling opportunities, enabling them to shift electrical loads effectively. HPs can convert electricity into heat, thereby facilitating energy storage through building thermal inertia or dedicated Thermal Energy

Storage (TES) systems. Additionally, they can harness ambient heat to produce thermal energy efficiently. Consequently, heat pumps are pivotal in the adoption of renewable energy and the transition to a low-carbon society in Germany.

As depicted in Fig. 1.2, the prevalence of HPs has seen a remarkable increase, tripling from 0.6 million to 1.8 million units over the past 12 years. Given this rapid growth, exploring the potential, obstacles and challenges associated with using HPs for demand-side flexibility becomes increasingly significant.

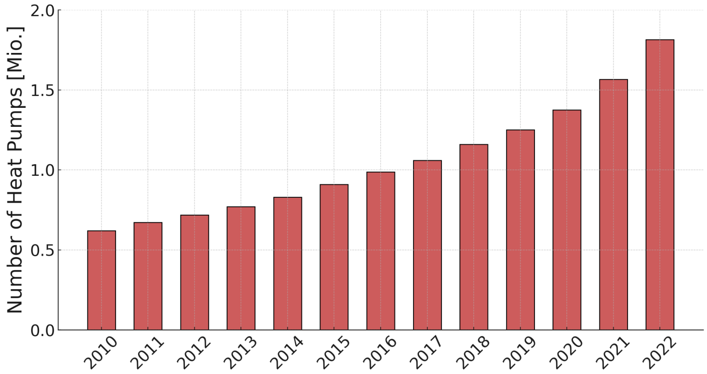


Figure 1.2: Number of heat pumps from 2010 to 2022 in Germany. Based on data from [18]

Several studies have already focused on the flexibility of residential HPs [19, 20, 21, 22, 23, 24]. In these studies, HP systems have emerged as a major component, and the electrification of heating system through the use of HPs in conjunction with TES has been identified as a promising measure for enhancing flexibility potential. HPs have the ability to decouple heat production from electricity demand and are currently the most promising technology for providing flexibility to the power grid [25]. They offer the possibility of modifying their operation in response to external signals. Furthermore, when combined with TES, HPs contribute significantly to the integration of fluctuating power generation [26].

1.4 Research questions

DRPs play a pivotal role in harnessing the flexibility of HPs for smart and sustainable energy consumption. As discussed in Chapter 1.2, DRPs consist of price-based and incentive-based programs. In Germany, several companies are exploring price-based solutions, such as Local Energy Markets (LEMs), to address local power imbalances. These markets facilitate the generation of dynamic electricity pricing tariffs in real time. Consequently, end-users and market participants are incentivized to operate their flexible loads during periods of lower electricity prices, thereby achieving grid-friendly outcomes.

Moreover, Direct Load Control (DLC), an incentive-based DRP, has gained increasing attention in recent years. This approach enables aggregators or system operators to remotely manage flexible loads within a district, aiming to meet economic or grid-related objectives. Additionally, utilizing flexibility for ancillary services, akin to regulating power, is another promising solution within incentive-based DRPs. The "Altdorfer Flexmarkt" pilot project, focusing on flexibility trading for ancillary service provision, is a notable example in this context [27].

These three approaches are both economically viable and can offer advanced solutions for leveraging the flexibility of residential HPs. However, despite extensive discussions in the literature on methods for providing HP flexibility, gaps remain in the flexibility estimation method, control strategies, regulatory framework and cost-benefit analyses. To address these challenges, this dissertation derives multiple research questions from current gaps, focusing on critical DRPs for future exploration. The selected questions, which represent the most significant contributions, are analyzed in detail, aiming to fill these research gaps. The gaps and corresponding questions are summarized as follows:

Advantages of heat pumps in local energy markets

LEMs in Germany represent an innovative and evolving aspect of the country's energy landscape. Rooted in the broader shift towards renewable energy sources and decentralized power systems, these markets have gained prominence in recent years [28]. The development of LEMs in Germany is primarily driven by the need to integrate an increasing amount of renewable energy, such as solar and wind power, into the existing power grid efficiently and reliably. This integration challenges the traditional centralized energy system and has led to a more community-focused approach [29].

In Germany, the growth of LEMs is also a response to the country's ambitious energy transition policy, known as 'Energiewende', which aims to significantly reduce greenhouse gas emissions and increase the share of renewable energy in the total energy supply [30]. LEMs empower consumers and small-scale producers to engage actively in the energy market, often through peer-to-peer trading platforms, enabling more efficient use of locally generated renewable energy and reducing reliance on the national grid. These markets are supported by technological advancements in smart grid technology, energy storage, and digital platforms that facilitate the local balancing of supply and demand. The development of LEMs in Germany reflects a transformative approach to energy management, emphasizing sustainability, decentralization and community participation.

Through the trading process LEMs can provide real-time tariffs for electricity and encourage end users to consume more electricity at times with lower electricity prices. As a result, LEMs could be promising in utilizing the flexibility of HPs. However, there are still some research gaps hindering the application of HPs within LEMs. Therefore, it becomes meaningful to verify whether LEMs can leverage the flexibility of residential HPs and how LEMs should be regulated for this purpose.

Existing research on LEMs often employs simplified models, relying on fixed household load profiles and generalized representations of flexibility resources [31, 32, 33, 34, 35, 36]. These models fail to accurately capture the unique characteristics of household energy devices, particularly impacting the precise analysis of residential HP flexibility. Consequently, there is a need for more detailed modeling of HPs and other relevant energy devices in simulations of LEMs.

Moreover, while prior studies have examined the general benefits of LEMs in terms of cost, self-consumption and residual peak demand, a comprehensive investigation into the impacts of high penetration levels of residential HPs within LEMs remains unexplored. This gap highlights the necessity for research that delves into both the advantages and challenges that HPs may introduce to LEMs in the future. Therefore, the first research question of this study aims to bridge these gaps:

RQ#1 What are the advantages of local energy markets with high penetration of residential heat pumps in terms of reducing energy costs and residual demand peaks? What factors affect the benefits of heat pumps within local energy markets?

Quantification of small-scale flexibility for ancillary services

Local flexibility markets in Germany have emerged as another innovative solution to manage the challenges brought by the increasing use of renewable energy sources. These markets play a vital role in balancing energy supply and demand on a community or regional level, addressing the intermittent nature of renewable energy [37].

Central to "Energiewende" in Germany local flexibility markets can enable smaller, decentralized energy producers and consumers to contribute actively to grid stability by offering ancillary services (often termed "flexsumers"). This is achieved by either supplying excess energy or modulating their consumption in response to local grid demands. These markets are made possible through advances in technology, particularly in smart grid and energy storage systems [38].

By fostering a more dynamic and responsive energy system, local flexibility markets in Germany are not just enhancing grid resilience but also encouraging local and sustainable energy initiatives, marking a significant shift towards a more integrated and efficient energy future. In recent years, a pilot project "Altdorfer Flexmarkt" focusing on flexibility trading for provision of ancillary services has emerged [27].

Facilitating flexibility trading and encourage greater participation in providing flexibility through ancillary services, it is crucial to establish quantification methods for flexibility in small-scale households. Numerous studies have explored the quantification of residential HP flexibility, predominantly focusing on responses to top-down external control signals [39, 40, 41]. However, these macroscopic approaches may not fully align with the requirements of flexibility provision as ancillary services, which necessitate a bottom-up quantification process. This methodology is akin to the balancing energy market but tailored for small household consumers, enabling them to trade their flexibility in local markets by selling it to system operators.

One challenge with this approach for flexsumers is to autonomously determine when and how much HP flexibility they can offer. Complications arise from the often unknown operational schedules of HPs and the difficulty in quantifying the available flexibility energy. Furthermore, current literature predominantly focuses on the potential flexibility of residential HPs, overlooking the economic losses associated with this flexibility. For effective trading in local markets, the pricing of ancillary services provided by HPs must be reasonable. Additionally, user comfort could be compromised by the unpredictability of domestic hot water usage [42]. These factors are critical in offering HP flexibility as an ancillary service but have not been extensively discussed to date. Therefore, the second research question of this dissertation aims to address these challenges:

RQ#2 How can the flexibility of residential heat pumps be quantified as ancillary service for market trading in local flexibility markets?

Impacts of district energy management system on heat pump flexibility through direct load control:

The implementation of a District Energy Management System (DEMS) for DLC is a significant step towards enhancing energy efficiency and sustainability at a community level. The DEMS serves as a centralized system that manages and optimizes energy consumption across various buildings within a district [43]. This is particularly relevant in Germany, where there is a strong focus on integrating renewable energy sources and reducing carbon emissions as part of the national "Energiewende" initiative.

The DLC of the DEMS allows for real-time regulation of energy usage in connected buildings, directly controlling essential systems like heating, ventilation, air conditioning and lighting [44]. By managing these loads, the DEMS can effectively balance energy demand with supply, especially in times of peak load or when renewable energy generation is fluctuating [45]. This approach not only contributes to grid stability but also increases energy savings and reduces the environmental impact at a district level, aligning with Germany's commitment to a more sustainable energy future.

Previous studies have highlighted the significant potential of centrally controlled HPs in DSM, particularly their adaptability to varying grid conditions and electricity prices [46, 47, 48, 49, 50]. These are also recognized for their contributions to peak shaving and load shifting, thereby enhancing grid reliability [51]. However, these studies often evaluate buildings on an individual basis rather than collectively at the district level, overlooking the coordination role of EMS in district-wide HP operation. Additionally, they tend to oversimplify the building sector in large district simulations, merely treating it as a heat sink with generic load profiles. This approach neglects crucial factors like thermal inertia in buildings and solar gains through windows, which are essential in accurately assessing the benefits of residential HPs. Furthermore, existing literature commonly assumes constant electricity prices and CO_2 emission factors, not adequately reflecting the real economic and environmental impacts of HP flexibility.

To address these limitations and comprehensively analyze the benefits of using DLC for leveraging HP flexibility at a district level, the following research question is proposed:

RQ#3 What economic and environmental benefits can the flexibility of residential heat pumps provide for neighborhoods under a district energy management system?

To effectively address the previously mentioned three research questions, it is necessary to develop energy models that accurately represent both the energy system and its associated framework. These models must be carefully parameterized with realistic data, including weather patterns, pricing trends and technical specifications, to ensure the validity of the simulation results. Additionally, it is crucial to assess the impact of residential HP flexibility in promoting smart and sustainable energy consumption. This evaluation should be conducted using a set of well-defined indicators. These indicators could include factors such as energy efficiency, cost-effectiveness, carbon footprint reduction and overall system reliability. By analyzing these indicators, the study can provide a comprehensive understanding of the potential benefits and challenges associated with the integration of HP flexibility into the energy system.

1.5 Research structure

This dissertation aims to explore three distinct DRPs that utilize the flexibility potential of residential HPs to foster smart and sustainable energy consumption. It addresses the previously identified research gaps and offers an in-depth evaluation and discussion on integrating flexibility into local energy systems. To accomplish these main objectives, the research is structured into three separate studies:

- **Local energy market (LEM)**: The first section of this dissertation investigates how LEMs can use **real-time pricing** to utilize the flexibility of residential HPs. As part of price-based DRPs, LEMs issue pricing signals that encourage consumers to use electricity during specific periods. This study covers the design and management of LEMs, identifies the role of HPs within these markets and evaluates the economic impact of utilizing HP flexibility. Additionally, it proposes a specialized regulatory framework to further enhance the adoption and efficiency of HPs in LEMs;
- **Home energy management system (HEMS)**: The second part of this dissertation focuses on estimating the flexibility potential of residential HPs through a HEMS. This system enables the provision of **ancillary services** to aggregators or system operators as part of an incentive-based DRP. In scenarios where grid congestion incur flexibility demand, aggregators or system operators can send flexibility calls to end-users (flexsumers), who then adjust their HP usage accordingly. Furthermore, this part introduces an innovative methodology for assessing the marginal cost of offering HP flexibility. This is particularly relevant for bidding in local flexibility markets, where accurate cost evaluation is crucial for effective participation;
- **District energy management system (DEMS)**: The third section of the dissertation evaluates the effectiveness of DEMS in exploiting the flexibility potentials of residential HPs through **direct load control**. In this approach, aggregators or system operators gain direct control over flexible loads by entering into agreements with end-users. They can then send control signals to these loads as needed. To assess the impact of DEMS, a district energy model is developed for a one-year simulation period. The analysis focuses on the energy savings, peak load reduction and carbon emissions reduction achieved at the district level.

The fundamental concepts behind providing flexibility using the aforementioned approaches are depicted in Fig 1.3. This figure illustrates the mechanisms of direct or indirect control and highlights the distinctions among the three DRPs discussed earlier.

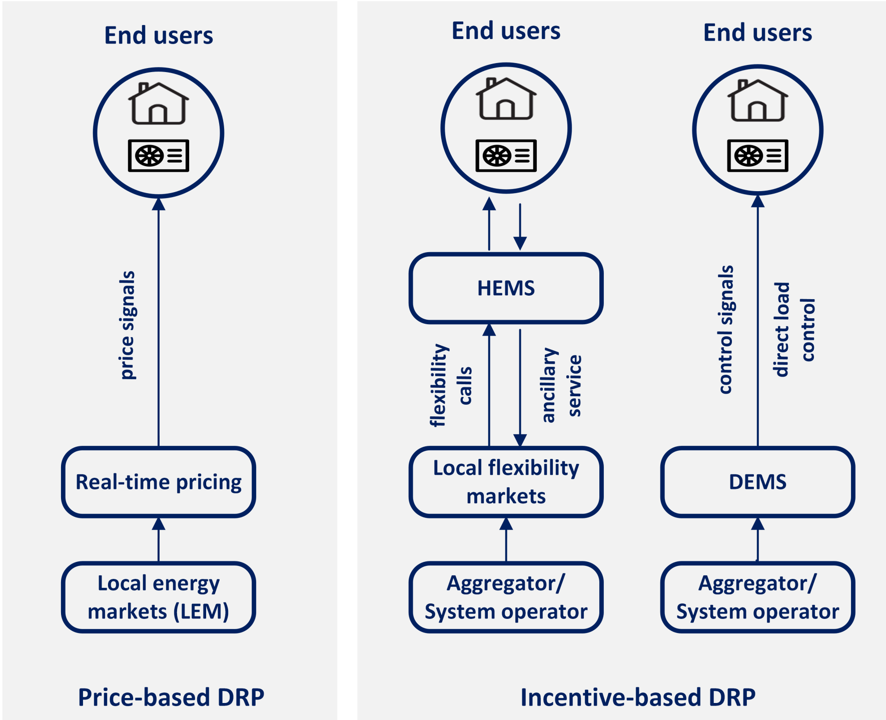


Figure 1.3: Basic principles of flexibility provision through the three DRPs

The core models in the three studies are HPs and EMS. These core models employ a consistent methodology across different DRPs. The HP model calculates Coefficient Of Performance (COP) based on weather conditions and heating system configuration, while the EMS optimizes HP operating schedules using forecasts. However, the application of EMS varies across different scenarios: (1) managing energy transactions in LEMs; (2) creating and submitting bids for ancillary services in local flexibility markets; (3) controlling all HPs within a district. Consequently, the EMS interacts with diverse actors or participants. In LEMs and traditional district, consumers and producers are key players, whereas in the context of ancillary services, end-users who are often termed 'flexsumers' provide flexibility. The research questions are addressed in the corresponding Chapters (3.1-3.3). The structure and interrelationships among the key elements and research questions are depicted in Figure 1.4.

The structure of remaining parts is as follows: Chapter 2 introduces the essential methodologies, including models and research design, illustrated through simplified process flow diagrams. The main body of the dissertation is found in Chapter 3, which comprises three distinct research studies: Chapter 3.1 explores the benefits of LEMs, particularly how real-time pricing can be used to harness the flexibility of residential HPs; Chapter 3.2 delves into the detailed quantification and analysis of HP flexibility for ancillary services in local flexibility markets, including thorough modeling of technical constraints and user behaviors; Chapter 3.3 examines the economic and environmental benefits of using a DEMS to control all HPs within a single district. Chapter 4 presents a comparative analysis of the three DRPs, discussing their respective strengths and weaknesses in achieving smart and

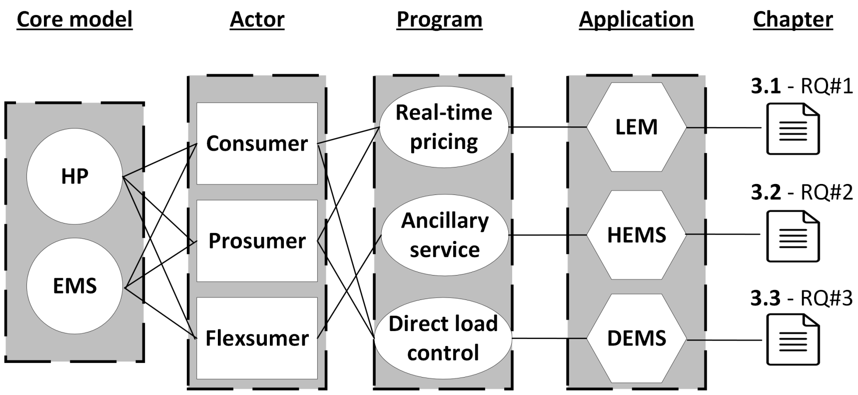


Figure 1.4: Relationship among research objects and questions

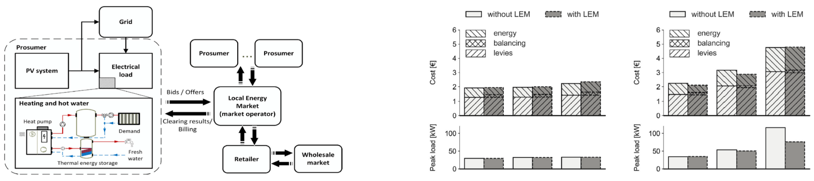
sustainable energy consumption. Chapter 5 summarizes the key findings from each study, drawing overarching conclusions about the utilization of HP flexibility and outlining future research directions in this area. The organizational structure of the dissertation is visually depicted in Figure 1.5.

Chapter 1: Introduction

Chapter 2: Methods

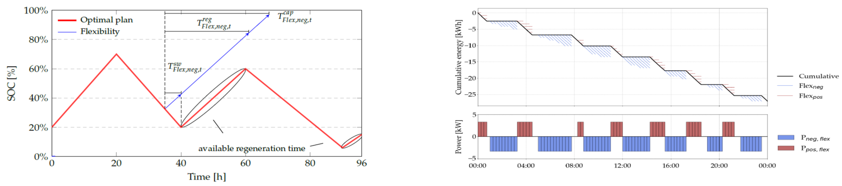
Chapter 3: Demand response programs for integrating heat pump flexibility

Chapter 3.1: Leveraging flexibility of heat pumps through local energy markets



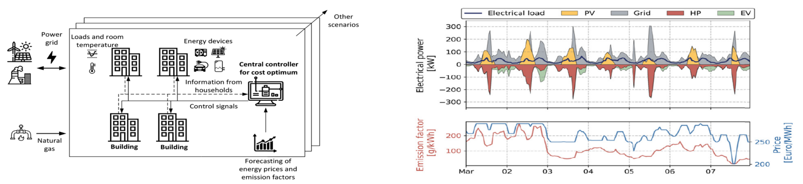
Paper #1: Leveraging flexibility of residential heat pumps through local energy markets

Chapter 3.2: Quantification of flexibility for small-scale flexibility trading



Paper #2: Flexibility estimation of residential heat pumps under heat demand uncertainty

Chapter 3.3: Providing heat pump flexibility through district energy management system



Paper #3: Cost-effective CO2 abatement in residential heating: A district-level analysis of heat pump deployment

Chapter 4: Discussion

Chapter 5: Conclusion and future research

Figure 1.5: Structure of the dissertation

Chapter 2

Methods

In this chapter, key methodologies employed in this research are introduced. The content is divided into two primary sections: models and process flow diagrams relevant to the research topics. The first section details the core models and supplementary parts that form the foundation of this dissertation and are integrated into all related publications. The second section presents simplified process flow diagrams to illustrate the basic data flow and interrelationships among simulation components. This aids in clarifying the simulation design and how it contributes to generating results that address the central research questions. The aim with this approach is to provide a concise overview of the research design for each topic, enabling readers to easily identify and engage with the aspects of this dissertation they find most compelling.

2.1 Core models and supplementary components

As outlined in Chapter 1.5, the HP and EMS models are pivotal in each simulation study. They represent the operational characteristics of HPs and the tailored control strategies applied to them, respectively. Furthermore, there are several supplementary components required to complete the simulation studies, including heat consumption profiles and key performance indicators.

2.1.1 Heat pump

In this dissertation, HPs are modeled using empirical function based on manufacturer data instead of simulating the whole thermodynamic cycles. This approach is common and has been used in several research related to applications of HPs [19, 21, 23, 25, 26]. It ensures sufficient prediction while reducing the calculation burdens when focusing a large-scale case study of HP flexibility.

The data and empirical function for obtaining HP characteristics stem from hplib [52], which are based on measurements from various manufacturers and provide functions of electricity demand and thermal power of HPs that correspond to the measurements. Specifically, a generic model of air source HPs is implemented, and it is assumed that the HPs can modulate between 0% and 100% of the rated thermal power. The inlet temperature is decided by the ambient air temperature, while its outlet temperature can be set in the range from 50 °C to 65 °C, depending on the heat emission system and usage purpose. As the ambient temperature changes frequently, the COP of HPs are also updated correspondingly, normally in a 15-minutes interval. The thermal power and the COP are calculated using the following equations:

$$P_{t,hp}^{elec} = x_t^{hp} cap_t^{hp} \quad (2.1)$$

$$P_{t,hp}^{heat} = x_t^{hp} cap_t^{hp} COP_t \quad (2.2)$$

$$COP_t = COP_{ref}(f_1 T_{amb,t} + f_2 T_{out} + f_3) \quad (2.3)$$

$$cap_t^{hp} = cap_{ref}(f_4 T_{amb,t} + f_5 T_{out} + f_6) \quad (2.4)$$

Here, COP_{ref} and cap_{ref} are the reference COP and electrical consumption under standard conditions, which refer to -5 °C ambient temperature and 60 °C warm water supply temperature. Based on these, $COP_{t,b}$ and cap_t^{hp}, the actual COP and rated electricity consumption, are calculated given the ambient temperature $T_{amb,t}$ and the supply temperature T_{out}. The parameters f_i are coefficients fitted using manufacturer measurements. The real electrical consumption $P_{t,hp}^{elec}$ can range from 0% to 100% of the rated electricity consumption cap_t^{hp} at time interval t. This feature is realized by an additional real variable, the modulation rate x_t^{hp}, which ranges from 0% to 100%. In addition, the thermal power $P_{t,hp}^{heat}$ is obtained by multiplying the real electricity consumption by the actual COP. The COP remains constant in each time interval (15 minutes).

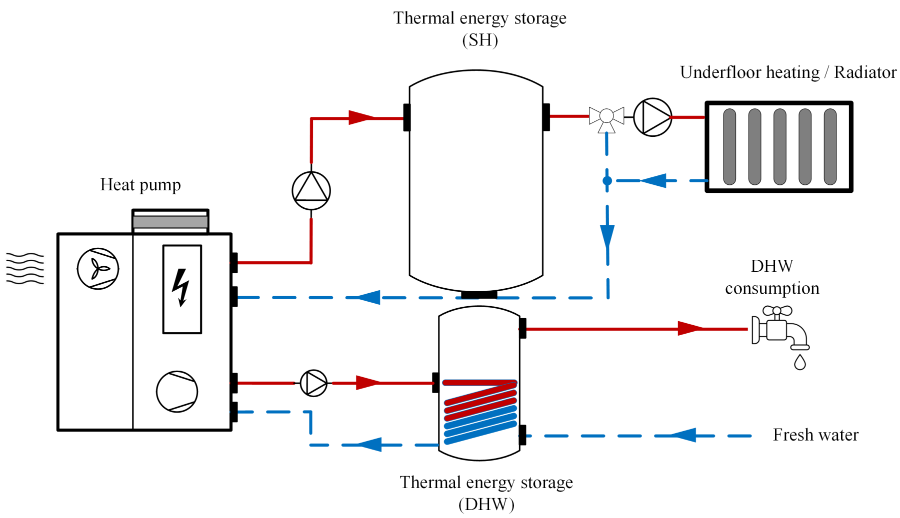


Figure 2.1: Scheme of the two-level heating system

TES is essential to decouple the heat generation and consumption and acquire more flexibility from HPs. In the studies, a two-level heating system is implemented, as illustrated in Fig. 2.1. In this system, the TES for Space Heating (SH) and Domestic Hot Water (DHW) are separated and charged by HPs with warm water with different temperatures. This configuration enables higher efficiency of HPs if the required warm water temperature for SH is lower than for DHW. The TES is assumed fully mixed without consideration of stratification. The SOC of TES evolves in each time interval depending on charging or discharging power and range from 0% and 100%. In addition, the self-discharge rate, charging and discharging efficiency are incorporated, which reflect the heat losses when storing and transferring heat. Equation (2.5 - 2.8) describe the characteristics of TES:

$$SOC_t = \eta^{sd} SOC_{t-1} + \frac{P^{heat}_{t,sto} \Delta t}{cap^{sto}} \tag{2.5}$$

$$P^{sto}_{t,sto} = \begin{cases} \eta^{char} S^{heat}_t & S^{heat}_t \geq 0 \\ S^{heat}_t / \eta^{disc} & S^{heat}_t < 0 \end{cases} \tag{2.6}$$

$$S^{heat}_t \leq S^{heat}_{max} \tag{2.7}$$

$$0\% \leq SOC_t \leq 100\% \tag{2.8}$$

where $\eta^{e,sd}$ indicates the self-discharge rate, while $\eta^{e,char}$ and $\eta^{e,disc}$ represent the charging and discharging efficiency. cap^{sto} is the capacity of TES, while S^{heat}_t is the thermal energy generated by HPs or discharged by the TES.

2.1.2 Energy management system

In general, an EMS is a system of computer-aided tools used by operators of electric utility grids to monitor, control and optimize the performance of the generation or transmission system. Also, it can be used in smaller-scale systems such as buildings. EMS is designed to help ensure that the energy generation meets the current and predicted energy demand, optimizes energy use to reduce costs and maintains system reliability and performance while minimizing environmental impact.

In this dissertation, the EMS has three specific forms: market agents for energy trading in LEMs, HEMs and DEMS. In the first case, the EMS is used to predict the energy consumption and generation which aids in energy purchases or sales in the LEMs; in the second case, the EMS is employed to determine the cost-optimal operating schedule of HPs and generate alternative viable plans; in the third case, EMS is used as a DEMS which globally optimizes the operation of HPs which are located in the same district and achieve the economic and environmental benefits. Regardless of its use cases, the core part of the EMS is the optimization of the operating plans of HPs.

To realize this optimization function of EMS in simulations, a Mixed-Integer Linear Programming (MILP) is employed. MILP is a mathematical method used for optimizing a linear objective function, subject to linear equality and inequality constraints, where some of the variables are required to be integers. In this dissertation, the objective function is always to minimize the energy cost, depicted in Equation (2.9). In this equation, $P^{elec}_{t,in}$ and $P^{elec}_{t,out}$ represent the import and export power of energy commodities over the boundary, respectively. The total energy costs are obtained by multiplying them by the import and export prices of the commodities $c^{elec}_{t,in}$ and $c^{elec}_{t,out}$, respectively. x is the variable representing control signals for flexible energy devices such as HPs and EVs.

Equation (2.10) and Equation (2.11) ensure energy balance at the building level for electricity and heat, respectively. Equation (2.10) establishes that the power flow across the boundary of a building is equal to the energy consumed by the fixed load $D^{elec}_{t,b}$, HPs

$P^{elec}_{t,b,hp}$ and EVs $P^{elec}_{t,b,ev}$, less the power generated by PV $P^{elec}_{t,b,pv}$. Similarly, Equation (2.11) states that the heat generated by HPs $P^{heat}_{t,b,hp}$, adjusted by energy for TES discharging or charging $S^{heat}_{t,b}$, should match the heat demand $D^{heat}_{t,b}$. Finally, Equation (2.12) imposes a constraint on the local grid or transformer, ensuring that the maximum import or export power does not exceed its capacity.

$$\min_{x} \sum_{t}(c^{elec}_{t,in}P^{elec}_{t,in} - c^{elec}_{t,out}P^{elec}_{t,out}) \tag{2.9}$$

$$s.t.\ P^{elec}_{t,in} - P^{elec}_{t,out} = D^{elec}_{t} + P^{elec}_{t,hp} + P^{elec}_{t,ev} - P^{elec}_{t,pv} \tag{2.10}$$

$$S^{heat}_{t} + P^{heat}_{t,hp} = D^{heat}_{t} \tag{2.11}$$

$$|P^{elec}_{t,b,in} - P^{elec}_{t,b,out}| \leq cap^{elec} \tag{2.12}$$

This optimization can also be incorporated into the Model-Predictive Control (MPC), which is a control technique that uses a system's mathematical model to predict future outcomes over a finite prediction horizon and optimizes control actions accordingly. MPC is used for market agents in LEMs and the control strategy in DEMS to achieve a more intelligent and smart control. The MPC has the potential to improve demand-side management by coordinating the operation of HPs in periods when electricity prices are low and can also be regarded as a part of EMS.

2.1.3 Heat consumption

Heat consumption comprises of two parts: SH and DHW. The heat consumption for SH is obtained by using a thermal network model for buildings. After obtaining the necessary building-related data sets, a 2nd order thermal network model developed by [53] is utilized. This model, also known as a resistance-capacitance model (RC-model), simulates the thermal behavior of zones within buildings, as shown in Fig. 2.2. It offers an optimal choice for district analysis due to its simplicity. In particular, this model considers changes in wall temperature, which is crucial for evaluating the flexibility offered by the thermal mass of the building. Equations (2.13 - 2.17) show more details of this RC model.

$$C_{EW}\frac{\Delta T_{EW}}{\Delta t} = \frac{T_{a,eq} - T_{EW}}{R_{rest}} + \frac{T_1 - T_{EW}}{R_{EW}} \tag{2.13}$$

$$C_{IW}\frac{\Delta T_{IW}}{\Delta t} = \frac{T_2 - T_{IW}}{R_{IW}} \tag{2.14}$$

$$C_{z}\frac{\Delta T_{z}}{\Delta t} = \frac{T_{vent} - T_{z}}{R_{air}} + \frac{T_{star} - T_{z}}{R_{aIL}} + \dot{Q}_{con} \tag{2.15}$$

$$C_{1}\frac{\Delta T_{1}}{\Delta t} = \frac{T_{EW} - T_{1}}{R_{EW}} + \frac{T_{star} - T_{1}}{R_{aEW}} + \dot{Q}_{EW} \tag{2.16}$$

$$C_{2}\frac{\Delta T_{2}}{\Delta t} = \frac{T_{IW} - T_{2}}{R_{IW}} + \frac{T_{star} - T_{2}}{R_{aIW}} + \dot{Q}_{IW} \tag{2.17}$$

$$20^{\circ}C \leq T_z \leq 25^{\circ}C \tag{2.18}$$

The parameters C_i represent thermal capacity of building components such as internal and external walls, while R_i represent thermal resistance between two building components.

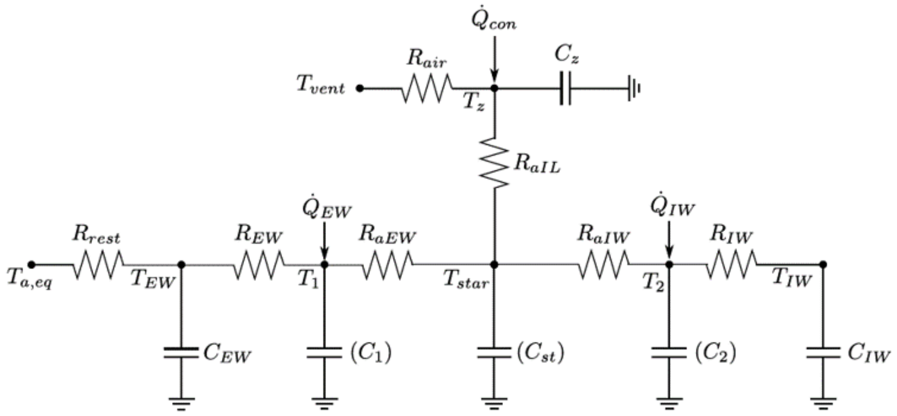


Figure 2.2: RC-model of one zone

T_i indicate the temperatures of building components. Dummy capacitors C_1, C_2 and C_{st} are introduced to simplify the equation formulation and the problem solving process. These dummy capacitors are set to values several orders of magnitude smaller than the actual capacitors. If these dummy values are sufficiently small, the resulting dynamic behavior exhibits a very short time constant and, therefore, does not affect the overall results. Currently, a value of 1 is assigned to the dummy capacitors. Equation (2.18) restricts the indoor temperature to ensure the comfort of the user to be satisfied. More details about this RC-model can be obtained in [53].

To reduce computational burden brought by the 2nd order RC model, a simplified form is applied to cases in which quick calculation is crucial, as depicted in Equation (2.19). This simplified form is used for flexibility trading or energy trading in this dissertation. This model is also used by [54] to consider the flexibility provided by building mass and describe the temperature evolution inside the building.

$$C_{th}\frac{\Delta T_z}{\Delta t} = \frac{T_z - T_{a,eq}}{R_{th}} + \dot{Q}_{con} \tag{2.19}$$

where T_z is the zone or room temperature, while $T_{a,eq}$ is the ambient temperature. R_{th} and C_{th} indicate the aggregated thermal resistance and capacitance, respectively. $\dot{Q}_{con}$ is the convective heat transfer by heating system.

For DHW consumption, the software, DHWcalc, can provide DHW load profiles. This model uses four categories of DHW to describe different DHW consumption patterns [55]. Each category has a specific occurrence probability and flow rate probability distribution. The assumptions applied in the original literature have been used in this study as well and are shown in Table 2.1:

category	average flow rate (l/min)	sigma (l/min)	duration (min)	portion (%)
short load	1	2	1	14
medium load	6	2	1	36
bath	14	2	10	10
shower	8	2	5	40

Table 2.1: Categories and probability of DHW consumption patterns

where average flow rate $\dot{V}_{mean}$ is the expectation of the distribution and sigma σ is the standard deviation. Duration and portion are the assumed flow duration and share of flow amount for each flow type, respectively. According to the parameters given in Table 2.1 and the assumption of gaussian-distribution, the probability of occurrence of each category of flow can be obtained by Equation (2.20):

$$P(\dot{V}) = \frac{1}{\sqrt{2\pi\sigma}} e^{\frac{-(\dot{V}-\dot{V}_{mean})^2}{2\sigma^2}} \tag{2.20}$$

2.1.4 Indicators

To evaluate the simulation results, appropriate indicators are essential. Besides economic and environmental indicators, Self-Consumption (SC) and Collective Self-Consumption (CSC) are ones of the most important indicators as they describe how much PV power is self-consumed at a household and district level. The SC refers to the percentage of energy prosumers use for their own production, while CSC is used to describe the utilization rate of PV generation over the whole neighborhoods. A high level of CS or CSC indirectly reflects the positive effects of the flexibility of HPs as they help to absorb more PV-produced electricity. In addition, SC and CSC can reflect the impacts of HP flexibility on the local and superior power grid. Fig. 2.3 and Equations (2.21-2.22) describe the difference between the two similar performance indicators in detail.

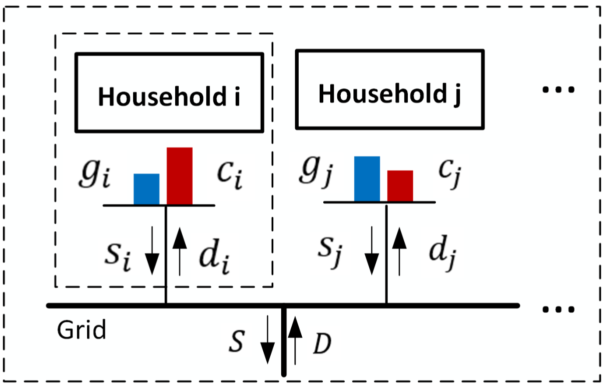


Figure 2.3: Boundary conditions for performance indicators. Surplus and deficit refer to residual generation and demand for individual households; surplus and deficit of community refer to residual generation and demand of the whole neighborhoods.

$$SC = \frac{\sum_t (g_{i,t} - s_{i,t})}{\sum_t g_{i,t}} \tag{2.21}$$

$$CSC = \frac{\sum_t (\sum_i g_{i,t} - S_t)}{\sum_t \sum_i g_{i,t}} \tag{2.22}$$

$g_i : generation \quad c_i : consumption$

$s_i : surplus \quad d_i : deficit$

$S : \ surplus\ of\ community\ \ (export)$

$D : \ deficit\ of\ community\ \ (import)$

2.2 Process flow diagrams of research topics

To deliver an overview how the research is conducted to answer the research questions, the main simulation components and steps in each research topics are explained to show the data flow and their relationship with help of process flow diagrams.

2.2.1 Advantages of heat pumps in local energy markets

To address the first research question, "What are the advantages of LEMs in enhancing the flexibility of residential HPs?", two distinct scenarios are constructed: one incorporating the LEM framework and the other following conventional energy purchase processes. The LEM scenario enables end users to trade electricity within LEMs.

Figure 2.4 illustrates the comprehensive process for analyzing the benefits of LEMs. Initially, relevant input data, including forecasts and technical parameters, is prepared and integrated into both scenarios for foundational setup. Additionally, the core model of HPs, adhering to technical constraints, is implemented in each scenario. Distinct control strategies are applied in each case: a rule-based control, reacting to the state of charge of TES, is used in the non-LEM scenario due to the absence of price signals. In contrast, the LEM scenario employs a MPC that leverages forecasts to optimize operating schedules and energy trade decisions. This MPC is realized by EMS model mentioned in Chapter 2.1.2, which forms the other core model of this dissertation.

For settlement processes, non-LEM users pay for their energy consumption directly with fixed prices, while LEM participants engage in market trading, paying market prices post-clearing. The resulting energy costs or profits from both scenarios are then compared. The final step involves quantifying the economic benefits of LEMs using data derived from these simulations.

2.2.2 Quantification of small-scale flexibility for ancillary services

To explore the second research question, "How can the flexibility of residential HPs be quantified and priced?", it is crucial to define flexibility precisely. In this context, flexibility

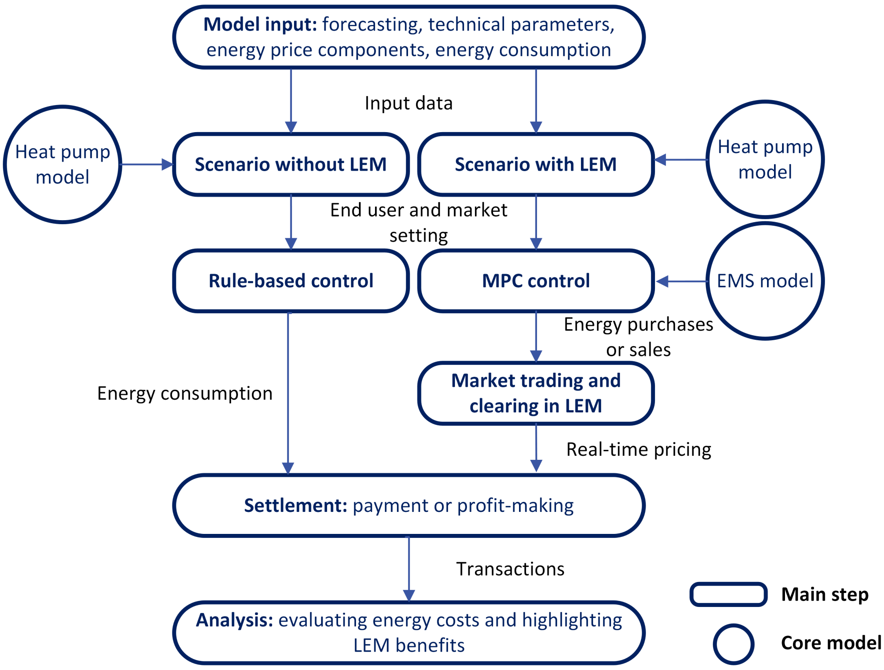


Figure 2.4: Method scheme of leveraging flexibility through LEMs

is defined as the ability to modify the original operational plans of HPs. This necessitates establishing procedures to determine these original plans and to develop viable alternatives.

For this purpose, two primary models are essential: the HP and the EMS. First, relevant input data is prepared as a foundational element for modeling the HP and heating system. During the modeling phase, the core HP model is integrated, alongside supplementary models like TES and thermal behavior of zones. The Home Energy Management System (HEMS), an extension of the core EMS model, uses MILP to derive optimal operating schedules, which serve as baseline or reference plans. The HEMS model then creates alternative schedules and assesses their feasibility and compliance with technical constraints. Schedules that are technically viable and maintain user comfort are considered flexibility offers. These can be marketed on platforms like local flexibility markets and utilized by grid operators. Figure 2.5 illustrates this entire process.

2.2.3 Impacts of district energy management system on heat pump flexibility through direct load control

To explore the third research question, "What are the economic and environmental benefits of using a centralized energy management system (a district energy management system or DEMS) to enhance the flexibility of residential HPs?", two scenarios are defined: one employing the DEMS and the other without it.

The task begins with preparing essential input data, focusing on energy prices and CO_2 emission factors which are crucial for assessing economic and environmental impacts. These data are then incorporated into the district energy system model, which includes HPs, TES, and building dynamics. This study considers the thermal inertia of buildings,

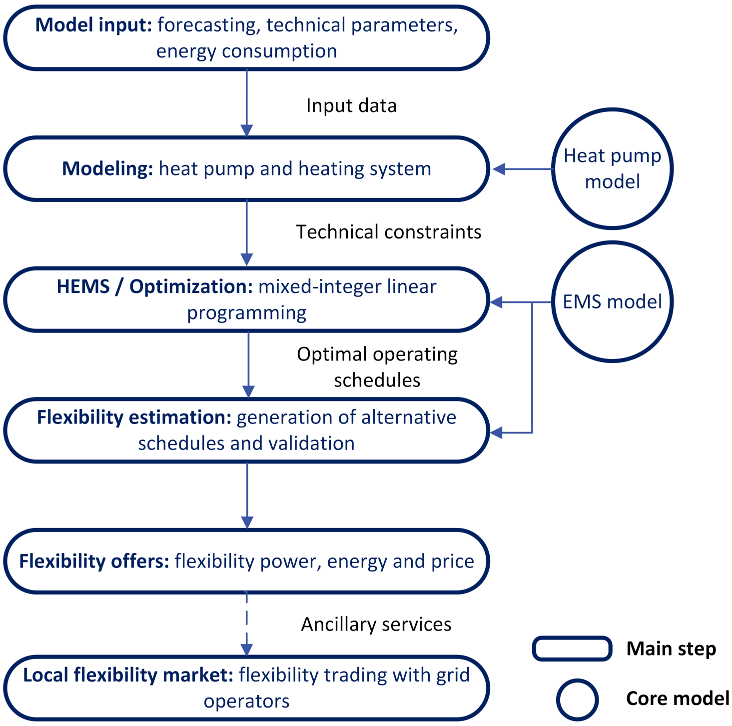


Figure 2.5: Method scheme of offering ancillary services via HEMS. Processes indicated by dashed arrows are not included in the scope of this study's modeling.

leveraging the flexibility potential in construction materials like walls and floors.

Following this, the EMS model is expanded into a DEMS. This DEMS is designed to aggregate forecast data and globally optimize the operation of flexible loads, particularly HPs, within the district. The DEMS then sends control signals to each HP and implements DLC. This approach allows for operation primarily during periods of lower electricity prices or reduced emission factors, thereby achieving energy cost savings and CO_2 emission reductions. The simulation covers a one-year period to account for seasonal variation, taking into account reduced space heating demand in summer.

Finally, a comprehensive analysis based on the simulation results quantifies the benefits of utilizing DEMS for HP flexibility provision. Figure 2.6 depicts the entire process.

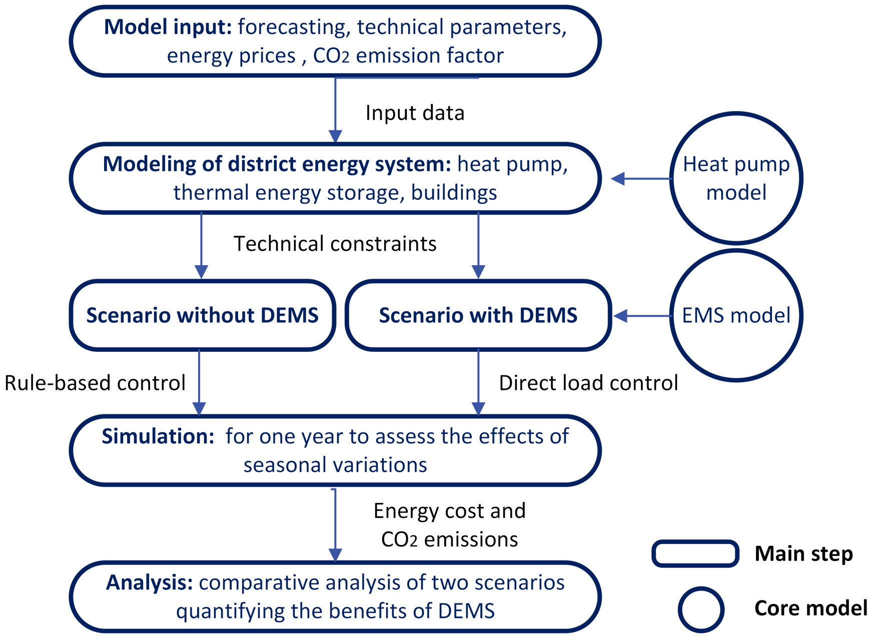


Figure 2.6: Method scheme of implementing DLC through DEMS

Chapter 3

Demand response programs for integrating heat pump flexibility

The surge in renewable energy presents challenges in power system stability due to its intermittent nature, as highlighted in [4, 7, 8]. Demand-side flexibility, crucial for maximizing the use of intermittent renewables and balancing the grid, is emphasized in [13, 14], with a focus on building energy flexibility. HPs, particularly when combined with TES, are identified as key in enhancing flexibility [19, 21, 23] and are considered a leading technology for grid flexibility [25, 26].

DRPs play a pivotal role in harnessing the flexibility of HPs to facilitate smart and sustainable energy consumption. These programs are essential not only for maintaining power quality in the electrical network but also for meeting the diverse needs of stakeholders such as system and market operators, energy consumers and suppliers. Alarcon-Rodriguez et al. emphasize the necessity of DRPs in ensuring the efficiency and stability of power systems [15].

There are generally two main categories of DRPs that support demand-side flexibility: price-based and incentive-based programs. Under these categories, three distinct studies have been conducted concerning various DRPs. These include: (1) implementing real-time pricing through LEMs, (2) providing ancillary services via HEMS in local flexibility markets, and (3) exercising DLC through DEMS. Each of these studies addresses specific research gaps concerning the flexibility of HPs. In the subsequent sections, each study will be briefly introduced, focusing on its scientific context and contributions, before delving into the detailed manuscript.

3.1 Leveraging flexibility of heat pumps through local energy markets

Scientific context

The effectiveness of price-based DRPs, such as time-of-use and real-time pricing, in managing generation capacity and reducing peak load, is highlighted in research like [56, 57, 58]. Additionally, the emerging concept of LEMs as a promising way to harness local flexibility is gaining attention. Through the trading process, LEMs can provide real-time tariffs for electricity and encourage end users to consume more electricity during periods of lower prices. As a result, LEMs could be instrumental in harnessing the flexibility of HPs. The comprehensive review in [59] and the market design discussed in [31] emphasize the potential of LEMs in balancing local supply and demand, reducing transmission congestion and integrating renewable energy sources more effectively. The economic benefits for individuals and communities within LEMs, such as cost reductions and increased profits, are substantiated by existing studies [60, 61, 62, 35]. Meanwhile, the effectiveness of LEMs in reducing peak demand is dependent on the utilization of control strategies, as indicated in [63, 64].

Existing research on LEMs often relies on simplified models, utilizing fixed household load profiles and generalized representations of flexibility resources [31, 32, 33, 34, 35, 36]. These models do not adequately capture the unique characteristics of household energy devices, which is particularly problematic for the precise analysis of residential HP flexibility. This issue underscores the need for more detailed modeling of HPs and other relevant energy devices in the simulations of LEMs. Moreover, while previous studies have examined the general benefits of LEMs in terms of cost, self-consumption and residual peak demand, the specific impacts of high penetration levels of residential HPs within LEMs have yet to be thoroughly explored. This research gap highlights the necessity for in-depth investigation into both the potential benefits and challenges that high penetration of HPs might pose to LEMs in the future.

Contribution

This paper presents an in-depth analysis of LEMs and their role in integrating HP flexibility. The study contrasts two scenarios: one with and one without a LEM, both assuming a high penetration of HPs. It utilizes agent-based modeling and double-sided auctions to simulate the market trading process in LEMs, offering a more complex and realistic approach than previous studies. This includes considering diverse household load profiles and detailed potential of HP flexibility.

A major focus of the research is on the economic analysis and regulatory frameworks. The study quantifies the economic advantages provided by LEMs and demonstrates that LEMs can bring substantial economic benefits to households, especially when they have HPs installed. It underscores the importance of reducing balancing costs and levies, a major component of total costs, for optimizing LEM performance.

The paper also explores the seasonal impact on LEM benefits, noting limited flexibility potential of HPs during summer due to reduced heating demand. It suggests strategies to manage residual demand peaks and recommends modifications in regulatory frameworks to maximize LEMs' financial benefits and mitigate grid congestion.

Overall, this research significantly advances the understanding of LEMs in leveraging HP flexibility, offering valuable insights for policymakers and energy system researchers. Its findings are instrumental in developing sustainable energy systems through market-based mechanisms.

Leveraging flexibility of residential heat pumps through local energy markets

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Open-source repository the data and models that support the findings of this study are openly available in lemlab.

Author contributions

Zhengjie You:	65 %	Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Validation, Writing - Original draft, Writing - review and editing.
Sebastian Dirk Lumpp:	10 %	Software, Resources.
Markus Doepfert:	10 %	Software, Resources, Writing – review and editing.
Peter Tzscheutschler:	5 %	Conceptualization, Methodology
Christoph Goebel:	10 %	Writing – review and editing, Supervision.

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Leveraging flexibility of residential heat pumps through local energy markets

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A R T I C L E I N F O

Keywords:
Local energy market
Heat pump
Power-to-heat
Demand-side response
Flexibility

A B S T R A C T

The integration of variable renewable energy sources such as wind and solar energy has made demand-side flexibility a critical aspect for balancing the power grid during fluctuating power generation. In recent years, heat pumps have gained increasing attention for their flexibility potential. While demand response programs have been extensively discussed to leverage flexibility, the market-based approach of local energy markets (LEMs) requires more attention. LEMs provide a marketplace for local energy exchange, facilitating a more balanced energy system by harnessing the flexibility of heat pumps at lower costs. Therefore, this study examines the economic benefits of leveraging flexibility of heat pumps through LEMs and the problems that may arise. An agent-based simulation of LEMs with double-sided auctions is utilized to consider prosumer behavior, incorporate model-predictive control, and employ detailed modeling of energy devices. According to the findings, a district where 40% of households use heat pumps can reduce their annual cost by 5.1% through a LEM. The study identifies several factors contributing to the relatively small economic benefits, including high balancing costs, excessive taxes and network charges, uneven distribution of benefits, and seasonal fluctuations. Additionally, the study proposes daily demand charges to mitigate high residual demand peaks resulting from heat pumps. In conclusion, the study emphasizes the key role of heat pumps in achieving economic benefits through LEMs and highlights the regulatory framework changes required to effectively tackle the challenges faced by LEMs with a large share of heat pumps.

1. Introduction

1.1. Motivation

The capacity of variable renewables, in particular wind and solar energy, has increased dramatically worldwide over the past decade. They are essential to achieving the transition to carbon-neutral electricity supply [1]. However, this development raises many questions about how to safely and robustly plan and operate a power system when generation is often dominated by renewables that fluctuate rapidly over short time periods [2,3].

Demand-side flexibility is critical in fully utilizing the electricity generated from intermittent renewable sources, such as wind and solar power [4]. It also plays a significant role in balancing the power grid and relieving it during peak hours [5]. Several studies have already focused on building energy flexibility, with particular emphasis on the heating system [6–8]. In these studies, heat pump (HP) systems have emerged as a major component, and the electrification of heating through the use of HPs in conjunction with thermal energy storage has been identified as a promising measure for enhancing flexibility potential. HPs have the ability to decouple heat production from electricity demand and are currently the most promising technology for providing flexibility to the power grid [9]. They offer the possibility of modifying their operation in response to external signals. Furthermore, when combined with thermal energy storage, HPs contribute significantly to the integration of fluctuating power generation [10].

Demand response programs (DRPs) are essential for leveraging the flexibility of HPs. DRPs must ensure power quality in the network while meeting the requirements of various entities, including system/market operators, energy consumers, and suppliers [11]. As an alternative to DRPs for solving local power imbalances, local energy markets (LEMs) have received increased attention in the literature. LEMs can help to balance power supply and demand locally, reducing transmission congestion and the need for redispatch measures and renewable energy source (RES) curtailment. By promoting a market-based approach, LEMs allow for the cost-effective formation of local energy balances between producers, prosumers, and consumers. Furthermore, market participants can benefit from advantageous local market prices, while prosumers can generate additional revenue by selling their energy directly to individual consumers. Therefore, it is essential to examine the use of LEMs as a means of leveraging the flexibility provided by residential HPs to minimize residual peak demand and energy costs, as these are crucial issues for system operators and market participants.

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Nomenclature

Abbreviations

COP	coefficient of performance
DHW	domestic hot water
DRP	demand side program
DSO	distribution system operator
HEMS	home energy management system
HP	heat pump
LEM	local energy market
MILP	mixed integer linear program
MPC	model-predictive control
PV	photovoltaic
RES	renewable energy source
RTC	real-time controller
RTP	real-time pricing
SH	space heating
SOC	state of charge
TES	thermal energy storage
TOU	time-of-use

Parameters

ΔT	trading horizon
Δt	time interval
η	efficiency
C	thermal capacitance
c	cost
d	bids
f	fitting coefficient
p	bidding price
R	thermal resistance
s	offers
t	time step
t_d	time step of delivery
T_{amb}	ambient temperature
T_{out}	supply temperature
u	utility

Variables

E	energy in storage
P	electric power
Q	thermal power
x	operation state

1.2. Related studies

DRPs are often utilized to take advantage of the flexibility of HPs. In [12], the participation of prosumers was financially compensated based on their contribution to system reliability improvement through direct load control. Similarly, direct load control programs were proposed utilizing interruptible loads, such as electric water heaters, to enable greater renewable energy generation [13,14]. Price-based demand response programs, such as time-of-use pricing, are also important in unlocking the flexibility potential of residential buildings. Studies suggest that ToU pricing can effectively manage generation capacity and reduce peak load [15,16]. Another approach is real-time pricing, which provides customers with a direct financial incentive to reduce their energy consumption during high-price periods [17].

In addition to demand response programs, the concept of LEMs is emerging as a promising way to harness local flexibility in a market-based way. Khorasany et al. [18] provides a comprehensive review of designing LEMs. It emphasizes the importance of identifying the players in these markets, outlining their goals, and explicating the reasons for market clearing. In [19], it establishes a joint energy market design including a regional level energy coupled market and a user-level distributed peer-to-peer transaction market. It proves that the distributed peer-to-peer transaction market at the user-level facilitates the accommodation of renewable energy and energy conversion technology and promotes more flexible energy consumption across a wider schedulable and tradable space. A number of studies have focused on the economic benefits for individuals and communities within LEMs. In [20], it is found that with a moderate level of PV penetration, auction-based peer-to-peer energy trading in the LEM result in a reduction of community energy costs by 30%. Luth et al. [21] found that peer-to-peer energy trading in LEMs results in 16% savings. When combined with centralized or decentralized battery storage, peer-to-peer trading yields 24% and 31% savings, respectively. Zhang et al. [22] showed that consumers can experience a minimum savings of 6.2% on their bills at different levels of PV penetration in a local peer-to-peer market. Spiliopoulos et al. [23] highlighted the economic benefits (£3.6–£4) for battery owners and positive outcomes in LEMs. In [24], it suggests that the combination of LEMs with a modified demand response strategy can achieve lower market clearing prices in favor of market participants by up to 32%.

Residual peak demand is also an important consideration in the context of LEMs. One proposed peer-to-peer energy market, as described in [25], was found to effectively smooth energy consumption from the external grid while meeting the unique needs of various user groups. In [23], a novel peer-to-peer energy exchange framework was presented, which improved the economic and resilient operation of micro-grids. The benefits of this framework were demonstrated through increased resilience (up to 80%) and battery life improvement (32%–37%). Furthermore, incorporating energy storage systems into LEMs can enhance self-sufficiency by reducing peak load and the amount of energy exchanged with the wholesale electricity market [26]. However, trading in LEMs alone may not necessarily reduce peak demand. Only when flexibility resources were utilized through appropriate demand response programs, a 40% reduction in peak demand was achieved [24]. In [27], a utility surcharge mechanism was employed to dispatch demand flexibility in peer-to-peer energy markets. The results indicate that the surcharge can effectively reduce peak load by nearly 50%.

1.3. Presented work

Previous research has shown that LEMs have the potential to bring economic benefits to communities and help to reduce grid congestion locally. However, existing studies that examine LEMs often use simplified models that rely on fixed household load profiles and generalized representations of flexibility resources. To date, there has been a lack of research exploring the flexibility potential of residential HPs within LEMs. Additionally, no previous studies have combined control mechanisms with LEMs to account for forecasting uncertainties and balancing costs and analyzed the impacts of LEMs on different types of households.

To better judge the viability of LEMs, it is important to know the real performance of LEMs as well as the problems faced by LEMs. On the one hand, the regulatory framework may have to be adapted to enable the local trade of electricity in LEMs. On the other hand, the amount and distribution of economic benefits in LEMs are essential to attract more participants into LEMs while ensuring fairness. In addition, there is an enormous increase of residential HPs until 2045 because of the energy transition in Germany, which aims to build a climate-neutral energy system. Thus, it is also of interest for policy-maker to

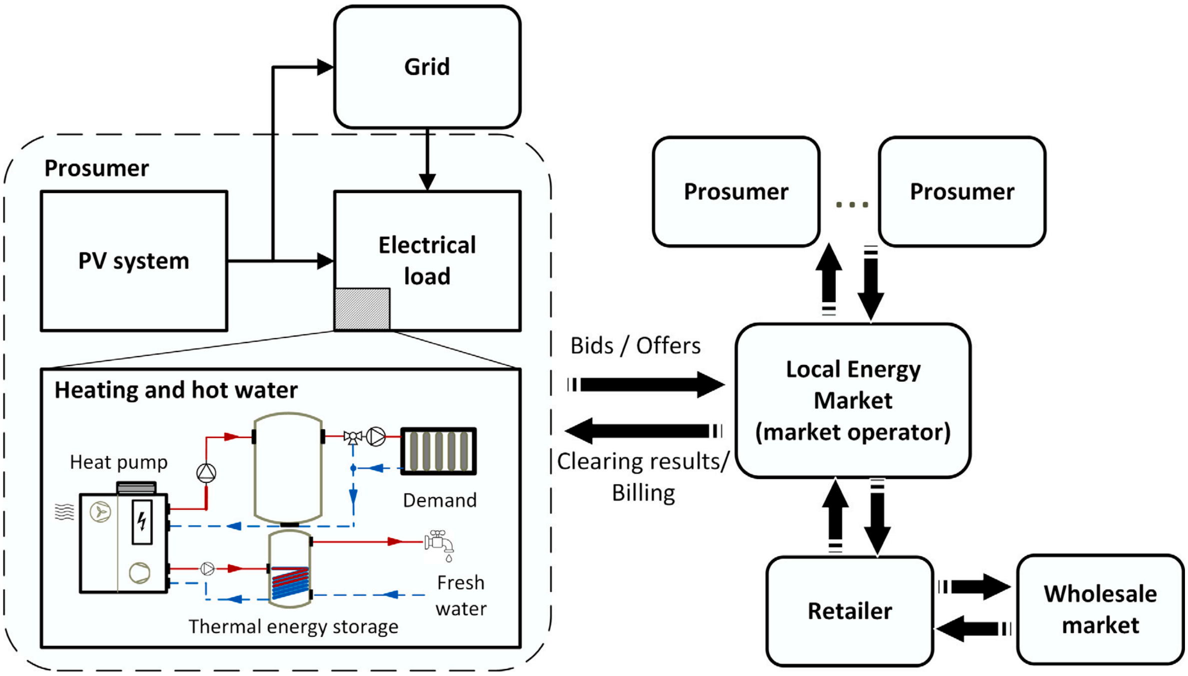


Fig. 1. Structure of the simulation tool lemlab with details of the heat pump system in a household.

know whether LEMs can cope with problems caused by a large share of HPs such as grid congestion. It is worth proving that LEMs can leverage the flexibility of HPs to achieve lower energy costs and relieve the potential congestion in a power grid. Therefore, our study, as a comprehensive study on the synergy effects between LEMs and HPs, can contribute to the concerns above and would assist other researchers and policy-maker to optimizing the LEM concept and its roll-out in the future.

This paper presents a methodology for modeling a LEM with double-sided auctions, considering varying penetration levels of residential HPs. Sellers, buyers, and the retailer are key players in the market. The retailer, uniquely, can also take the roles of both buyer and seller, thereby connecting the LEM to wholesale markets. The model provides detailed representations of energy devices and takes into account control strategies, forecast errors, and balancing costs of market participants. Furthermore, it evaluates the performance of the LEM compared to a benchmark scenario without the LEM to quantify the economic benefits of the LEM. The contributions of the papers are listed as follows:

- analysis of economic benefits of prosumers taking part in LEMs with a large share of HPs;
- analysis of barriers preventing LEMs from achieving greater economic benefits and operating in a grid-friendly manner;
- proposals for changes of the regulatory framework required to address the problems faced by LEMs with a large proportion of HPs.

The rest of the paper is organized as follows. Section 2 introduces the research method, including models for market trading and the HP system. In Section 3, the input datasets and simulation settings are outlined, followed by a presentation of the simulation results in Section 4. The implications of the results and the limitations of the study are discussed in Section 5 and Section 6, respectively. Finally, Section 7 summarizes the key contributions of the paper.

2. Method

This study uses lemlab, an agent-based simulation tool, to simulate LEMs with periodic double-sided auctions. To perform the research presented in this paper, we extended lemlab to allow for the simulation of HPs and thermal energy storage. The basic structure of lemlab is presented in Fig. 1.

The core of lemlab is formed by the agents, which are active participants in the modeled LEM. Retailers and prosumers are currently implemented as agents in lemlab. Retailers are intermediaries that link the LEM to the wholesale market. They can purchase excess energy in the market or import energy from outside to meet energy demand. They typically offer fixed buy and sell prices and serves as the link to the wholesale market. In contrast, prosumers are physical agents operating household appliances that generate, consume, or store energy. Prosumers are capable of optimizing the operational plans of household appliances based on predictions. For the sake of simplification, we will use the term “prosumers” to refer to both producers and consumers in this study.

In general, prosumers must complete the following steps to achieve energy exchange in the LEM:

1. **forecasts**: make forecasts about weather, demands, and electricity prices;
2. **model-predictive control**: use the model-predictive control (MPC) to generate the optimal schedules for their flexible loads such HPs, EVs, and batteries;
3. **submitting bids**: send their bids and offers to the LEM based on the optimal schedules prior to the delivery time
4. **market clearing**: match the demand and supply and clear the market;
5. **receiving results**: receives the market clearing results for the delivery time after the market clearing;
6. **real-time control**: use real-time controller to adjust the operating states of the flexible loads at the delivery time according to the electricity procured from the LEM;
7. **settlement**: settle the consumption or generation soon after the electricity has been delivered

The steps 1 to 5 should be repeated for every rolling horizon prior to the delivery time step. Prosumers should check the clearing results from the previous rolling horizon to ensure that the procured electricity is sufficient for their energy demand at the time step of delivery.

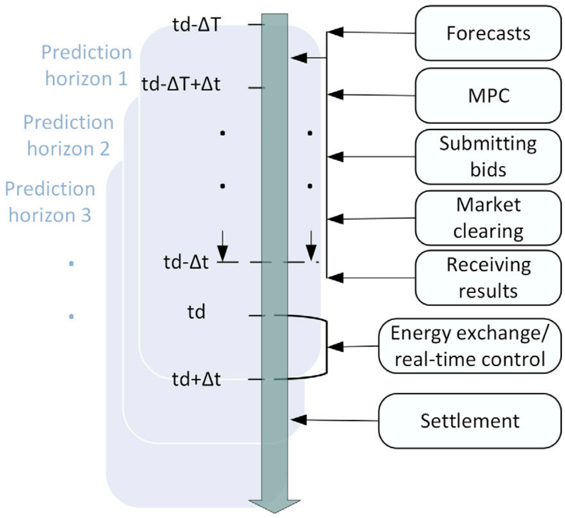


Fig. 2. Timeline of the trading process in the LEM.

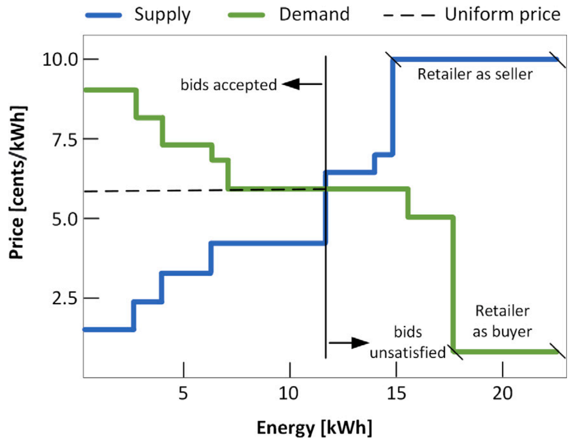


Fig. 3. Visualization of a double-sided auction.

Otherwise, they should continue bidding at later time steps until they have obtained enough electricity. During the delivery time step, the physical flow of energy takes place, and real-time control is activated to ensure precise consumption. Finally, the costs are settled based on the metering data that reflects the real consumption. The whole process is illustrated in Fig. 2.

In the following subsections, we introduce the bidding strategy and market clearing process, the HP system and the control mechanism. Limited by the scope, the description of other parts of lemlab is omitted in this work. However, more information about lemlab is available in [28].

2.1. Market clearing and bidding strategy

The LEM uses a future market design, which is the most common market design found in the literature [29]. Therefore, the LEM undergoes clearing every 15 min, with a 24 h trading horizon, allowing prosumers to trade electricity up to 24 h in advance. This allows the LEM to function as a day-ahead, intraday, or near real-time market. If prosumers are unable to fulfill their energy demand in one round of market clearing, they can continue submitting their bids in subsequent trading cycles. During settlement, any energy imbalances resulting from a deviation from the traded position lead to additional balancing costs. The local electricity market proposed in this study adopts a centralized two-sided auction format, similar to wholesale electricity markets. Agents submit their bids to a market operator at a time interval in a standardized bid format. The objective of the market is to maximize social welfare [18]. Mathematically, social welfare SW is formulated by the sum of the bidders' utility u minus the sum of producers' costs c (Eq. (1)). The bids and offers are denoted as d_i and s_j, respectively. n_B and n_S represent the number of buyers and sellers. To achieve maximum social welfare, the market operator organizes the bids in decreasing order and offers in increasing order, establishing the demand and supply curve. The intersection of the demand and supply curve is known as the market closing price, which is then communicated to each agent and used for settlement.

$$\begin{aligned} max \;\; SW &= \sum_{i=1}^{n_B} u_i(d_i) - \sum_{j=1}^{n_S} c_j(s_j) \\ s.t. \;\; \sum_{i=1}^{n_B} d_i &= \sum_{j=1}^{n_S} s_j \end{aligned} \tag{1}$$

The two-sided auction allows for consumption and production bids to be part of the same market clearing process. The market operator ensures a balance between total consumption and total generation among the accepted bids. Additionally, the auction operates as a uniform price auction, with all accepted bids paying or receiving the same market price. All buyers who bid above or equal to this price can buy, while all sellers who sell below or equal to this price can sell. To balance the market, the retailer also act as a seller or a buyer. The retailer either sells the energy required by consumers with a high price or purchases the excess energy with a low price. This makes his placement at the end of the trading priority which leads to more local energy trading. The double-sided auction process is visualized in Fig. 3. The uniform pricing for the double-sided auction allows the bids to reveal their true valuation [30].

Prosumers must decide on the quantity and pricing of their bids prior to the delivery interval. The bid quantity is based on electrical demand or generation forecasting, calculated using model predictive control discussed in Section 2.3. A linear trading strategy is used for the bid prices. Prosumers who buy energy aim to purchase it at the lowest price initially. After each round of market clearing, any remaining unaccepted bids' prices gradually increase until prosumers offer the highest price they are willing to pay in the final time step before the delivery period. Conversely, prosumers who sell energy begin by bidding at the highest price and gradually decrease the price as the delivery time approaches. This behavior is described by the following equation:

$$p_{t,bid} = p_{max} - (t_d - t)\Delta p, \quad \forall t_d - \Delta T \leqslant t \leqslant t_d \tag{2}$$

$$p_{t,offer} = p_{min} + (t_d - t)\Delta p, \quad \forall t_d - \Delta T \leqslant t \leqslant t_d \tag{3}$$

$$\Delta p = \frac{p_{max} - p_{min}}{\Delta T} \tag{4}$$

where t and t_d represent the current time step and the delivery period. p_{max} and p_{min} are the price ceiling and floor. ΔT is the trading horizon selected by the prosumer, which can range from 6 to 24 h. Δp is the price increment in the next time step when the bids are not accepted completely.

2.2. Heat pump system

For this study, we have extended the original lemlab code to include a HP model. The HP system is comprised of the thermal energy storage (TES) and the HP. They should fulfill the heat demand, including space heating (SH) and domestic hot water (DHW). As the supply temperatures for SH and DHW are usually different, a two-storage system is implemented to ensure higher efficiency, as shown in Fig. 1.

The HP is modeled using hplib [31]. It is based on measurements from various manufacturers and provides functions of electricity demand and thermal power of HPs fitted to the corresponding measurements. With regard to the type, a generic model of air source HPs is implemented. It is assumed that the modulation from 0% to 100% is possible for the HP. The following equations are used to calculate the thermal power and the coefficient of performance (COP):

$$COP_t = f_1 T_{amb,t} + f_2 T_{out} + f_3 \quad (5)$$

$$P^{cap}_{hp,t} = P_{hp,ref}\,(f_4 T_{amb,t} + f_5 T_{out} + f_6) \quad (6)$$

$$Q_{hp,t} \le P_{cap,t} \cdot COP_t \quad (7)$$

$$P_{hp,t} = \frac{Q_{hp,t}}{COP_t} \quad (8)$$

where COP_t and $P^{cap}_{hp,t}$ are the COP and the electricity consumption given ambient temperature $T_{amb,t}$ and supply temperature T_{out}. $P_{hp,ref}$ is the electricity absorbed by HP at reference operating point. f_i are parameters fitted using the manufacturer measurements. Modulation of the thermal power of HP $Q_{hp,t}$ is possible from 0% to 100% of the rated thermal power. The COP is assumed constant during the modulation. $P_{hp,t}$ is the real electricity consumption of the HP.

The HP is capable of switching between the generations of SH or DHW. To model this behavior without additional integer variables, a new variable Δt^{sh} is defined, representing the time supplying TES for SH within one time interval. Because the length of the time interval stays constant throughout the simulation, the maximum thermal power is adjusted instead depending on the operation time allocation for SH and DHW demands in one time interval (Eqs. (9)–(10)). This approach also allows the HP to switch the supply temperature more frequently.

$$Q^{sh}_{hp,t} \le \frac{\Delta t^{sh}_t}{\Delta t} P^{sh}_{cap,t} \cdot COP^{sh}_t \quad (9)$$

$$Q^{dhw}_{hp,t} \le \frac{\Delta t - \Delta t^{sh}_t}{\Delta t} P^{dhw}_{cap,t} \cdot COP^{dhw}_t \quad (10)$$

The TES is assumed fully mixed. The TES can be charged by HPs or discharged to supply the heat demand for SH or DHW. Depending on the operation, the state of charge (SOC) of the TES evolves every time step, as shown in Eq. (11).

$$E_{tes,t} = E_{tes,t-1} + (Q_{hp,t}\eta_{tes} - \frac{Q_{load,t}}{\eta_{tes}}) \cdot \Delta t \quad (11)$$

$$SOC_t = \frac{E_{tes,t}}{E^{cap}_{tes,t}} \quad (12)$$

$$0 \le SOC_{tes,t} \le 1 \quad (13)$$

where E^{TES}_t is the thermal energy stored in the TES, while $Q_{load,t}$ is the heat demands. The TES model are used for SH and DHW separately.

To consider the flexibility provided by building mass, a simple model is used to describe the temperature evolution inside the building based on [32]. The change in room temperature depends on heat loss and heating power from heating system:

$$\theta_t = \theta_{t-1} - \frac{\theta_{t-1} - \theta_{amb}}{R_{th} C_{th}} + \frac{Q_{load,t}}{C_{th}} \quad (14)$$

where θ_t is the room temperature, while θ_t is the ambient temperature. R_{th} and C_{th} indicate the thermal resistance and capacitance, respectively. The room temperature θ_t is restricted from 18 °C to 22 °C.

2.3. Control mechanism

The control mechanism is comprised of two parts: model-predictive control (MPC) to obtain the optimal schedules and real-time controller (RTC) to implement the schedules. They are usually incorporated into the Home Energy Management System (HEMS). Prosumers need MPC to obtain accurate load prediction and submit bids for participating in the LEM. However, if a prosumer buys less electricity than originally planned through the LEM, the RTC will be required to adjust their power demand through flexible loads.

The optimization within MPC requires information such as the states of all household appliances and storage systems, as well as the predictions of PV generation and electricity price. Based on this information, it can run a mixed integer linear program (MILP) to find the cost-optimal schedules for the flexible loads of the prosumer. The MPC updates the cost-optimal schedules every hour with a prediction horizon of 24 h. The following objective function needs to be minimized, given constraints for the household appliances:

$$obj = \min \sum_t \left[\sum_i P^-_{grid,t}(-c_{t,lem} + c_{t,levy-}) + \sum_j P^+_{grid,t}(c_{t,lem} + c_{t,levy+}) \right] \quad (15)$$

where $P^-_{grid,t}$ and $P^+_{grid,t}$ represent the electricity exported to and imported from the power grid, respectively. $c_{t,lem}$ is the electricity price from the market clearing. $c_{t,levy-}$ and $c_{t,levy+}$ are levies for export and import. t refers to the time steps within 24 h.

The power balance is given by Eq. (16), which ensures the generation to be equal to the power demand within one household.

$$P^+_{grid,t} - P^-_{grid,t} = P_{HP,t} + P_{load,t} - P_{PV,t} \quad (16)$$

Once the values for P^+grid,t, and P^-grid,t are available to prosumers, they can use these values to determine how much energy they need to purchase or sell and place their bids in the LEM, as explained in Section 2.1. Due to the competitive nature of the market, prosumers may not always have all their bids accepted by the LEM, which means they may need to adjust their energy consumption accordingly. Therefore, it is necessary to run the RTC after procuring electricity in the LEM to modify real power consumption. The task of the RTC is to make the real power demand converge to the bids accepted by the LEM. It can vary the operating state of flexible loads to meet this requirement as much as possible, as outlined in Eqs. (17) and (18).

$$obj = \min \sum (P^{rtc}_{grid,t} - P_{market,t})^2 \quad (17)$$

$$P^{rtc}_{grid,t} = P^{rtc}_{HP,t} + P^{rtc}_{load,t} - P^{rtc}_{PV,t} \quad (18)$$

where $P_{market,t}$ the power transfer required by the bids accepted in the LEM. The other variables marked with rtc represent the real control signals sent by the RTC instead of the schedules from the MPC.

Based on Eq. (18), the flexibility potential from HPs can be utilized by adjusting their power consumption to bring the total electrical load $P^{rtc}_{grid,t}$ closer to the energy purchased in the LEM $P_{market,t}$. As a result, the flexibility potential of energy devices can assist in avoiding balancing costs.

To reflect the situation of traditional electricity sales, simulations without the LEM use a rule-based control for energy devices instead of a HEMS with MPC and RTC. Fig. 4 illustrates the rule-based control approach employed for managing HPs with TES for DHW. The control method is primarily based on the warm water temperature within the TES. Furthermore, the control method enables modulation operation to prevent frequent switching. The TES for DHW maintains a minimum and maximum SOC of 40 °C and 65 °C, respectively.

2.4. Measures to reduce residual demand peaks

The LEM would result in network congestion if the prosumers make comparable forecasts and activate their flexible load at the same time. In a previous study, the nodal pricing has been applied to limit the power transfer between the different locations based on the network constraints [33]. This measure considers network transfer limitations explicitly when clearing the market. However, this solution might cause comfort losses because prosumers cannot buy enough electricity on some occasions. They must stop using certain household appliances or

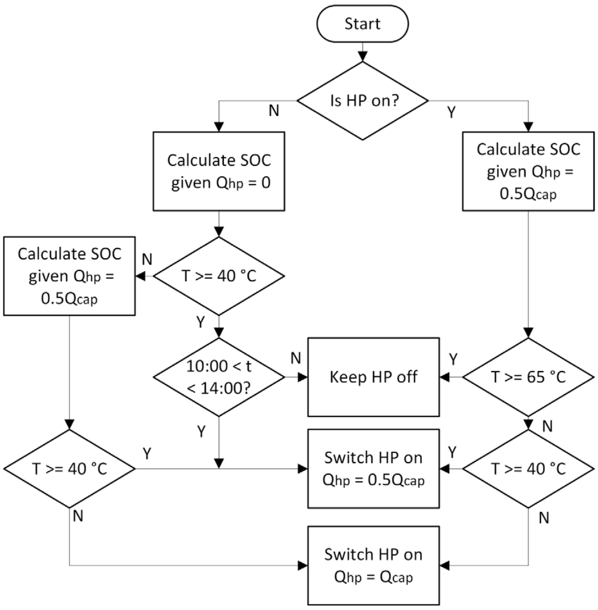


Fig. 4. Rule-based control for the heat pump system with TES for DHW.

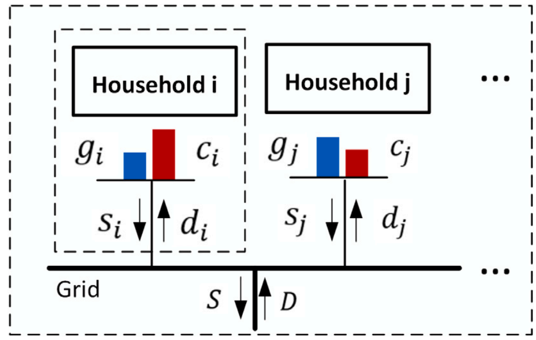


Fig. 5. Boundary conditions for performance indicators. Surplus and deficit refer to residual generation and demand for individual households; surplus and deficit of community refer to residual generation and demand of the whole neighborhoods.

g_i : *generation* c_i : *consumption*

s_i : *surplus* d_i : *deficit*

S : *surplus of community (export)*

D : *deficit of community (import)*

pay high balancing prices. In [27], a utility surcharge mechanism has been employed to leverage demand flexibility and improve the power system reliability, which, however, requires additional quantification of flexibility demand by the system operator.

In our study, instead, another measure called daily demand charges is proposed, which charges additional costs from prosumers according to the peak loads during one day. This is easily applicable and allows the MPC controller to deal directly with the power peaks while minimizing the sum of energy cost and demand charges. To consider the daily demand charges, the optimization objective of the MPC in Eq. (15) is modified as follows:

$$obj = \min \sum_t \Big[P^-_{grid,t}(-c_{t,lem} + c_{t,levy-}) + P^+_{grid,t}(c_{t,lem} + c_{t,levy+}) \Big] + P^+_{peak,t} c_{peak} \quad (19)$$

where $P^+_{peak,t}$ is the maximum of $P^+_{grid,t}$ within the next 24 h, which represents the peak demand. A penalty charge for high demand peaks is included as daily demand charges, denoted as c_{peak}.

2.5. Performance indicators

The following performance indicators are applied as metrics evaluating the impacts of residential HPs and LEMs: daily average cost, residual peak demand, self-consumption and collective self-consumption.

The daily average cost represents the daily electricity cost of each prosumer. The peak load indicates the maximum power flow at the local transformer. The self-consumption (CS) refers to the percentage of energy prosumers use for their own production, while collective self-consumption (CSC) is used to describe the utilization rate of PV generation over the whole neighborhoods. In general, self-consumption and collective self-consumption can reflect the impacts of LEMs on the local and superior power grid. Fig. 5 and Eqs. (20)–(21) describe the difference between the two similar performance indicators in detail.

$$SC = \frac{\sum_t (g_{i,t} - s_{i,t})}{\sum_t g_{i,t}} \quad (20)$$

$$CSC = \frac{\sum_t (\sum_i g_{i,t} - S_t)}{\sum_t \sum_i g_{i,t}} \quad (21)$$

3. Case study

3.1. Weather data and household demands

The weather data was sourced from OpenWeather and Solcast for Munich, Germany [34,35]. Although the original resolution of the weather data was one hour, we used linear interpolation to adjust it to match the 15-minute resolution of the electricity demand data. The time span of the weather data ranges from January 1st, 2021 to December 31st, 2021. The temperature and humidity data were obtained from OpenWeather [34], while the global horizontal irradiance and the direct horizontal irradiance were sourced from Solcast [35].

The DHW demand of prosumers was obtained from DHWcalc. The DHWcalc is a computer program for generating DHW demand profiles based on statistics [36]. For the scenarios without the LEM, the SH demand of prosumers are generated under thermostat control for room temperature via SimulationX. SimulationX is software for the simulation of technical systems. The SH demand for the scenarios with the LEM is optimized by the MPC and then determined after the RTC sends the control signals to the HP system.

The electricity demand time series were obtained from households in Bavaria, Germany, and were measured every 15 min between 2009 and 2010 [37]. These households did not have any HPs or EVs, so the measurements represent pure household demand. To align with the weather data from 2021, we fitted the data to the same time span.

3.2. Sizing of energy devices

For each prosumer, the HP is sized by the maximum thermal power demand. This thermal power should meet the maximum heat demand for SH provided a ambient and supply temperature of −7 °C and 50 °C, respectively. The DHW demand is not considered in the HP sizing because of the intermittent occurrence which can be compensated by the TES. On the other side, the TES for SH and DHW is sized separately. The TES of DHW should meet the highest DHW demand for 30 min, while the TES for SH should cover the SH demand for 2 h alone. The temperature range of the TES for SH and DHW are 30 °C–45 °C and 40 °C–65 °C, respectively. This ensures that the warm water temperature can satisfy the comfort requirement even when the SOC approaches 0%.

Table 1
Parameters for household demand and energy devices.

Parameter	Unit	Value
Number of households	–	50
Power consumption	kWh/a	3000–4000
DHW consumption	l/d	200
HP thermal power	kW	12
TES volume for SH	l	200
TES volume for DHW	l	200
PV peak power	kW	3–4

Table 2
Forecasting methods. Naive: same as last day; naive average: the average of last 7 days; perfect: perfect knowledge of the future.

Forecast	Method
Power demand	Naive
SH demand	Perfect
DHW demand	Naive average
Electricity price	Naive
PV power	Perfect

Table 3
Cost components and retailer prices.

Type of cost	Price [€/kWh]
Electricity price	MCP
Levies (+)	0.18
Levies (−)	0.00
Balancing price (+)	0.05
Balancing price (−)	0.05
Retailer price (+)	0.10
Retailer price (−)	0.01

The peak power of the PV system depends on the annual electricity consumption of the household. Every 1000 kWh/a of household electricity consumption corresponds to a 1 kW peak power of the PV system. The power and capacity for home batteries are fixed at 3.5 kW and 3.5 kWh, respectively. The PV generation time series were sourced from Sunny Portal of SMA in 2021 [38]. Typical parameters of one household are shown in Table 1.

3.3. Forecasts and cost components

Regarding the forecasting necessary for the MPC controller, various methods are employed (Table 2). Typically, a "perfect forecast" is used for information closely tied to weather conditions, such as SH demand and PV power. For data with high levels of randomness, "naive forecast" and "naive average forecast" are implemented. The "naive forecast" assumes today will be the same as yesterday, while the "naive average forecast" uses the average from last week instead of yesterday's data.

The cost for prosumers consists of three components: energy costs from the LEM, levies, and balancing costs. The energy costs are settled based on the market clearing price in the LEM, which changes with each clearing round. Levies refer to taxes and network charges, while balancing cost is incurred when a prosumer's consumption or generation does not align with the bids accepted by the LEM. The retailer price refers to the bid prices of the retailer. Information about the pricing parameters is summarized in Table 3. The (+) symbol indicates when prosumers are importing energy, and the (−) symbol indicates when they are exporting energy.

3.4. Simulation setup

To investigate the benefits of the LEM together with HPs, we perform simulations of different scenarios. At first, the scenarios are divided into two groups. One group is simulated with the LEM, while the other is without the LEM. Then, the simulation results are compared in terms of the performance indicators described in Section 2.5.

The neighborhoods consist of 50 prosumers, which represent a typical size of a LEM. To establish scenarios that achieve a specific penetration level for HPs, a subset of households is selected to adopt them. In our study, we use 40% penetration level for HPs, as anticipated for the year 2050 in [39]. Therefore, 20 households are randomly selected to possess this technology. Similarly, we select 50% of the prosumers to have PV systems.

To thoroughly examine the advantages of LEMs in various weather conditions, simulations have been conducted separately for each season: transition (spring and fall), summer, and winter, each lasting one week. To guarantee the accuracy of the results, each scenario is simulated 20 times for one week to obtain the average values. The entire case study is divided into three parts:

- **benefits of LEMs and HPs**: quantification of the economic benefits of LEMs by comparing the performance indicators with LEMs to those without LEMs. The penetration level of HPs is set at 0% or 40% to evaluate their effects. The analysis includes energy and economic outcomes, with a specific focus on the distribution of economic benefits across different types of households;
- **daily demand charges**: a novel measure is proposed to avoid high peaks in LEMs, and its advantages and shortcomings are evaluated;
- **parameter analysis**: the influences of TES sizes, PV penetration, network charges, and forecasting methods on LEMs are examined.

4. Results

4.1. Benefits of LEMs and HPs

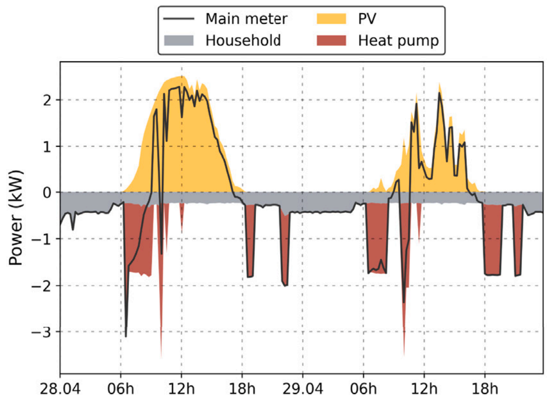
The first part of this section explores the differences in load and generation profiles between scenarios with and without the LEM from various perspectives. Then, we examine the effect of expanding HPs on power flows and electricity prices in the LEM scenarios. The next part shows the distribution of economic benefits in detail. Finally, the benefits of LEMs are analyzed with the help of the performance indicators. For clarity, some figures illustrating the time series show results for only two days.

4.1.1. Typical household schedules

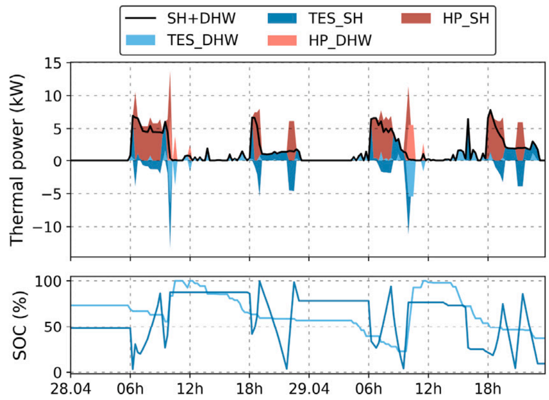
Depending on whether the LEM exists, the schedules of household appliances can have different patterns. Fig. 6 shows the power or load profiles within one household. In the scenario without the LEM, the operation of heat pumps simply follows the rule-based control. The HP is switched on immediately after the SOC of TES becomes low and keep charging the TES until the TES is nearly full (see Fig. 6(a)–6(b)). In contrast, better utilization of PV power can be achieved with the LEM. By forecasting PV power and heat demand, the MPC controller utilized in the LEM can optimize the schedules of the HP operation. Fig. 6(c) shows that the HP runs mainly at times around noon to achieve the maximum COPs with minimum electricity costs. The controller always tries to discharge the TES in the early morning and then charge the TES when the PV power is available, as depicted in Fig. 6(d). Therefore, PV power is less fed into the power grid compared to the base scenario. This indicates that HPs achieve higher self-consumption of PV power.

4.1.2. Power flows in the local power grid

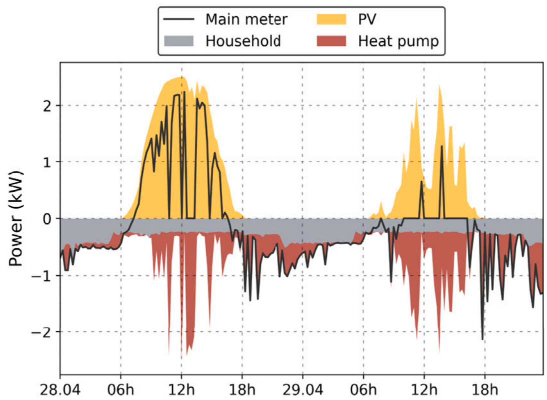
The LEM can improve the balance of power supply and demand in the local power grid and reduce the power peaks on the transformer because it can indirectly regulate the consumption of flexible loads and match it with renewable power. However, its effects can differ significantly depending on the season. Fig. 7(a) presents a comparison of the power flows at the local power grid for scenarios with and



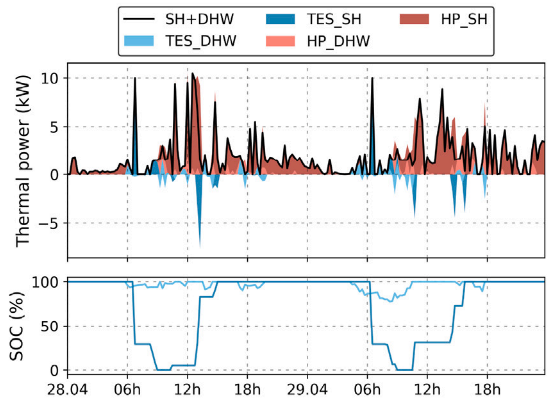
(a) Power balance without the LEM



(b) Heat balance without the LEM



(c) Power balance with the LEM



(d) Heat balance with the LEM

Fig. 6. Generation and demand profiles of one representative household.

without the LEM in summer. The energy surplus and demand with the LEM are nearly the same as those without the LEM. This situation is due to the absence of SH demand in summer. The heat demand for DHW can only absorb a minor share of PV power. In transition time, as depicted in Fig. 7(c), the energy surplus with the LEM is lower than that without the LEM, which is due to the MPC control, which better adapts the operation of HPs and other flexible loads to the PV generation. On the demand side, the frequency of load peaks in the scenario with the LEM is lower than that without the LEM. This is due to the fact that rule-based control induces higher demand peaks for individual households, which can stack for multiple households and result in high power peaks within the neighborhood. In winter, the flexibility of HPs can still efficiently reduce the energy surplus (Fig. 7(e)). However, the absolute reduction of the energy surplus is minimal because of the lower solar radiation in winter.

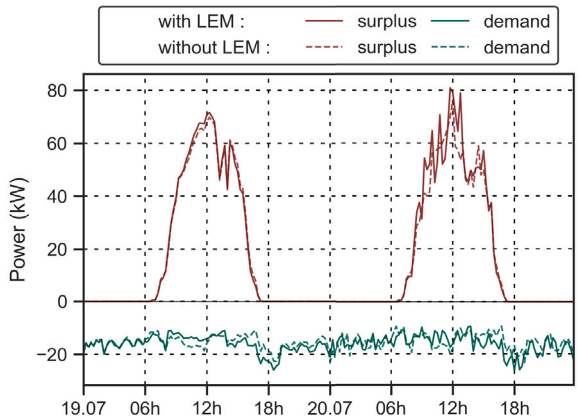
The comparison suggests that only when there is enough heat demand calling for HP operation the LEM can effectively reduce the energy surplus of prosumers with PV. On the demand side, the LEM can slightly mitigate the high demand peaks but cannot ensure a noticeable reduction of demand power peaks compared to those without the LEM. This may stem from the lack of economic incentives for prosumers to flatten their load profiles in the LEM.

It is also important to note that the terms “surplus” and “demand” used here refer to the aggregate surplus and demand of all households prior to mutual energy exchange. This distinguishes the influences of the LEM on feed-in power and demand.

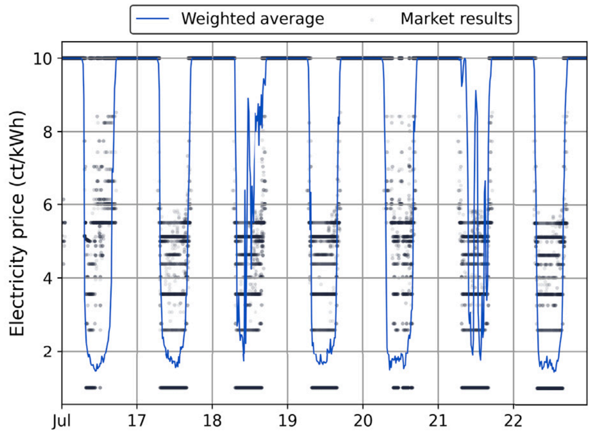
4.1.3. *Electricity prices in local energy markets*

LEMs aim to provide advantageous electricity prices by facilitating lower local market prices for all participants. Energy buyers can save costs by using electricity cheaper than the retailer prices, while energy sellers can earn more money compared to direct sales to the retailer. These electricity prices are determined by the market clearing process. Fig. 7(b)–7(f) illustrates the market results and average electricity prices for one week in summer, transition, and winter, respectively. The market results represent the market clearing prices for each time step. They are distributed from 1 cent/kWh to 10 cent/kWh, which are the lowest bid price and the retailer selling price, respectively. There could be several different market clearing prices at a time step because prosumers can trade several rounds prior to delivery time.

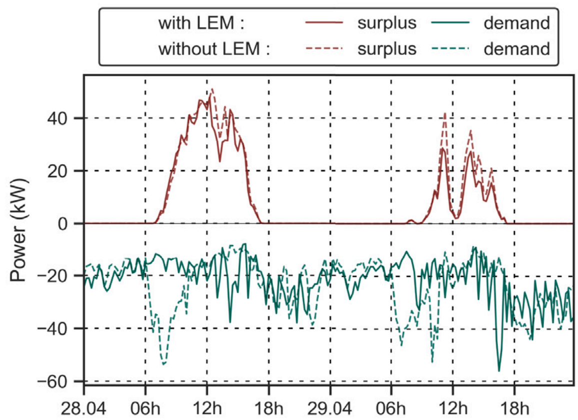
The average prices are weighted by the traded amount of energy. Although the weighted average prices at night are all identical to the retailer’s supply price due to the lack of renewable energy, the market clearing prices in the LEM fluctuate in day time. It can be observed that it drops significantly once PV generation is abundant in transition time and summer. In summer, most bids are cleared at 1 cent/kWh in the middle of the day because of the sufficient supply of PV power and the lack of heat demand. In contrast, the market clearing prices in transition time fluctuate strongly. This stems from the diverse operation schedules of heat pumps. Once multiple prosumers plan to run their heat pumps simultaneously, they submit their bids in the LEM for the same delivery time, causing the increase in market clearing prices. When there is no heat demand, the market clearing prices drop to a low level. In winter, the situation is totally different. Owing to the high heat demand and low supply of PV power, electricity prices are always cleared at a high level. Even though some trading is completed at 5–6 cents/kWh, most are at 10 cents/kWh. Therefore, the cost-saving potential of the LEM for prosumers in winter is not obvious.



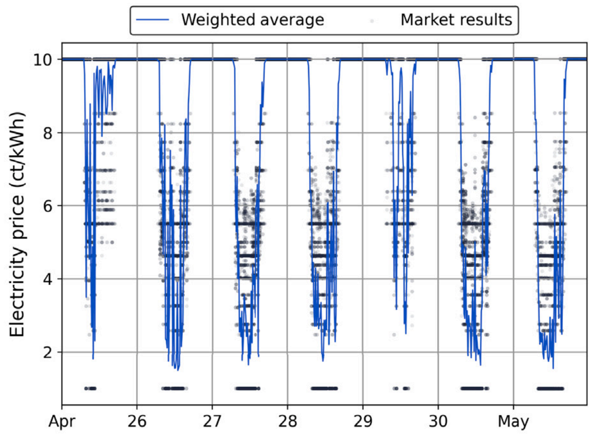
(a) Power flows in summer



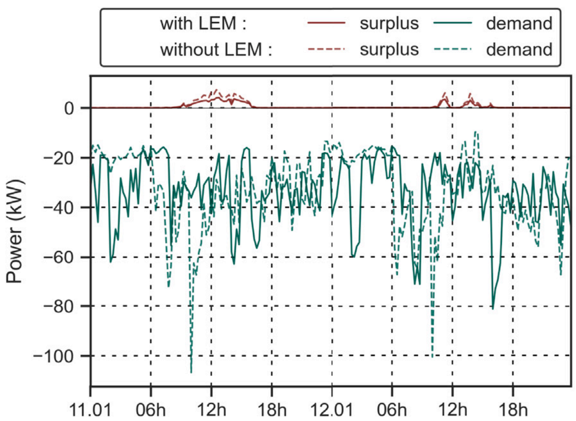
(b) Market clearing prices in summer



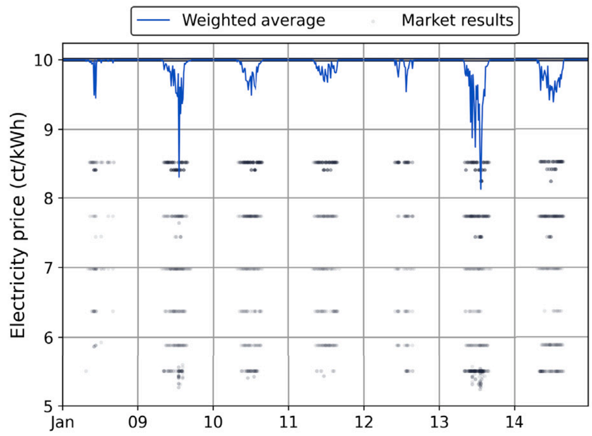
(c) Power flows during transition times



(d) Market clearing prices during transition times



(e) Power flows in winter



(f) Market clearing prices in winter

Fig. 7. Seasonal variations of power flows and electricity prices.

4.1.4. Impacts of household types

Although the LEM can offer attractive electricity prices for all market participants, the impacts vary across different types of households, leading to unequal economic benefits. In Fig. 8, the costs and energy purchased of 20 prosumers from 50 prosumers are demonstrated to show the differences of benefits in transition time. The household types are divided into (1) prosumers with HP, (2) prosumers with PV, (3) prosumers with both HP and PV, and (4) others. The costs represent the total costs, including energy, balancing, and levy costs, subtracted by revenue. More details about different cost parts are presented in Table 4. The data shows the average cost values of the same type of prosumers. The energy costs refer to the purchase cost for buying electricity in the LEM.

Prosumers without HP and PV can rarely benefit from the LEM. Although they can save energy costs by using cheaper electricity for fixed loads, they do not have enough flexibility to maximize these benefits.

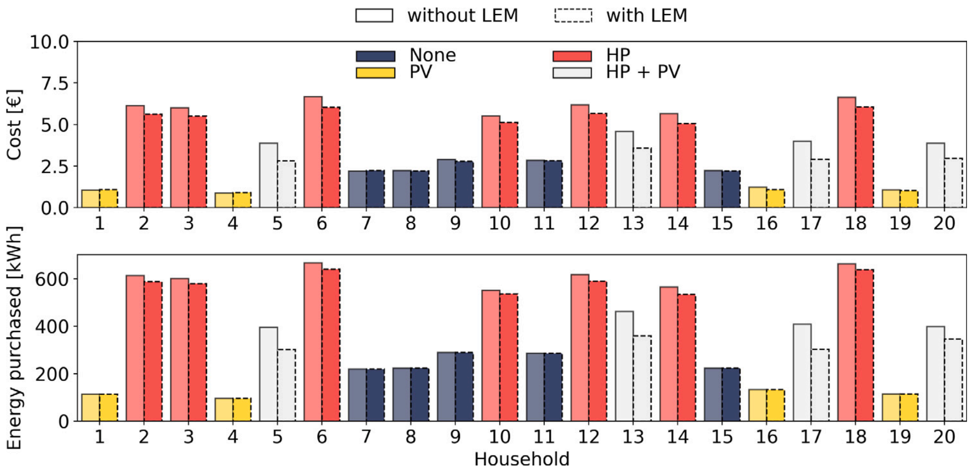


Fig. 8. Average daily cost and energy purchased for 20 households.

Table 4
Comparison of daily average cost (€) with detailed cost parts during transition times.

	None		PV		HP		PV+HP	
	Without LEM	With	Without LEM	With	Without LEM	With	Without LEM	With
Energy cost	0.89	0.71	0.51	0.51	2.18	1.69	1.47	1.06
Revenue	0.00	0.00	−0.10	−0.37	0.00	0.00	−0.08	−0.14
Balancing	0.00	0.16	0.00	0.18	0.00	0.14	0.00	0.11
Levies	1.60	1.60	0.91	0.91	3.92	3.77	2.65	2.13
∑	2.49	2.47	1.32	1.23	6.10	5.59	4.04	3.16

On the other hand, they suffer from the additional balancing costs in the LEM incurred by the forecast errors, which further undermine the economic benefits of the LEM. The reduction of daily average costs from 0.89 € to 0.71 € is offset by the balancing cost of 0.16 €. Therefore, the total cost for prosumers without HP and PV stays nearly the same after the transition to the LEM.

Prosumers with only PV have much lower total costs compared to others because of fewer energy costs and more revenues. However, they cannot benefit much from the LEM either. One might think that the prosumers with PV should have significant benefits in the LEM because they can sell their energy surplus at higher prices. However, the prosumers with PV also suffer from the extra balancing costs, which are even more than those of prosumers without PV. Although the revenue by selling electricity increases by almost three times, the total benefits shrink to an average value of only 0.09 € per day.

For prosumers only with HP, a total cost saving of 8% for total costs can be observed. The savings stem mainly from the energy costs. This type of prosumers has the flexibility from HPs to enable demand response. They usually run their HPs in the middle of the day to achieve a cost-efficient operation because the electricity prices at those times are lower. In addition, they also have less balancing costs compared to the prosumers without HPs. This is due to the inherent flexibility of HPs' operation, which can adapt the electrical consumption closer to the electricity purchased in the LEM. This can avoid a part of the balancing costs. The prosumers with HP also have fewer levy costs because they usually run their HPs at high COPs and therefore decrease the electricity imported from the power grid.

The biggest benefits can be found for the prosumer with both PV and HP. On the one hand, they can leverage the flexibility of HPs to realize better utilization of PV power. On the other hand, they also benefit from more revenues by selling energy surplus and less balancing and levy costs owing to a higher self-consumption rate. Therefore, this type of prosumers achieve can reduce their average daily cost by 22% from 4.04 € to 3.16 €, which is the highest saving of the four types of households.

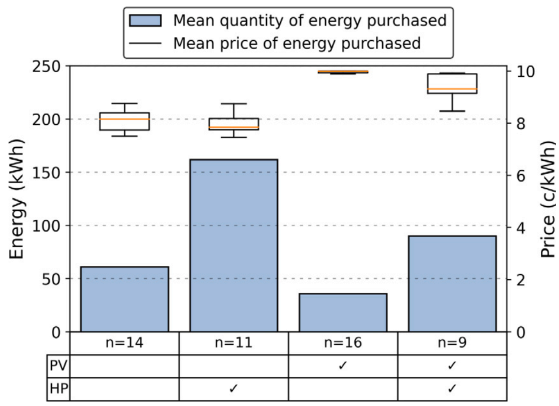


Fig. 9. Energy purchased and mean buying price per household type.

The weighted average prices paid by each type of prosumers in the LEM are presented in Fig. 9. It shows which type of prosumers can buy electricity at lower prices and how much energy they need from the LEM. Generally, the prosumer without PV can buy electricity at lower prices because they need electricity during the daytime, and the electricity prices during the day are usually lower than those at night. Therefore, the weighted average prices are only around 8 cents/kWh. Within them, the prosumers with HP show slightly lower electricity prices than those without HP, indicating the flexibility effects of HPs. In contrast, the prosumers with PVs pay high electricity prices in the LEM as they are often the supplier of electricity. They only buy electricity at night when there is no PV power and therefore pay average prices close to the retailer prices. If the prosumers with PVs also have a HP, they can buy electricity from the LEM when their own PV power production is not sufficient for the operation of their HPs. Thus, this type of prosumers has lower average buying prices compared to the prosumers with only PV.

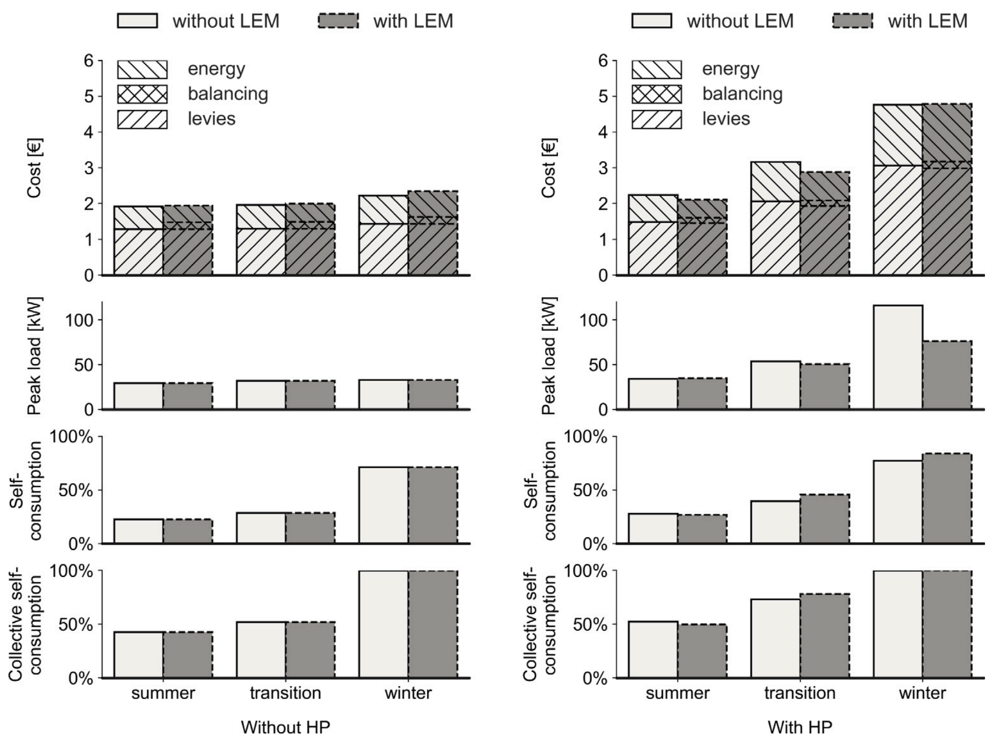


Fig. 10. Impacts of the LEM and HPs on performance indicators.

4.1.5. Impacts of LEMs and HPs

The impacts of the LEM and HPs on the cost, peak load, self-consumption, and collective self-consumption during various seasons are illustrated in Fig. 10. It summarizes the results from Section 4.1.1 to 4.1.4.

The cost refers to the daily average cost for each household. As the penetration of HPs increases from 0% to 40%, the cost rises dramatically due to the sector coupling that partially converts fuel usage into electricity consumption. For scenarios without HPs, the LEM does not provide any benefits. In summer and transition time, the savings in energy costs by the LEM are completely offset by the additional balancing costs. In winter, there are no savings in energy costs owing to the lack of PV power, and the extra balancing costs cause even higher total cost in the LEM compared to that without the LEM. Similarly, there is almost no changes in terms of peak load, self-consumption, and collective self-consumption, regardless of the season.

For scenarios with HPs, the utilization of the LEM results in lower costs compared to scenarios without the LEM. The savings in energy costs can compensate for the added balancing costs in the LEM. This is due to the additional flexibility provided by the HPs, which allows for better utilization of PV power and lowers levy costs by increasing self-consumption. However, these saving effects are not the same in different seasons. The most savings are observed in transition time. The reason is that there is enough heat demand and sufficient solar power during transition times, which are both necessary to make full use of the advantages of LEMs. In winter, nobody sells energy surplus because of the lack of PV power, and the electricity prices in the LEM are close to the retailer prices. Therefore, there is almost no savings in energy costs or levies. In summer, there is abundant PV energy leading to lower electricity prices in the middle of the day. However, there is no considerable heat demand, and only the fixed loads during the day benefit from cheaper electricity prices.

Regarding the residual demand peak, the results obtained are significantly influenced by the season time. As the heat demand increases from summer to winter, the residual demand peak increases significantly. The main reason is the enormous electricity consumption caused by HPs in cold seasons. However, the residual demand peak in the scenario without the LEM increases more rapidly than that with the LEM. This is due to the randomness of prosumers' behavior for energy consumption if there is no LEM. There are no definite price incentives, and all household appliances operate simply following rule-based control, as shown in Fig. 6. This causes high residual demand peaks in winter. On the contrary, the LEM leads to relatively lower peak loads in winter. This effect is due to the price incentives in the LEM, causing HPs to run at times with PV power. In summer, the impact of the LEM is minimal owing to the lack of heat demand. The sufficient supply from PV generation allows for advantageous electricity prices within the LEM. During transition times, residual demand peaks suggest that the LEM is not fully capable of flattening the load profiles even when PV production and heat demand are both present.

In terms of self-consumption and collective self-consumption, the cases with the LEM outperform those without the LEM in transition time and winter, implying that the prosumers can reduce the feed-in power from PV generation by installing an HP. It reveals that the LEM can effectively reduce the energy surplus that needs to be fed into the local and external power grid. On the other hand, self-consumption and collective self-consumption are lower in summer. This indicates that no heat demand for SH negatively influences the advantages of the LEM.

To gain an overview of annual savings in different scenarios, an estimation of annual cost is made based on the average daily costs. The results are shown in Table 5. An added annual cost of 21 € can be seen in the transition into LEMs if there are no HPs installed. In contrast, a saving of 62 € is obtained if 40% of households have HPs.

The contribution of different households to the annual cost reduction are illustrated in Fig. 11. It shows the dominant role of HPs in achieving more profit in the LEM, although they account for a lower fraction of households in the district.

4.2. Daily demand charges

In this study, we propose the use of daily demand charges, as introduced in Section 2.4, to mitigate potential demand peaks that may occur at high levels of HP penetration. To evaluate the effectiveness of this measure, we conducted an additional case study with the same

Table 5
Average annual cost of four scenarios [€].

	HP (0%)		HP (40%)	
	Without LEM	With	Without LEM	With
Energy cost	269	239	439	389
Revenue	−17	−38	−15	−52
Balancing	0	72	0	59
Levies	484	484	791	758
Σ	735	756	1216	1154

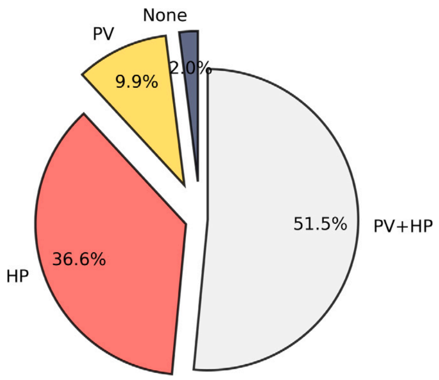


Fig. 11. Economic benefit distribution over different types of households.

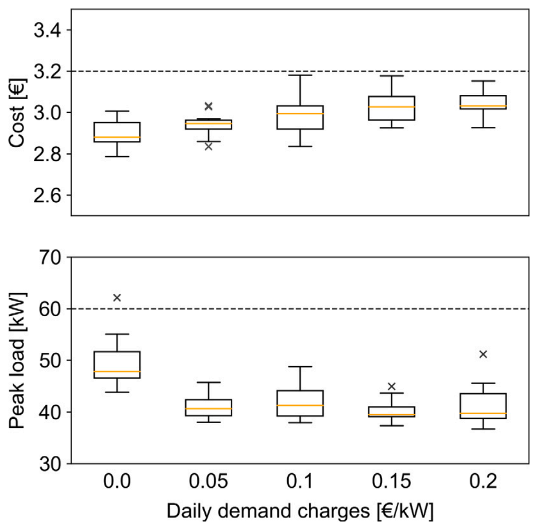


Fig. 12. Cost and peak load under different daily demand charges. The dashed lines indicate the benchmark from cases without the LEM.

basic configurations as in Section 4.1.5, except for fixing the season to transition time. For each variant of the daily demand charges, 20 cases were simulated to show the distribution. Fig. 12 illustrates the influence of the daily demand charges on the average cost and peak load.

A higher cost is observed when the daily demand charge increases from 0 €/kW up to 0.2 €/kW. As the daily demand charge increases, the MPC controller trades off electricity cost against the daily demand charge. On some occasions, it may result in lower overall costs to run flexible loads at times with higher prices than with lower prices. However, the effect of the daily demand charge on peak load quickly reaches its maximum. A noticeable 15% drop in peak load occurs as the daily demand charge increases from 0 €/kW to 0.05 €/kW. Beyond this range, additional increases in daily demand charges do not result in a further decrease in peak loads in the district.

The nodal pricing approach used in previous research imposes a cap on energy supply for a delivery interval without considering the individual energy demand of prosumers. As a result, prosumers who submit their bids earlier or at higher prices tend to secure electricity during network congestion, while others who are unable to secure enough energy face discomfort and financial losses. This may worsen the reliability of the LEM. Additionally, this approach could create competition among prosumers and drive up the price of traded electricity, thereby undermining the cost-saving potential associated with the LEM.

In contrast, the daily peak charges approach sets a clear objective for prosumers and encourages them to flatten their load profiles. As a result, prosumers can adjust their flexible loads through market agents and controllers from the beginning without the risk of electricity shortages that comes with power supply limitations. Furthermore, a low daily peak charge of 0.05 €/kW already results in a significant decrease of peak load, which translates to only 0.1 € extra cost per day per prosumer. Therefore, the daily peak charge approach is more cost-effective and reliable than the nodal pricing approach, making it a more feasible measure for mitigating power peaks within the LEM.

The proposed measure of daily peak charges can be replaced with a simple reward system, which can achieve similar results. In this reward system, prosumers receive economic rewards when their peak load is low. The reward gradually increases as the peak load decreases. The value of this reward would be calculated based on the savings in grid expansion costs that the prosumer achieves by reducing the peak load on the grid. In addition, these two measures can also be combined to enhance their effectiveness.

4.3. Parameter analysis

This section investigates the impact of various parameters on the daily average cost, aiming to identify opportunities for enhancing the benefits of a LEM through specific measures. The following parameters have been selected for investigation: thermal energy storage size, photovoltaic penetration, network charges, and forecasting method for electrical load. The remaining parameters will stay unchanged, as specified in Section 4.1.5, except for fixing the season to transition time.

Fig. 13 illustrates the influence of different parameters on the daily average cost. Oversizing the TES is anticipated to offer increased flexibility in operating HPs and reduce costs. However, due to the TES capacity being relatively small compared to the building's thermal mass and the seasonal variation in heat demand, its overall impact is considered negligible. Given the investment cost of TES, deploying larger TES units may not be economically viable.

Although higher PV penetration is expected to result in lower electricity prices and total costs for prosumers within the LEM, the scenarios with the LEM show similar performance to those without the LEM as the PV penetration increases. There are two reasons for this observation. Firstly, the surplus PV production cannot be fully utilized due to limited heat demand and storage capacity. Consequently, any excess PV energy must be sold to the retailer at a fixed rate of 1 cent/kWh, regardless of the presence of LEMs. Secondly, high PV penetration leads to increased balancing costs, which offset the marginal benefits introduced by the LEM.

The network charges, which are a component of levies, could be partially reduced when locally generated and consumed power does not rely on the transmission grid. This reduction is only possible with LEMs, as they can provide evidence of the energy source, whereas traditional electricity sales cannot achieve this. Assuming that network charges for the transmission grid account for 40% of the total network charges, the parameter analysis examines the effects of reducing this portion of network charges by 25% to 100%. The results indicate that even a 25% reduction can lead to a 63% increase in the economic benefits of LEMs. Furthermore, if the network charges for the transmission grid are completely eliminated, the daily average cost would decrease to 2.07 €.

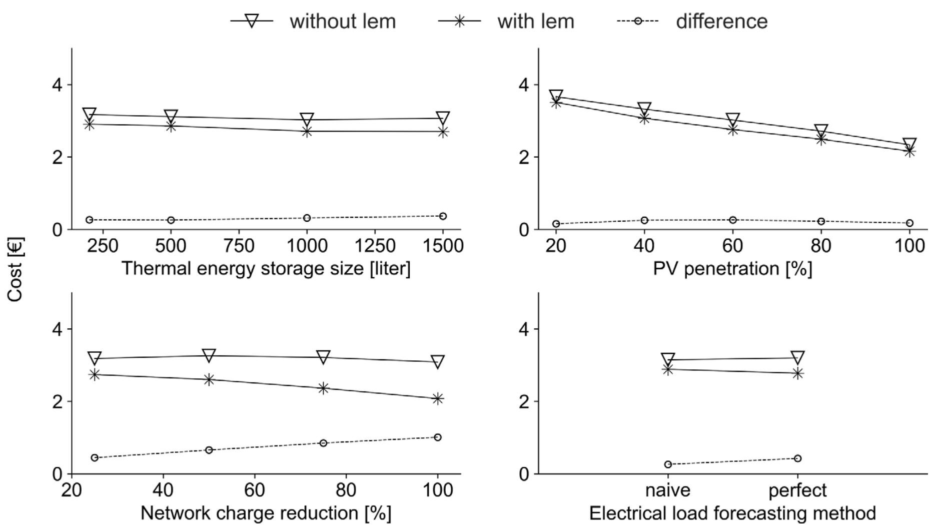


Fig. 13. Impacts of parameters on the average daily cost.

Regarding the forecasting method, its impact is evaluated by comparing the "naive" and "perfect" methods. In our study, the "naive" method is employed for predicting the electrical loads of households. In this case, the "perfect" forecasting method is utilized to assess its cost-saving benefits. By employing the "perfect" forecasting method, the additional balancing costs resulting from forecasting errors in electrical loads can be mitigated. The results indicate that the daily average cost has decreased from 2.89 € to 2.77 €, corresponding to a 72% reduction in balancing costs.

Based on the results of the parameter analysis, it is evident that oversizing the TES and increasing PV penetration do not lead to significant improvements in the economic benefits of LEMs. However, improving the accuracy of load forecasting can help mitigate balancing costs and result in a slight reduction in overall costs. The most influential factor is the reduction of network charges, which has the potential to significantly enhance the advantageous role of LEMs.

5. Discussion

5.1. Economic benefits of LEMs

LEMs can bring significant advantages in the form of attractive prices for local prosumers. With the ability to trade with other participants in the market, prosumers are no longer subject to the fixed price set by retailers and can often buy electricity at a lower price and sell it at a higher price. This can be particularly beneficial for HPs, which can take advantage of low electricity prices by using their flexibility. Furthermore, these economic incentives in LEMs have positive externalities, as it encourages market participants to leverage more flexible loads, which facilitate the efficient operation of the power grid and the seamless integration of renewable energy sources.

The results of our simulation study emphasize the economic benefits that can be achieved by implementing a LEM with a substantial integration of HPs. Our analysis reveals that with a 40% penetration level of HPs in the LEM, households can save an average of 62 € annually, corresponding to a 5.1% reduction in their overall annual costs.

The reduction in energy costs from 439 € to 389 € is one of the primary drivers of the cost savings. This highlights the key role of LEMs in enabling prosumers with HPs to optimize their energy consumption and lower their energy bills. Furthermore, the increase in revenue and the reduction of levies account for 31% and 27% of the total savings, respectively. These findings indicate that LEM implementation provides an efficient framework for prosumers to effectively manage their flexible loads and achieve cost reductions.

The results suggest that HPs play a key role in achieving cost savings through the LEM, acting as demand-side flexibility to leverage price advantages. When no HPs are installed for any prosumers, the LEM actually increases the annual cost by 21 € instead of resulting in 62 € savings. Furthermore, the findings indicate that prosumers with HPs contribute the most to the cost reduction associated with the LEM, with potential savings of up to 22% during the transition period.

The results of our study differ from previous research on the benefits of LEMs in optimizing the use of DERs, as we only observe a 5.1% reduction in overall annual costs. There are several reasons for this discrepancy. Firstly, our focus on HPs as flexibility resources may limit the potential economic benefits compared to studies that consider a wider range of DERs. Secondly, our analysis takes into account all cost types and seasonal effects, which may reduce the monetary advantages typically associated with LEMs. However, despite these factors, our results provide a more accurate reflection of LEM performance when HPs are the only flexibility resource being considered.

5.2. Problems faced by LEMs

Our study finds that although LEMs hold the potential for economic benefits, their wider utilization is limited by factors such as balancing costs, levies, seasonal variations, uneven distribution of benefits, and high residual demand peaks caused by a large number of HPs.

LEMs require prosumers to take responsibility for maintaining their own power balance, which can incur balancing costs in cases where there are disparities between their predicted electrical loads and the actual consumption, as well as between PV production and feed-in power. This differs from with conventional electricity sales, where prices are fixed and settled after consumption. Therefore, these balancing costs can potentially undermine the economic advantages of LEMs.

Apart from balancing costs, another significant factor contributing to the cost of LEMs is taxes and network charges, commonly referred to as levies. These charges constitute more than half of the overall costs in Germany and are influenced by the quantity of energy imported into the district. Increasing energy efficiency and promoting self-consumption can marginally alleviate these charges. However, the significant levies still undermine the relative cost savings obtained through LEMs. Despite achieving an 11.4% reduction in energy costs, the overall cost reduction is merely 5.1%. This considerable disparity diminishes the appeal of LEMs to potential market participants, highlighting the challenge of overcoming the burden imposed by levies.

The advantages of LEMs with high penetration of HPs exhibit seasonal variations, with the most significant benefits observed during transition periods when there is simultaneous PV power and heat demand. During these times, the cost savings are maximized. However, the economic benefits are reduced during summer months as there is limited heat demand, resulting in savings that are only half of those during transition periods. In winter, the absence of PV production results in higher electricity prices, leading to minimal economic benefits.

The benefits of LEMs are primarily experienced by users with flexible loads. As discussed in Section 4.1.4, prosumers who can adjust their electricity consumption based on market prices enjoy the majority of LEM benefits, while those without such flexibility do not reap as many advantages. Additionally, users with only PV, who play a crucial role in LEMs as distributed energy providers, often face discouragement from participating due to uncertainties in both consumption and production. These uncertainties lead to substantial expenses for balancing energy. Furthermore, the intense competition to sell PV electricity in LEMs, driven by the concentrated timing of solar supply, depresses selling prices and reduces profitability. The disparity in benefits over different types of households poses a significant challenge to the promotion of LEMs and limits their potential.

The substantial increase in the number of HPs can result in higher peak loads, which can pose a risk to the stability of the power system. Therefore, it is crucial for LEMs to effectively manage and mitigate residual demand peaks in order to maintain system stability and prevent grid congestion. However, the analysis conducted in Section 4 indicates that LEMs face challenges in achieving this goal, particularly during summer and transition periods. The primary reason for this is that prosumers often lack the motivation to flatten their own load profiles, which contributes to high residual demand peaks when aggregated. Furthermore, prosumers have a tendency to consume more electricity when prices are low, resulting in unexpected spikes in electrical demand. These spikes can be attributed to inaccurate price forecasts that fail to account for the over-reaction of prosumers as well as the current network congestion.

5.3. Regulatory framework for LEMs

A tailored regulatory framework should address the problems outlined in Section 5.2, ensuring fair financial gains for all market participants and promoting grid-serving behavior.

Mitigating balancing costs is important within LEMs. The imposition of penalties for power imbalances is necessary to prevent the misuse of electricity and ensure the normal operation of LEMs. However, it is reasonable to establish a threshold for penalizing power imbalances that takes into consideration the inherent uncertainties faced by small-scale prosumers. For instance, small power imbalances are not penalized, or imbalances in different directions could be balanced within a specific timeframe, such as on a daily basis. This approach would alleviate concerns among market participants. Furthermore, improving the accuracy of forecasting models can contribute to reducing balancing costs, as demonstrated in Section 4.3. By improving the precision of energy consumption predictions, prosumers can better anticipate their energy needs and make necessary adjustments accordingly. Therefore, new regulatory frameworks could offer financial support to incentivize the integration of advanced forecasting models within LEMs.

Lowering levies within LEMs can bring advantages for all participants. Levies currently encompass more than half of the overall costs, thereby diminishing the market's ability to offer competitive prices. Specifically, network charges, which constitute approximately 40% of the levies, could be minimized by avoiding transmission fees when locally generated electricity is consumed. This possibility arises from the fact that LEMs present a viable approach to determining the local origin of electricity, as all market participants are situated within the same district. In fact, Germany previously implemented comparable regulations referred to as "avoided network charges" to incentivize self-generation of electricity prior to 2023.

Considering the seasonal variations of HPs' flexibility, it becomes evident that relying solely on HPs as flexibility resources may not fully leverage the advantages of LEMs throughout the year. Hence, HPs require complementary flexibility from other sources, such as electric vehicles, batteries, and combined heat and power systems. Additionally, to ensure the comprehensive coverage of local energy supply within LEMs, there should be alternatives to PV production, such as small-scale wind or hydro power plants. Overall, the diversity of DERs must be considered for the further development of LEMs.

Regarding the allocation of economic benefits, it is reasonable to provide prosumers with flexible devices with greater opportunities for cost savings. This serves as a positive incentive and encourages the adoption of flexible devices such as HPs or home batteries to maximize the benefits of LEMs. However, households which solely rely on PV systems may not be satisfied with market trading since their earnings are not guaranteed. Therefore, the new regulations need to encourage and fund PV users to install more flexible loads or batteries, allowing them to obtain greater advantages from participating in LEMs.

To address high demand peaks, LEMs can benefit from additional measures within the regulatory framework, such as the implementation of daily demand charges, as proposed in Section 4.2. These charges serve as incentives for prosumers to flatten their individual load profiles, independent of the behavior of others. This proactive approach results in a significant reduction of up to 20% in residual demand peaks. The daily demand charges paid by prosumers could be rewarded to those with lower demand peaks, making the total cost neutral and encouraging grid-serving behaviors. This approach can utilize the flexibility provided by residential HPs, while addressing the risks associated with their growth.

6. Limitations

Simulation studies have limitations, such as potential inaccuracies and assumptions made in the model, which cannot entirely replace real-world situations. This study is further limited by the LEM specifications with a future market design without separate day-ahead and intraday markets, which may not represent all types of LEMs or peer-to-peer markets. Additionally, the study is limited by the lack of intelligence in the bidding strategy of prosumers, as they are not able to learn and adapt over time, which could have affected the results.

The study does not compare the performance of LEMs to demand response programs or direct control approaches because the real benefit and cost of these measures to leverage the flexibility of HPs are not only sensitive to different inputs but also difficult to determine. Furthermore, these measures are often applied in different situations, making it impossible to make direct comparisons.

7. Conclusion and future work

This paper addresses the research gap exploring the flexibility potential of residential HPs within LEMs and proposes a methodology to model a LEM with double-sided auctions, considering detailed modeling of energy devices, control strategies, and forecast errors. The paper compares the performance of the LEM with a benchmark scenario without the LEM given a large number of HPs and analyzes the impact of the flexibility of HPs on the LEM across different seasons. The study also proposes daily demand charges to reduce the residual demand peak in the LEM and conducts a parameter analysis to identify important factors that affect the LEM.

The key findings of this work are: (i) LEMs can provide economic benefits to households, leading to an annual cost savings of 5.1% if 40% of households have HPs, (ii) balancing costs and levies (taxes and network charges) constitute approximately 70% of total costs, and mitigating these costs is crucial to enhance the economic advantages derived from LEMs, (iii) the benefits of LEMs exhibit seasonal variations when considering only PV and HPs, and the largest benefits occur during transition times, while winter has no economic benefits, (iv) LEM benefits are primarily experienced by users with HPs (>85%), which would discourage other users from participating, (v) the regulatory framework needs to be revised to address issues such as high balancing costs, levies, seasonal variations, uneven distribution of benefits, and high residual demand peaks caused by a large number of HPs.

Future research could incorporate additional price factors, such as the investment cost for HPs and the savings achieved through reduced grid expansion, to determine the optimal penetration level of HPs in the future. In addition, it is worthwhile to examine the effectiveness of incorporating the states of the power grid into the price formation process in the LEM to prevent grid congestion. Furthermore, it would be important to verify the efficacy of the proposed regulatory framework in enhancing the financial gains of LEMs and reducing power grid stress.

CRediT authorship contribution statement

Zhengjie You: Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sebastian Dirk Lumpp:** Methodology, Software. **Markus Doepfert:** Software, Writing – review & editing. **Peter Tzscheutschler:** Funding acquisition. **Christoph Goebel:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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3.2 Quantification of flexibility for small-scale flexibility trading

Scientific context

HP usage is anticipated to increase for energy consumption in Europe [40, 65]. Meanwhile, local flexibility markets in Germany have emerged as an innovative solution to manage the challenges brought by the increasing use of renewable energy sources [37]. A local flexibility market is a concept where flexibility can be provided and traded as ancillary services, allowing active participation of energy consumers. This market facilitates economically efficient trading of flexibility among end users and ISOs, which contributes to flexibility provision. Therefore, it becomes meaningful to to investigate how to effectively provide ancillary services of HPs in local flexibility markets [66].

To achieve the purpose, the flexibility of HPs should be quantified as bids submitted to local flexibility markets. Several studies in this field have contributed to quantification of HP flexibility. Research papers have explored the potential of HPs in demand-side management, particularly emphasizing their efficiency in peak shaving and ensuring thermal comfort [67, 68]. Similarly, studies like [39, 69] have developed a process for generating flexible offers from HPs and other household devices, integrating these into a comprehensive model. The importance of optimal control to maximize the flexibility of building energy systems is highlighted in [40, 70], with a specific focus on using building datasets for optimization and dynamic simulations. Additionally, the feasibility of flexibility provision by HPs is assessed using a modified optimal power flow method, as discussed in [71]. Case studies, such as those in [41, 72], delve into the impact of aggregating HPs and the uncertainties in forecasts and building parameters, underscoring the benefits of including domestic hot water demand in optimization models. Finally, the critical role of TES in offering flexibility, especially in buildings with volatile electricity supply, is emphasized in studies like [40, 71, 73, 74].

Existing studies have focused on measuring flexibility by examining how buildings or household appliances respond to top-down control signals [39, 40, 41]. This approach, however, offers a broad, macroscopic perspective of flexibility quantification which does not align with the concept of ancillary service provision. In addition, the approach by [75] for providing flexibility rely on long-term contracts, which usually lead to uniform profits of all participants, reducing their willingness to participate actively. Furthermore, there's a notable gap in research regarding methods for quantifying market-ready flexibility, specifically adapted to local flexibility markets. Another underexplored area, mentioned in [42], is the impact of flexibility provision on user comfort, particularly in the context of the unpredictable nature of domestic hot water consumption.

To address the identified research gaps, this paper introduces a novel methodology for quantifying the flexibility of residential HPs, specifically tailored for providing ancillary services in local flexibility markets. This methodology incorporates a capacity reservation method to maintain user comfort. Consequently, this innovative approach not only enhances the understanding of how to quantify flexibility but also facilitates the integration of HP flexibility by enabling the provision of ancillary services in local flexibility markets.

Contribution

This paper introduces an advanced approach to quantifying the flexibility of HPs, with a focus on the necessary technical limitations for optimal operation and flexibility provision. It establishes the concept of decentralized flexibility management, enabling flexumers to effectively control and utilize the flexibility of residential HPs. A key element of this study is the detailed analysis of technical constraints in flexibility provision, considering factors such as switch points, the remaining capacity of TES and available regeneration time. Depending on the pricing strategy, potential revenues from flexibility trading could be about 10% of the original electricity prices, equivalent to roughly 3 cents per kWh of provided flexibility [76]. The research also explores the impact of flexibility provision on end-user thermal comfort, an area not extensively studied before. It proposes a solution - capacity reservation - to tackle the unpredictability of domestic hot water consumption, a frequent issue in home energy management systems. Simulation results validate this approach, showing minimal user discomfort with an average of only 2.5 minutes of unsatisfactory time per day and a maximum temperature decrease of no more than 2.3 °C. These outcomes are significant as they illustrate the practicality of maintaining thermal comfort while providing flexibility in energy use.

Additionally, this method supports day-ahead flexibility trading in local flexibility markets, a vital feature to meet the future needs of these markets and to boost end users' acceptance by minimizing the discomfort associated with flexibility provision. This approach has broad implications, contributing to the long-term energy transition by facilitating the integration of renewable energy into the grid.

To enhance accessibility and practical application, the paper includes all models and algorithms in an open-source tool, OpenTUMFlex [77]. This tool helps researchers and stakeholders in applying these techniques in areas like HEMS and the development of local flexibility markets and power grid.

In summary, this paper not only fills existing research gaps but also paves the way for future developments in managing and utilizing residential energy flexibility for flexibility trading.

Flexibility Estimation of Residential Heat Pumps under Heat Demand Uncertainty

Authors Zhengjie You, Michel Zade, Babu Kumaran Nalini, Peter Tzscheutschler

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Open-source repository the data and models that support the findings of this study are openly available in OpenTUMFlex.

Author contributions

Zhengjie You:	75 %	Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Validation, Writing - Original draft, Writing - review and editing.
Michel Zade:	10 %	Software, Writing - review and editing.
Babu Kumaran Nalini:	5 %	Software.
Peter Tzscheutschler:	10 %	Formal analysis, Funding acquisition, Project administration, Supervision, Writing - review and editing.

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Article

Flexibility Estimation of Residential Heat Pumps under Heat Demand Uncertainty

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Abstract: With the increasing penetration of intermittent renewable energy generation, there is a growing demand to use the inherent flexibility within buildings to absorb renewable related disruptions. Heat pumps play a particularly important role, as they account for a high share of electricity consumption in residential units. The most common way of quantifying the flexibility is by considering the response of the building or the household appliances to external penalty signals. However, this approach neither accounts for the use cases of flexibility trading nor considers its impact on the prosumer comfort, when the heat pump should cover the stochastic domestic hot water (DHW) consumption. Therefore, in this paper, a new approach to quantifying the flexibility potential of residential heat pumps is proposed. This methodology enables the prosumers themselves to generate and submit the operating plan of the heat pump to the system operator and trade the alternative operating plans of the heat pump on the flexibility market. In addition, the impact of the flexibility provision on the prosumer comfort is investigated by calculating the warm water temperature drops in the thermal energy storage given heat demand forecast errors. The results show that the approach with constant capacity reservation in the thermal energy storage provides the best solution, with an average of 2.5 min unsatisfactory time per day and a maximum temperature drop of 2.3 °C.

Keywords: heat pump flexibility; demand-side response; energy management; optimization; forecast uncertainty; comfort loss

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1. Introduction

With the penetration of intermittent and fluctuating renewable energy generation positioned to increase in the coming years, there is a growing need for low-cost and practical Ancillary Services (AS) to absorb the renewable related imbalance between generation and demand [1]. Demand Response (DR), the ability to control electrical energy consumption based on power grid incentives, is emerging as a low-cost alternative to conventional fast-ramping generation resources [2]. Additionally, the study in [3] foresees that a complete electrification of the heating sector will eventually lead the heat pumps' demand to reach 26% of the total electricity consumption in Europe. This places the heat pump dominant in the field of DR. Furthermore, the study in [4] has proved that energy savings of up to 80% can be achieved with the implementation of an optimal control of the HVAC with heat pumps. Therefore, special attention has been given to exploiting the applications associated with heat pumps.

In the literature, several works deal with the assessment of the flexibility given by building energy management systems. In [5], flexibility potential could be quantified by generating deviation from the optimal plan by adjusting the objective function with regard to energy consumption (low or high) solely in the timespan of flexibility. Meanwhile, it used a cost curve to present the additional associated costs. Similarly, another study performed simulations with a diversified thermostat set point of buildings to develop a novel demand response estimation framework [2]. In addition, the authors have performed a multi-agent-based simulation of three building cluster types and studied the impact of the available flexibility on the residual substation load. Although a high penetration of heat pumps and photovoltaic systems can violate the transformer's limits, a significant improvement in the substation load can still be seen with the help of the Demand Side Management [6]. Moreover, it has been found that the flexibility of a building energy system is difficult to quantify using a single flexibility indicator. Therefore, the authors have proposed that flexibility needs to be evaluated in three dimensions: time, power and energy [7]. In addition, the key factors affecting the flexibility potential have been investigated over the last three years. In general, the flexibility available is affected by penalty signals, ambient temperature and the operations of the energy storage [8–10].

In particular, a number of studies have developed models to estimate the flexibility potential of the heat pump. The authors in [11,12] have provided an overview of the possible Demand Side Management applications in the field of heat pumps and evaluated its efficiency in providing peak shaving and thermal comfort. In [13,14], a generic flexible offer generation and evaluation process that extracts flexibility from heat pumps and other household devices is presented and incorporated in a unified model. As indicated in [1,15], an optimal control is imperative to obtain the maximum flexibility provided by a building's energy system. An approach has been proposed that allows for the various available building datasets to be relied on to build the models required for optimization tools or dynamic simulations [15]. In addition, an approach to estimate the time-dependent flexibility potential of a heat pump system is proposed. It used a modified Optimal Power Flow (OPF) to evaluate the feasibility of the flexibility provision [16]. Furthermore, case studies have been performed to investigate the impact of the aggregation of heat pumps and uncertainties inherent in forecasts and building parameters [17,18]. It is revealed that it is beneficial to include domestic hot water (DHW) demand within the optimization model to deal with the high unpredictability of the DHW consumption. However, uncertainty in building parameters does not have a significant impact on the optimization of heat pump operation. In contrast, Thermal Energy Storage (TES) is essential to offer flexibility in the heat pump system, as indicated in [1,5,16]. Through active management and suitable scheduling schemes of the HP and the TES, it is possible to provide flexibility for the power system through sustainable energy buildings where the electricity supply is highly volatile [19].

For the provision of flexibility, the aforementioned research has mainly focused on the centralized coordination of controllable household devices. Meanwhile, the German government has used various support measures to continuously adapt flexibility provision to market developments [20]. A flexibility market is a concept for the utilization of flexibility, their efficient use and the assurance of a coordinated call-off [21,22]. Instead of passive participation, energy consumers have higher flexibility to enable a market supply that meets market conditions. In addition, the flexibility market allows for a "cellular" approach, where the flexibility requirements are determined on the scale of individual units, rather than a top-down approach based on an aggregate calculation of expected demand and supply [20]. Moreover, local flexibility markets enable an economically efficient solution to trade flexibility among distribution system operators and other participants (e.g., aggregators). This will incentivize the flexibility provision [23,24].

Although many studies have proposed methods to quantify flexibility, they tend to look at the response of the building or household appliances to external control signals from the top down. This means these approaches estimate flexibility only from a macroscopic perspective [1,13,17]. In addition, uniform prices and contracts for all flexibility provider will hurt their motivation to actively participate in the flexibility provision [25]. However, few studies have focused on the development of a tool to quantify the tradable flexibility to address future needs regarding flexibility markets and considered the benefits of using flexibility for prosumers. Moreover, user comfort may be affected by providing flexibility due to the unpredictability of DHW consumption [9]. However, this has not been discussed very much to date.

This paper aims to find a simple yet effective method to quantify the flexibility of domestic heat pumps without affecting the user comfort, while covering the gaps mentioned in the previous paragraph. Unlike the demand response approaches that consider mainly the reaction of residential units to external signals, the methodology in this paper quantifies the flexibility of residential heat pumps based on the optimized operating plan and the state of the TES and describes the flexibility in form of flexibility power and energy for each time block. This nature enables the day-ahead trading on the flexibility market. Furthermore, the capacity reservation in thermal energy storage is implemented to avoid the negative impact of flexibility utilization on the prosumer comfort. It is expected that the warm water temperature in the TES can be maintained above the set point at all times. To validate this concept, a forecast-simulation methodology has been used to test its effectiveness in dealing with the unpredictability of DHW consumption.

This paper is structured as follows. Section 2 provides the mathematical models applied to represent the heating and electrical system as well as the optimization algorithm. Section 3 introduces the methodology used to estimate the flexibility potential of heat pumps in three steps. Furthermore, a number of solutions to deal with the DHW consumption's randomness is discussed in Section 4. Section 5 presents and discusses the obtained results, while Section 6 discuss the main findings and conclude the paper, respectively.

2. Modeling and Optimization

In this section, the modeling approaches of the heating system and the optimization algorithm using Mixed Integer Linear Programming (MILP) are introduced. All modeling and calculations processes are carried out in the framework of open-source software OpenTUMFlex. For more information, please refer to Supplementary Materials [26].

Figure 1 shows the general steps involved in flexibility generation. The flexibility estimation process begins with the gathering of the heat demand time series and available context information such as the technical parameters of the heat pump, electricity prices, etc. The next step includes the preprocessing of the raw information into an adequate format for analysis. The main steps include modeling the heating system required for the generation of the optimal operating plans. Subsequently, the solver integrated in OpenTUMFlex performs process scheduling and finds an optimal operating plan for the heat pump. Finally, the flexibility estimation step includes the derivation of new operating plan for the heat pump and the calculation of flexibility power and energy with regard to necessary technical restrictions. The last two steps visualize the flexibility power and energy in a graphical and table form and statistically evaluate the impact of unpredictable DHW consumption on prosumer comfort.

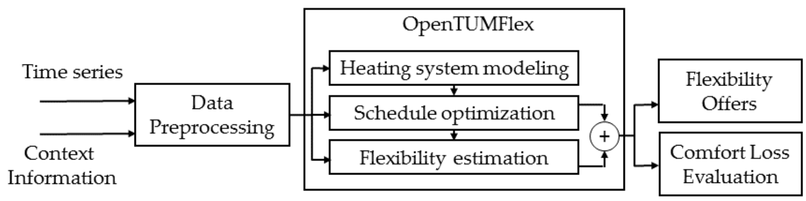


Figure 1. The general flexibility quantification process of the heat pump in OpenTUMFlex.

2.1. Models

The model used to represent the heating system consist of two main components: the HP, which generates heat, fulfilling the demands, and the TES, which serves as a buffer to avoid the simultaneity of generation and consumption.

2.1.1. Heat Pump

The heat pump is a component that uses electricity to generate heat. The ratio between the generated heat and electrical power is the Coefficient of Performance (COP). Mathematically, it can be described as follows:

$$COP = \frac{Q^{HP}}{W^{HP}} \tag{1}$$

Here, Q^{HP} and W^{HP} represent the heat flow and electrical power. The higher the COP, the more efficient the heat pump. In this paper, ground-source heat pumps (GSHP) are considered. Their COP can be influenced by many factors. For GSHP, the COP is mainly affected by ground temperature and the supply temperature of warm water. To ensure the linearity of the model, the ground temperature and the supply temperature of the HP are set as parameters for each simulation. Based on the experimental data of the heat pump (Stiebel Eltron), the COP curve can be derived using the following formula:

$$\Delta T = T_s - T_{env} \tag{2}$$

$$COP = 0.0002\Delta T^2 - 0.07\Delta T + 5.67 \tag{3}$$

$$Q^{HP}_{therm}[\text{kW}] = 0.1916 T_{env}[^\circ\text{C}] + 6.4 \tag{4}$$

where T_s and T_{env} are the supply and ground temperature, respectively. Q^{HP}_{therm} is the thermal power of the heat pump depending on the ambient temperature, given an average supply temperature of 60 °C. With regard to the operational behavior of the heat pump, it is assumed the HP has two working states without any modulation: on/off. Thus, a binary variable is used to describe the state of the heat pump operation:

$$Q^{HP}_t = x^{HP}_t Q^{HP}_{therm,t} \tag{5}$$

$$W^{HP}_t = \frac{Q^{HP}_t}{COP_t} \tag{6}$$

In this equation, x^{HP}_t is the binary variable indicating the operational state of heat pump at a certain time step. The electrical power consumed W^{HP}_t can then be calculated by Equation (6).

There are also constraints avoiding the frequent switch on/off, which keeps the HP off for $N_{min,off}$ time steps once it is turned off and the heat pump on for $N_{min,on}$ time steps once it is turned on, as indicated in Equations (7) and (8). In this article, $N_{min,off}$ and $N_{min,on}$ are both set to 4, which means 1-hour minimum duration for switch on/off given each time step of 15 min.

$$(x^{HP}_{t-1} - x^{HP}_t) \cdot N_{min,off} \leq T_{min,off} - (x^{HP}_t + x^{HP}_{t+1} + ... + x^{HP}_{t+N_{min,off}-1}) \tag{7}$$

$$(x^{HP}_{t-1} - x^{HP}_t) \cdot N_{min,on} \leq x^{HP}_t + x^{HP}_{t+1} + ... + x^{HP}_{t+N_{min,off}-1} \tag{8}$$

2.1.2. Thermal Energy Storage

To provide flexibility and fulfill DHW and Space Heating (SH) demand, a heat storage with a spiral-tube heat exchange will be used. The combined storage consists of an internal heat exchanger to separate fresh water and heating water.

$$E^{TES}_t = E^{TES}_{t-1} + (Q^{HP}_t - Q^{SH}_t - Q^{DHW}_t) \cdot \Delta t \tag{9}$$

$$SOC_t = \frac{E^{TES}_t}{E^{TES}_{cap}} \tag{10}$$

$$T^{TES}_t = (T^{TES}_{max} - T^{TES}_{min}) SOC_t + T^{TES}_{min} \tag{11}$$

where E_t^{TES} is the energy stored in the TES, while Q_t^{SH} and Q_t^{DHW} are the heat load of SH and DHW, respectively. Meanwhile, the State of Charge (SOC) is the level of charge relative to its capacity. The warm water temperature in the TES can be estimated by Equation (11), given that the TES is perfectly mixed.

2.2. Heating System

2.2.1. Heat Load

The heat load consists of SH and DHW. The heat load profiles for SH are derived based on the Hotmaps Project database, which is part of the Horizon 2020 Projects. The datasets have a temporal resolution of 1 h [27]. The year-specific profiles, generated based on the synthetic hourly profiles for typical days, are used for further simulation.

Regarding the region of NUTS2, DE21 (Upper Bavaria) was selected as the region where the case study was conducted. The specific heat demand refers to standard WSVO 95, which indicates a value of $100\,\mathrm{kWh}/(\mathrm{m}^2 \cdot \mathrm{a})$. The heating area is assumed to be 140 m^2.

As the yearly heat demand profiles only offer a temporal resolution of 1 h and the normal time-step of flexibility estimation in OpenTUMFlex is 15 min, the heat demand of 1 h will be distributed linearly.

The software, DHWcalc, can provide the DHW consumption data. This model uses four categories of DHW to describe different DHW use patterns [28]. Each category has a specific occurrence probability and flow rate probability distribution. The assumptions applied in [28] have been used in this study as well and are shown in Table 1:

Table 1. Categories of DHW consumption patterns.

Category	Average Flow Rate (L/min)	Sigma (L/min)	Duration (min)	Portion (%)
short load	1	2	1	14
medium load	6	2	1	36
bath	14	2	10	10
shower	8	2	5	40

Where average flow rate $\dot{V}_{mean}$ is the expectation of the distribution and sigma σ is the standard deviation. Duration and portion are the assumed flow duration and share of flow amount for each flow type, respectively.

According to the parameters given in Table 1 and the assumption of gaussian-distribution, The probability of occurrence of each category of flow can be obtained by Equation (12):

$$P(\dot{V}) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(\dot{V}-\dot{V}_{mean})^2}{2\sigma^2}} \tag{12}$$

2.2.2. Assumption for Heating System

Considering the conclusion of [5], the thermal characteristics of the building are neglected and the static heat load from Section 2.2.1 is implemented to represent the SH load of the household. Therefore, a constant room temperature is assumed inside the house. This implies that the thermal inertia of the building is not taken into account to offer flexibility. These assumptions avoid exhausting the flexibility potential with regard to the thermal inertia of the building and can be treated as a buffering mechanism for possible comfort losses.

The supply temperature out of the heat pump was assumed as 60 °C, which avoids sanitary problems n DHW and increases the maximum heat capacity of the TES. A conventional heat pump cannot reach a supply temperature of 60 °C without a severe efficiency drop. Thus, for a higher supply temperature, a medium-temperature heat pump was considered. The reference and maximum temperature of the TES was set as 40 °C and 60 °C, which indicates that the SOC of the thermal energy storage is 0% and 100%, when the warm water inside is uniformly 40 °C and 60 °C, respectively. The TES was assumed to be perfectly mixed to make it possible to quantify the comfort loss without an enormous calculation burden.

As the time resolution of the software DHWcalc was set up at 1 min to describe each type of draw-off, it does not fit the 15-min time interval in OpenTUMFlex. Therefore, the DHW heat demand calculated from DHWcalc will be averaged into a 15 min time interval to suit the formats in OpenTUMFlex. Regarding the DHW consumption forecasts, a naive forecasting method was implemented by averaging the last 30-days' historic data. Subsequently, the thermal energy consumption within each time step can be obtained by integrating the required heating power. Based on the TES capacity, the required minimum SOC can be obtained for each time step. The minimum SOC considers both the trivial SH heat load and the possible extremely high DHW consumption that has occurred in the last 30 days. Therefore, the TES, with this minimum SOC, is capable of fulfilling the SH and DHW heat load simultaneously, even when forecast errors of DHW consumption occur. Repeating this process for all time steps, the minimum SOC curve for the TES with 600 L volume and 20 °C temperature spread can be estimated as the "min", as shown in Figure 2. In addition, the heat loads of SH and DHW are shown as well.

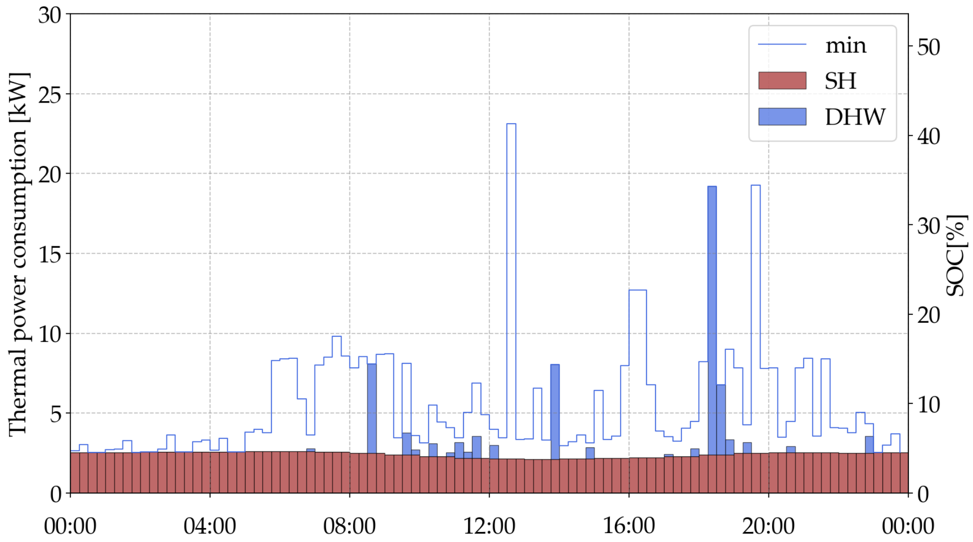


Figure 2. Load profiles for SH and DHW in winter and the minimum SOC requirement.

2.3. Optimization

This section presents an optimization algorithm to coordinate the operations of all main household appliances. The objective of the optimization is to find a cost-optimal schedule of each appliance while fulfilling all the constraints. In general, theses components are considered in the HEMS: Electric Vehicle (EV), Photovoltaic (PV), Battery (BAT) and Heat Pump (HP). The other electrical and heat loads are treated as inflexible loads.

With regard to electricity balance, the sum of electrical generation and consumption must be equal. The relationship can be represented by Equation (13)

$$P_t^{PV} + P_t^{Grid,in} + P_t^{BAT,disc} = P_t^{HP} + P_t^{EV} + P_t^{Bat,char} + P_t^{Grid,out} + P_t^{Load} \tag{13}$$

where power generation of each type is placed on the left side and power consumption on the right side. P_t^{PV}, P_t^{HP} and P_t^{EV} are the electrical powers consumed by PV, HP and EV, respectively. $P_t^{Grid,in}$ and $P_t^{Grid,out}$ indicate the power import and export with the grid. $P_t^{Bat,char}$ and $P_t^{Bat,disc}$ represent the charging and discharging power of the battery. Charging and discharging cannot occur at the same time. P_t^{Load} is the inflexible load of the household.

Similar to the electricity balance, the heat balance is constructed in the same way, such that the thermal generation and consumption must be equal:

$$Q_t^{HP} + Q_t^{TES,disc} = Q_t^{Load} + Q_t^{TES,char} \tag{14}$$

On the left side of this Equation (14) is the thermal power of each heat generating device, including the discharging power of the TES, while the heat load Q_t^{Load} and the charging power of the TES $Q_t^{TES,char}$ is positioned on the right side.

For the TES, the optimal end SOC should be determined by extending the original simulation time horizon. For instance, a 1.5-day simulation will be carried out first and the SOC of the time point at 24 h will be used as the optimal end SOC for the next 1-day simulation. To decrease the required computation time, the end SOC must be greater than the optimal end SOC [29].

According to the constraints and the models, the solver can minimize the total energy cost by scheduling the operation plan of each household appliance. The costs mainly cover the fuel and electricity cost, which is dependent on the gas and electricity prices. Thus, the objective function for this model can be formulated by Equation (15):

$$\min_{P_t, Q_t} \sum_t \frac{Q_t^{Boiler}}{\eta^{Boiler}} \cdot c_t^{Gas} + (P_t^{Grid,in} - P_t^{Grid,out}) \cdot c_t^{Elec} \tag{15}$$

where c_t^{Gas} and c_t^{Elec} are the predicted gas price and electricity price, respectively. Based on the objective function, the solver will determine the optimal operation time of each household appliance.

Since the objective function is linear and integer variables are utilized to represent the operational states of the HP, this optimization problem can be categorized as Mixed Integer Linear Programming (MILP), which can be easily solved by matured solvers (Cplex, GLPK or Gurobi) within several minutes when the optimization is within 24 time steps. Figure 3 shows an example of the optimization results.

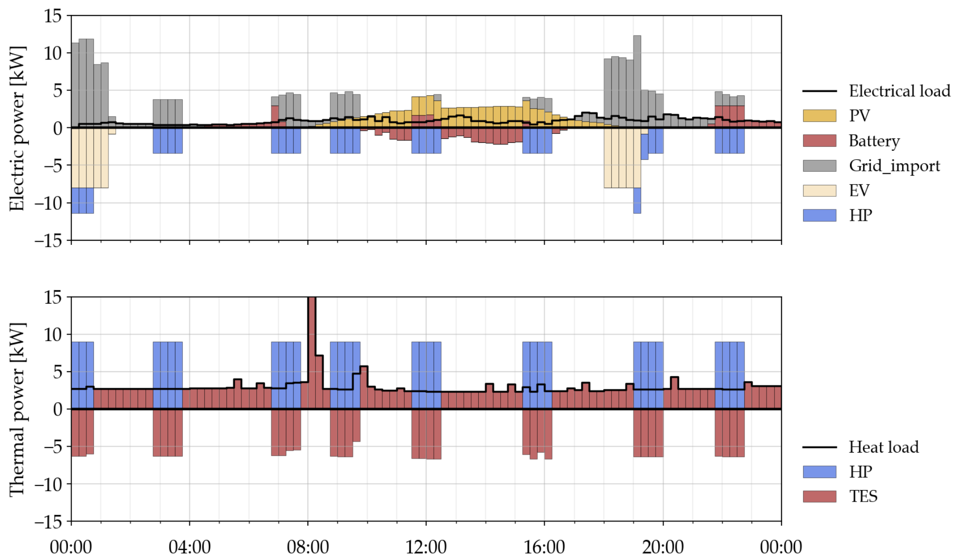


Figure 3. Optimization results of household appliances: electric and thermal power balance.

3. Flexibility Estimation

In this section, specific methods to estimate flexibility are introduced. Flexibility of the heat pump can be regarded as the possibility of shifting the HP operation during the day. Based on the optimal operation plan of the HP, potential deviations can be offered at each time step. They are distinguished into two types. Positive flexibility means turning off the HP in situations where it would otherwise run, while positive flexibility indicates that the heat pump is forced on when it would usually be turned off. The flexibility provision is not arbitrary and requires many restrictions. They are usually divided into three types:

- Switch point;
- Remaining capacity of thermal storage system;
- Available regeneration time.

The first restriction implies that the flexibility can only be offered until the next switch point. As Figure 4 illustrates, positive flexibility can only be provided when the heat pump is on, as it cannot reduce the electrical load by changing the operation of the heat pump when it is already off. Thus, positive flexibility can hold up until the next switch point. In contrast, negative flexibility is available when the HP is off. Therefore, the duration limit of flexibility regarding the first restriction can be formulated by Equation (16):

$$T^{sw}_{Flex,t} = t_{s,t} - t \tag{16}$$

Here, $t_{s,t}$ is the time step number until the next switch point, while t is the time step by which the flexibility potential is estimated.

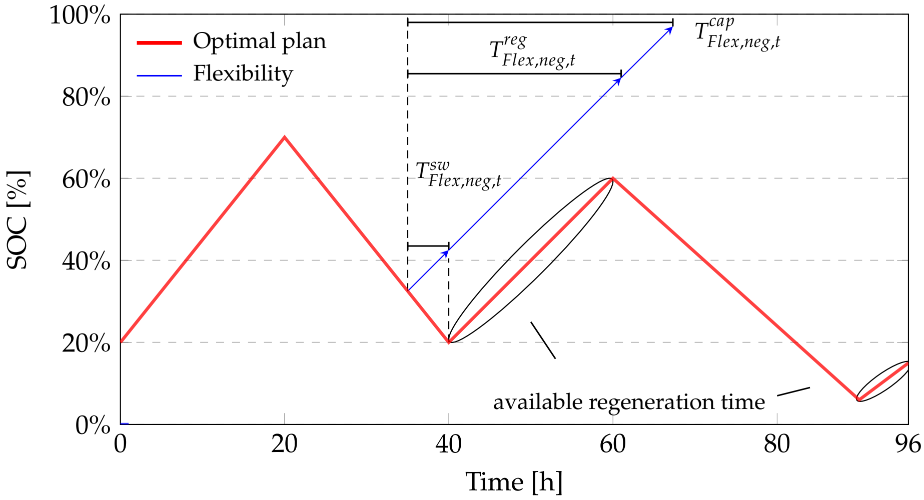


Figure 4. Restrictions with regard to flexibility estimation: switch time, capacity and regeneration time.

Another restriction is the remaining capacity of the TES, because the heat pump cannot keep charging or discharging when the thermal storage is full or empty. With regard to positive or negative flexibility, the duration limit can be obtained by Equations (17) and (18), respectively:

$$T^{cap}_{flex,pos,t} = \frac{SOC^{TES}_t \cdot E^{TES}_{cap}}{(Q^{HP}_{avg} + Q^{load}_{avg}) \cdot \Delta t} \tag{17}$$

$$T^{cap}_{flex,neg,t} = \frac{(1 - SOC^{TES}_t) \cdot E^{TES}_{cap}}{(Q^{HP}_{avg} - Q^{load}_{avg}) \cdot \Delta t} \tag{18}$$

where Q^{HP}_{avg} and Q^{load}_{avg} is the average thermal power of the heat pump and heat load within next two hours, which is the typical duration of HP flexibility. With respect to positive flexibility, the duration limit indicates how many time steps the TES can afford without the heat supply from the heat pump. Negative flexibility, however, requires a low SOC of the TES. The higher the SOC, the smaller the remaining space for excessive heat generated from the HP. Therefore, the remaining capacity of the TES is used to calculate the flexibility duration limit of negative flexibility.

After delivering the flexibility, the system states will change and the original schedule for the time becomes infeasible. Hence, the operation plans for each devices need reoptimization during the interval from the flexibility duration termination to the end of one day. The reoptimization aims to realize the same system states at the end of the day as the original plan, such as the SOCs of TES. Therefore, it is imperative to generate enough time steps for the regeneration of TES. Following the positive flexibility provision, the thermal energy stored in TES decreases and more charging time is needed afterwards for the heat pump to produce heat, so that it can nearly reach optimal SOC in the end. The same is true for negative flexibility: if the remaining available regeneration time is insufficient to consume the additional thermal energy that is generated, the SOC of the TES will exceed the required amount by too much. As a consequence, the duration of flexibility with respect to the available regeneration time is restricted by Equations (19) and (20), in the timestep number.

$$T^{reg}_{flex,pos,t} = \sum_{t=t_f+1}^{t_e} [Q^{HP}_t = 0] \tag{19}$$

$$T^{reg}_{flex,neg,t} = \sum_{t=t_f+1}^{t_e} [Q^{HP}_t > 0] \tag{20}$$

where t_f and t_e are the last timestep of the delivered flexibility and the whole timespan. Here, the Iverson Brackets, which take the value 1, for which the statement is true, are used to count the the number of suitable timesteps.

As all the three types of restrictions for the flexibility duration are already known, the final flexibility durations have to satisfy all of the above, so the minimum of these values is taken:

$$T^{HP}_{flex,t} = min(T^{sw}_{flex,t}, T^{cap}_{flex,t}, T^{reg}_{flex,t}) \tag{21}$$

According to the flexibility duration, the flexibility power and energy, which are the average power and the total energy delivered within the flexibility, can be obtained by Equations (22) and (23):

$$P^{HP}_{flex,avg,t} = \frac{\sum_t^{t_f} P^{HP}_t}{T^{HP}_{flex,t}} \tag{22}$$

$$E^{HP}_{flex,t} = P^{HP}_{flex,t} \cdot T^{HP}_{flex,t} \cdot \Delta t \tag{23}$$

The flexibility power indicates how much power deviation controlling of the heat pump can provide and the flexibility energy is the integral of the flexibility power within the flexibility duration. This flexibility estimation process will iterate for every timestep being considered, and acquire flexibility for the whole interval.

4. Methods Dealing with Stochastic Characteristic of Hot Water Consumption

4.1. Reservation of Minimum SOC

Since the day-ahead forecast of the heat load of SH is accurate enough, its forecast error can be neglected. However, the heat load of DHW is strongly affected by the user behavior and reflects an obviously stochastic characteristic, especially at the level of a single residential unit. Consequently, unexpected situations could occur while delivering the flexibility of heat pump, e.g., the temperature of warm water inside is not sufficient for trivial usage. To avoid these unwanted situations, the approach of capacity reservation is applied to cope with the unpredictability of DHW consumption. Using this approach, a certain percent of the heat capacity of TES must be reserved as a buffer, in case of unexpected user behavior and DHW consumption. The basic idea is to record the maximum warm water consumption in the last 30 days for each time step and recognize it as the possible worst case, which would also happen in the viewed day. This will ensure that the temperature of TES would not decrease below 40 °C. Nevertheless, the reservation of partial space in TES places additional constraints on the optimization of heat pump operation and flexibility estimation, which will increase energy costs for the heating system and reduce the available flexibility offered by the heat pump.

For the concept that the household has one TES for both SH and DHW, three options are considered to cover up the unpredictability of DHW consumption, in the form of the required minimum SOC curve in Figure 5:

1. **Dynamic**: use the maximum DHW consumption for each 15 min from the last 30 days to represent the potential risk of high consumption peaks;
2. **Constant**: use overall maximum DHW consumption from the last 30 days for the period 7:00–24:00;
3. **Parabolic**: use the parabolic curve to cover the typical peaks of one day.

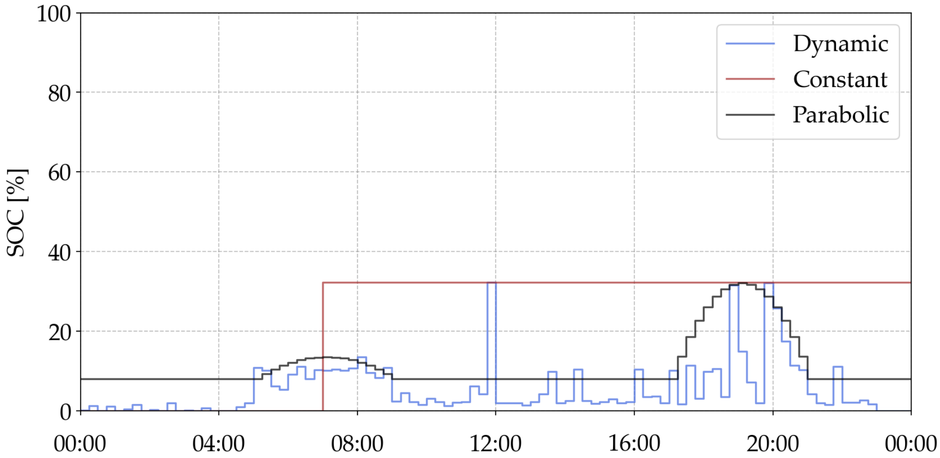


Figure 5. Minimum SOC curves: dynamic, constant and parabolic.

As seen from Figure 5, the first option generates a dynamic limitation curve, which changes itself every time step. The dynamic curve finds the maximum DHW consumption for each 15 min from the last 30 days and uses it to directly represent the potential DHW consumption peaks. This means that the possibility that the required thermal energy for DHW exceeds these thresholds is nearly 0%, even when forecast errors occur. Therefore, the influence of stochastic user behavior on the DHW consumption would be weakened. In comparison with the dynamic curve, the curve with constant values part of the time uses the overall maximum value of DHW-15min-consumption within the last 30 days to set a one-day minimum SOC value for TES from 07:00 to 24:00. The period from 00:00 to 07:00 is not taken into account because there is usually no heat consumption during this time period. This option ensures additional safety margins by raising the limits for most of the day. It also reduces the optimization complexity by simplifying the MILP problem. Another option with the parabolic limit finds a compromise between the first and second option. First, it gives a baseline for the whole day, which is a quarter of the maximum. Further, the peak hours in the morning and evening will be dealt with separated maximum values at these times, respectively. The amplitude and duration of the peak hours depends on peak flow rates and the assumed possibility distribution. Finally, a parabolic curve is used to reflect the importance of different times within the peak hours. Stricter restrictions are given at times when peak DHW consumption is more likely to occur. This solution will bridge the unexpected appearance of large DHW loads and keep user comfort unaffected.

4.2. Evaluation of Performance

Evaluation of the performances of different options require adequate evaluation methods. As the main purpose of this article is to provide flexibility service by heat pump without affecting the user comfort, the evaluation procedure concentrates on two factors: total flexibility energy and unsatisfactory time. To simply the assessment of flexibility potential, only the quantity of available flexibility is taken into account. For instance, the evaluation sums up all the offered flexibility energy for the whole day, but neglects the average flexibility duration. Additionally, the positive and negative flexibility will be treated equally. Therefore, the total flexibility energy is estimated with Equation (24):

$$E_{flex,total} = \sum_{t=t_0}^{t_e} |E_{flex,t}| \tag{24}$$

With regard to the assessment of influences on user comfort, the unsatisfactory time and temperature drops are applied to perform the negative effects of unforeseen DHW consumption. Here, the reference temperature of TES (40 °C) is assumed to be the lowest temperature that can still meet the comfort requirements of the user. Once the temperature drops below 0 °C, its duration will be counted as unsatisfactory time. Meanwhile, the magnitude of the warm water temperature drops will be described by an additional parameter, temperature drop, with the assumption that every 5% SOC decrease below 0% corresponds to 1 °C temperature drop. For the whole day, the overall temperature drops are estimated by root–mean–square deviation (RMSD) while assuming the expected value as 0 °C. The RMSD describes how far the actual temperature deviates from the minimum required temperature and shows the severity of large temperature drops:

$$t_{unsat,day} = \sum_{t=t_0}^{t_e} [T_{drop,t} > 0] \cdot \Delta t \tag{25}$$

$$T_{drop,day} = \sqrt{\frac{1}{N} \sum_{t=t_0}^{t_e} T_{drop,t}^2} \tag{26}$$

5. Results and Discussion

In this chapter, the results of a case study will be demonstrated. The basic settings and input data come from Section 2. The minimum run time and pause time of the HP is set at 2 h. The timespan of the simulation is 30 days (January). First, the general format of the flexibility estimation results is introduced. Then, the three different options handling the stochastic behavior of DHW consumption will be compared based on the aforementioned performance evaluation methods.

5.1. Flexibility Offers

Following the estimation procedure introduced in Section 3, the flexibility potential of the heat pump can be quantified properly. A one-day example is demonstrated with Figure 6. Here, the total electricity consumption of heat pump is illustrated by the black line. The value is always negative because, in the context of OpenTUMFlex, all the energy consumed has negative values. Additionally, the blue and red lines, which are derived from the black line, are the flexibility of the heat pump, which can potentially be utilized by the system operator if needed. The horizontal width of the blue and red lines represents the flexibility duration and the vertical height means the flexibility energy for each time step. Comparing this diagram with the SOC curve below, their relationship is clearly visible. When the heat pump is turned on, the SOC of TES will increase, as well as the absolute value of cumulative energy. Afterwards, the flexibility of the heat pump will be estimated by Equations (16)–(18). The heat pump cannot always offer flexibility up until the next switch point because the TES becomes full or empty before the switch point if the flexibility lasts longer. For instance, in the time period between 11:00 and 12:00, all the flexibility offers are shorter than half an hour because of the DHW consumption peaks at 12:00. Therefore, the flexibility can only be partially utilized during this period. The flexibility power for each time step is shown in the lower diagram.

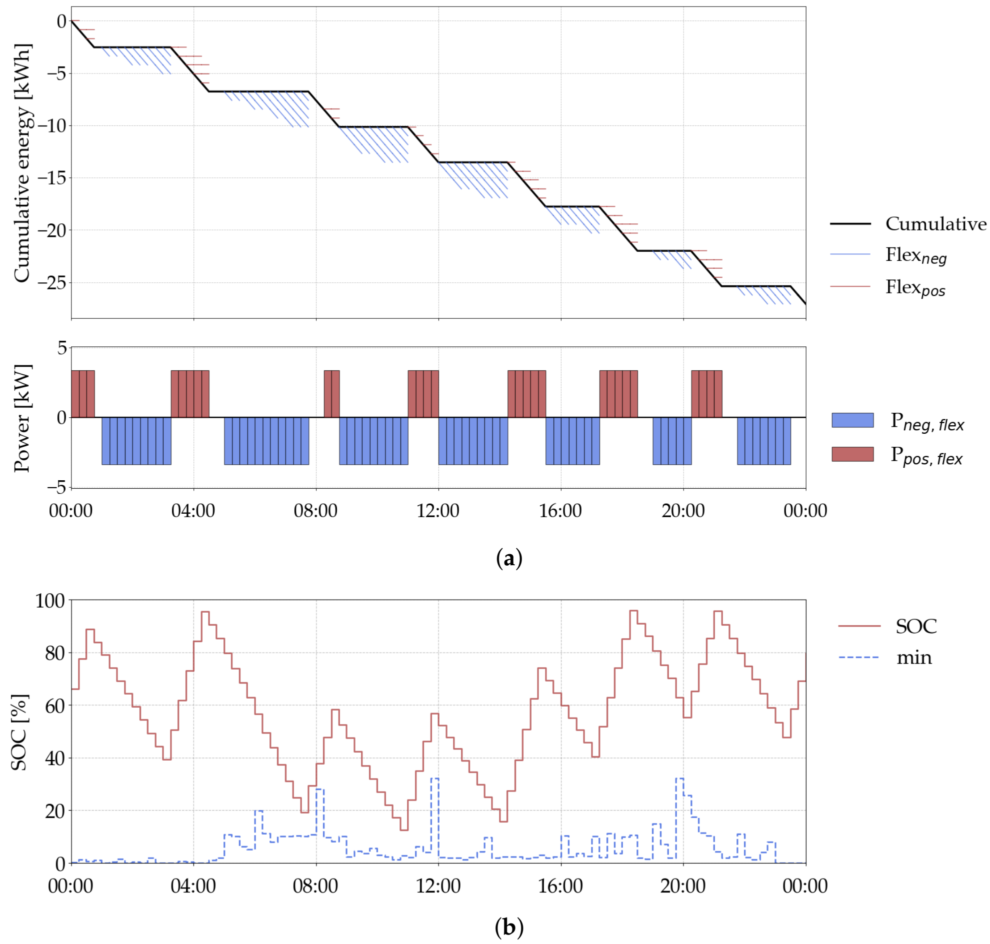


Figure 6. Results of flexibility estimation (**a**) cumulative energy of HP electricity consumption (black), positive flexibility offers (red), negative flexibility offers (blue) and flexibility power (**b**) actual SOC profile, minimum SOC for capacity reservation.

Flexibility offers can also be summarized in tabular format, which facilitates the trading process in the flexibility platform. A prosumer can use OpenTUMFlex to generate flexibility offers in tabular form and upload it directly to the trading platforms. Table 2 provides an example of how the tabular format of flexibility offers looks like within the period duration of 16:00–17:45. Here, the scheduled power consumption based on the optimal operational plan, its corresponding positive and negative flexibility power and energy can be clearly obtained.

Table 2. Tabular form of flexibility results (16:00–17:45): scheduled power, negative and positive flexibility power, negative and positive flexibility energy.

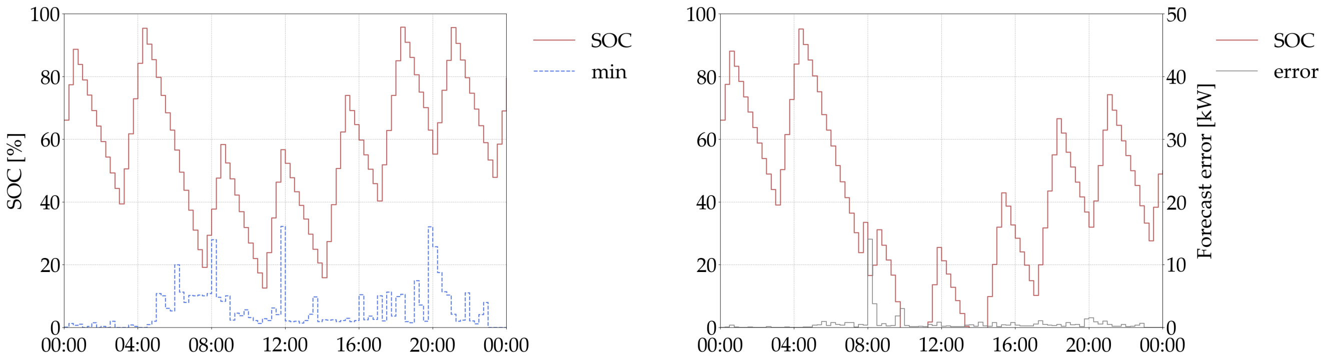
Time	P_{opt} (kW)	P_{Neg} (kW)	P_{Pos} (kW)	E_{Neg} (kWh)	E_{Pos} (kWh)
16:00	0	−3.39	0	−1.69	0
16:15	0	−3.38	0	−2.52	0
16:30	0	−3.38	0	−2.52	0
16:45	0	−3.41	0	−1.71	0
17:00	0	−3.41	0	−0.86	0
17:15	−3.38	0	3.38	0	1.69
17:30	−3.39	0	3.39	0	1.70
17:45	−3.25	0	3.25	0	2.47

5.2. Comparison of Methods Dealing with Unpredictability

As mentioned in Section 4.1, three different options handling the unpredictability of DHW consumption would avoid the negative effects of flexibility provision on user comfort. The basic idea of these options is to set a lower bound of SOC of TES to deal with the unexpected situation. To compare the performance of three different options, a 15-day case study was performed. The simulations were divided into two sessions for each option: forecast and validation. The optimal operation plan generated in the forecast session needed to be reviewed in a validation session. In the forecast session, the DHW consumption used its average value of the last 30 days, whereas the actual demand profile of DHW was utilized in the validation session. The calculation of flexibility potential and unsatisfactory time of the heat pump was performed for 30 days in a row, given weather data history from the last 30 days, gaining relatively convincing results. In the simulation round, the comfort loss was considered to occur when the SOC of TES fell below 0%, because the supply temperature for SH and DHW became lower than 40 °C. The unsatisfactory time and weighted average temperature deviation are summarized for each option.

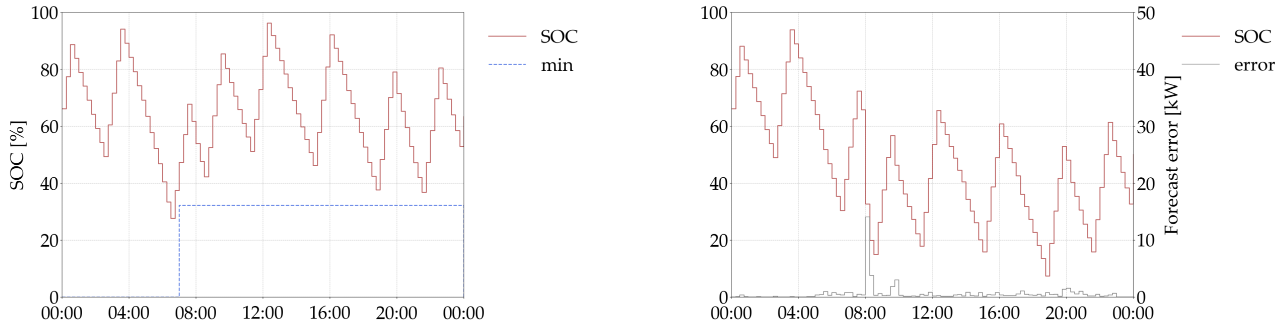
- **Forecast**: generate optimal schedule for heat pump day-ahead based on predefined restrictions;
- **Simulation**: test if the generated optimal schedule of the heat pump can fulfill the minimum comfort requirement in the viewed day.

In Figures 7–9 the results of the 1-day simualtion based on different options are illustrated as an example. In the forecast session (a), both the SOC profile and the lower bound of the TES SOC are demonstrated. In the simulation session (b), both the SOC profile and the unsigned forecast errors are represented. This makes it easy to compare the SOCs in these two sessions and observe when the forecast errors occur.



(**a**) (**b**)

Figure 7. Results of simulation with dynamic SOC limit: (**a**) Forecast (**b**) Simulation.



(**a**) (**b**)

Figure 8. Results of simulation with constant SOC limit: (**a**) Forecast (**b**) Simulation.

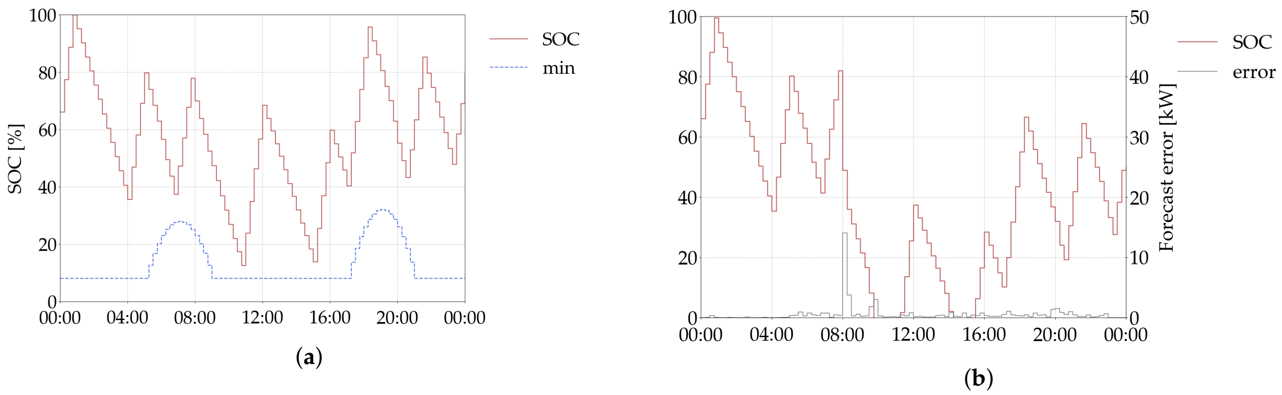


Figure 9. Results of simulation with parabolic SOC limit: (**a**) Forecast (**b**) Simulation.

In Figure 7, the dynamic constraint used to cover the stochastic DHW usage is applied. The red line indicates the SOCs over the day. It can be seen the SOCs of the TES stay always in the required range, between the full state and the minimum bound determined by a predefined dynamic curve. By applying these extra limits for the SOC of the TES, it is expected that the reserved fraction of the thermal storage capacity can provide a "safety" margin for prosumer comfort, which means that the warm water temperature in the TES should not drop below a certain threshold even if there is a serious prediction error in the DHW consumption. To test its performance, the simulation session is needed. Given that the time schedule of the heat pump on the viewed day is unchanged, the real SOC curve of TES can be obtained by simulating the heating system again with actual DHW consumption instead of forecasts. Due to some unpredictable DHW consumption, as indicated by the grey lines in (b), it can be observed that the SOC of TES drops below 0% between 10:00 und 14:00. This means the comfort loss occurs because of the relatively low SOC states of TES in this period. This would appear once the DHW consumption on the observed day greatly exceeds the long-term average, because the forecast of the DHW consumption uses the average of the last 30 days. From (b), it is obvious that the largest forecast error occurs at 08:00. As a result, the SOC of the TES decreases by 30% after this time point, which further leads to a temperature drop of the warm water in the TES below 40 °C.

Similarly, this procedure can be performed for the case with a constant bound of SOC. The advantage of using a constant bound of SOC is that it provides a higher "safety" margin to cope with the unpredictable DHW consumption. However, it reserves more capacity in the TES and may cause losses in the flexibility potential, because the volume of the TES offering flexibility is not exhausted. In Figure 8, a better performance can be viewed when comparing (a) and (b), because the constant constraint avoids the low-SOC situation and allows for an additional buffer for the prosumer comfort. Here, the SOC of TES remain in the required range in the simulation session.

In addition, a combination of the first and second option would be meaningful as an alternative solution for capacity reservation in the TES, namely a parabolic lower bound. This option gives a moderate "safety" margin compared to the other options and is used to find a better balance between the user comfort and the flexibility potential. According to the simulation results, the scenario with parabolic limit shows no obvious improvement in Figure 9.

The analysis above refers to this 1-day simulation and only gives a brief overview of the impacts of different options. In the next section, the advantages and disadvantages of each option will be analyzed quantitatively in a statistical way with the help of the indicators discussed in Section 4.2.

5.3. Evaluation of Methods for Capacity Reservation

In order to quantitatively analyze the advantages and disadvantages of each option, the indicators discussed in Section 4.2 will be used, including total flexibility energy, unsatisfactory time and temperature deviation. Additionally, the situations after using flexibility will also be discussed. As when and how much flexibility would be required by the system operator is unknown, the unsatisfactory time and temperature deviation after using flexibility are only roughly estimated by assuming that each flexibility is equally likely to be utilized by the system operator. The acquired values can still demonstrate how flexibility usage will influence these indicators.

As shown in Figure 10, the unsatisfactory time denotes the negative impact of inaccurate DHW consumption forecasts on customer comfort. Within the simulation results of 30 days, option 2 with constant SOC restriction has the best performance, with a maximum unsatisfactory time of 75 min/day and mean value of 2.5 min/day, while others lead to more unsatisfactory times in terms of magnitude and quantity. In addition, the distribution of temperature drops in every 15 min time-block can be observed in Figure 11. They all have about the same average value. Nevertheless, option 2 with constant SOC restriction still has a small degree of variation, in which the most severe temperature drop is limited to 3.7 °C.

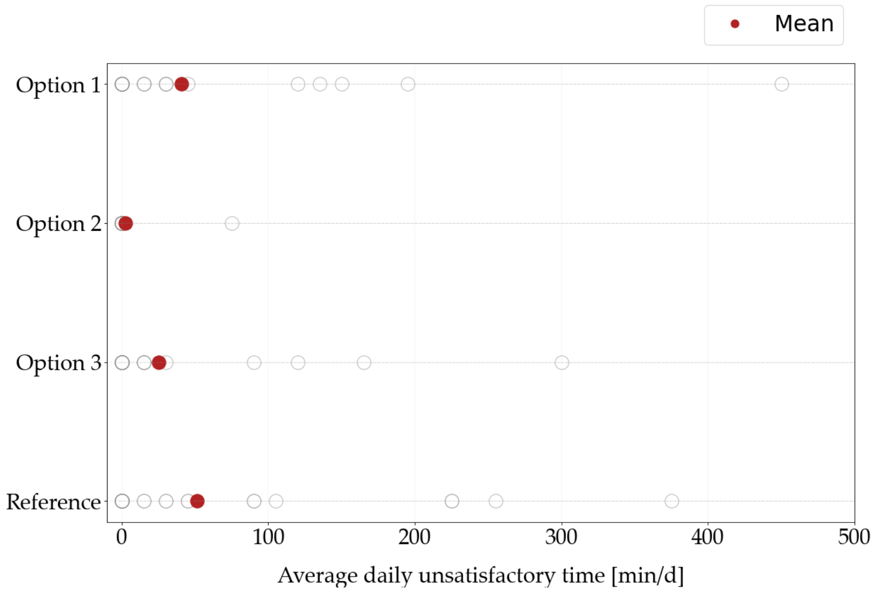


Figure 10. Distribution and mean value of the unsatisfactory time for three different capacity reservation options.

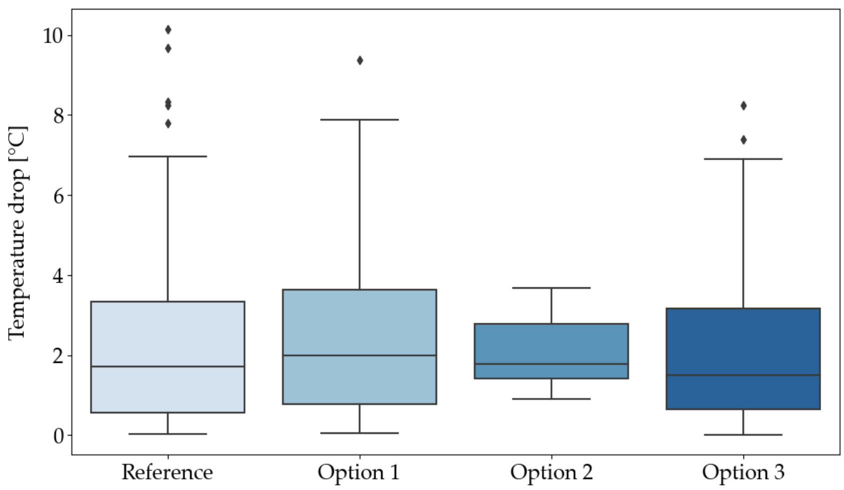


Figure 11. Temperature drops for three different capacity reservation options.

Table 3 summarizes the evaluating indicators. In general, all three options resulted in better performance compared to the reference scenario. Among the solutions, option 1 with dynamic restriction provides slightly more flexibility potential, while option 2 with constant restriction produces the least flexibility. Nevertheless, the differences in the available flexibility energy among the three options are not particularly noticeable. As opposed to this, the unsatisfactory time and temperature drop show a significant difference. The prosumer will notice little comfort loss in the scenario with a constant SOC lower limit, as its unsatisfactory time has a mean value of 2.5 min per day. In contrast, the results imply that the prosumer will suffer from comfort losses for 41.0 min for the first dynamic option, and 25.5 min for the parabolic one on a daily average. Simultaneously, these two options have reached 2.9 °C and 2.7 °C of temperature drop, statistically. The mean value here is slightly greater than these in Figure 10 because it also considers the outliers. Furthermore, how the flexibility usage will influence these evaluating indicators is revealed. In general, the influence of flexibility usage on the unsatisfactory time is not certain, although temperature drops become greater. In summary, either option, as it stands, is effective in reducing the impact of the stochasticity in DHW consumption. In the case of using option 2, there is only an average of around 2.5 min per day when the water supply temperature becomes too low, and the maximum temperature drop is within 2.3 °C. Therefore, the comfort of the prosumer is only affected to a fairly small extent, when he prepares to offer flexibility through this capacity reservation strategy.

Table 3. Comparison of three options dealing with the stochastic characteristics of DHW consumption in total flexibility energy, unsatisfactory time and temperature drop.

Option	E_{Flex} **(kWh/d)**	t_{unsat} **(min/d)**	T_{drop} **(°C)**	$t_{unsat,Flex}$ **(min/d)**	$T_{drop,Flex}$ **(°C)**
1	158	41.0	2.9	38.7	3.2
2	140	2.5	2.3	3.7	2.4
3	153	25.5	2.7	27.3	2.9
ref	158	51.5	2.8	48.6	3.0

To conclude the results from the case study, the three options suggest a slightly differentiated flexibility potential. Nevertheless, the simple strategy with a constant SOC lower bound for the TES performs best with regard to the unsatisfactory time and the temperature drop and should be proposed to deal with the demand uncertainty in future research.

5.4. Comparison of Flexibility Utilization Approaches

From the previous studies, there are lots of approaches studying the demand flexibility of heat pumps. In [8], the author uses a novel methodology, Flexibility Function, to characterize the energy flexibility. It mainly investigates the demand response curve of different types of buildings to penalty signals and uses indicators to quantify and evaluate the cost-saving potential of using this method. This study gives a good perspective to exploit the flexibility potential of buildings and districts with regard to diverse penalty signals (price, CO_2, etc.). However, it only estimates the flexibility from a macroscopic perspective, leaving all control of the household appliances to the intelligent controller, without accounting for the prosumer comfort. In [10], it focuses on proposing new control strategies that maximize the gains from the demand side response. It uses complex modeling to make the results more convincing. At the same time, however, the complexity of its models makes its application elsewhere difficult. In addition, it does not consider the benefits of using flexibility for prosumers from an economic perspective. In [30], the time series of the flexible power consumption of the heat pump is optimized with regard to peak power reduction and load factor increase. Hence, its objective is to find an operating plan of the heat pump that is optimal for grid operation. This methodology can estimate the impact of demand responses of the heat pump on the grid, but requires a centralized control of a pool of heat pumps. In addition, this approach is not feasible to generate flexibility offers of individual residential units. Therefore, the research results cannot be implemented directly in the flexibility trading.

In contrast with these previous studies, this paper focuses on the decentralized management of the flexibility, instead of the centralized control or responses to penalty signals. The prosumers themselves decide the operating plan of the heat pump by Home Energy Management System and trade the alternative operation options of the heat pump on the flexibility market. Therefore, it describes an approach to utilize the flexibility from a microscopic perspective. Additionally, the methodology evaluate the demand flexibility by indicators such as flexibility power, energy and duration with a time interval of 15 min. This nature enables the trading on the flexibility market. Furthermore, this study investigates the warm water temperature drops inside the TES when offering flexibility and reserves a fraction of the thermal storage capacity in coping with the risk of comfort losses. The simulation results of 30 days denote that a constant SOC lower bound for the TES results in the best performance.

6. Conclusions

This paper proposes an novel approach to quantifying the flexibility of heat pumps combined with a thermal energy storage with regard to necessary technical restrictions. It suggests the decentralized flexibility management, which allows the prosumers to manage and utilize the residential flexibility actively. Furthermore, it analyzes the impact of offering flexibility on the thermal comfort of prosumers for the first time, and incorporates a viable solution to cope with the risk of unpredictable domestic hot water consumption. From the results, it is revealed that the capacity reservation in the thermal energy storage using a constant state of charge lower bound achieves the best performance. The simulations with this solution indicate that there is an average of 2.5 min unsatisfactory time per day and the maximum temperature drop never exceeds 2.3 °C given a predetermined operation schedule of the heat pump. Therefore, the proposed methodology enables the day-ahead flexibility trading on the local market to address future needs regarding flexibility markets and increases the prosumer acceptance, offering flexibility by reducing their discomfort, which contributes to energy transition in the long term.

All presented models algorithms are incorporated as an open-source tool in OpenTUMFlex for the interested parties and provide them with the opportunity to integrate the implemented methods for their research such as the investigation of the flexibility potential in Home Energy Management System and the local flexibility market design. Within the framework of OpenTUMFlex, the proposed flexibility quantification methodology will be further developed and evaluated. Specifically, more data will be collected to cover more types, such as air-source heat pumps from different manufacturers. The possibility of applying non-linear optimization programming will have to be investigated to find a better balance between model accuracy and computation time. Additionally, the development of aggregation methods will contribute to the widespread use of the flexibility potential in domestic heat pumps.

Supplementary Materials: The model OpenTUMFlex is open-source and accessible online at https://zenodo.org/record/4251512.

Author Contributions: Conceptualization, M.Z. and Z.Y.; methodology, Z.Y.; software, M.Z., Z.Y. and B.K.N.; validation, Z.Y.; formal analysis, Z.Y.; writing, Z.Y.; supervision, P.T.; project administration, P.T.; funding acquisition, P.T. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

AS	Ancillary Service
ASHP	Air Source Heat Pump
BAT	Battery
CHP	Combined Heat and Power
COP	Coefficient of Performance
DHW	Domestic Hot Water
DR	Demand Response
EV	Electric Vehicle
HEMS	Home Energy Management System
PV	Photovoltaic
SH	Space Heating
TES	Thermal Energy Storage

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3.3 Providing heat pump flexibility through district energy management system

Scientific context

HPs are increasingly recognized as a key technology for reducing CO_2 emissions from residential SH and DHW [78]. The European Heat Pump Association's study suggests that widespread HP implementation could cut CO_2 emissions in the residential heating sector of some European countries by 35% [79]. Carvalho et al. propose that replacing natural gas-based heating with efficient HPs could lead to a 60% reduction in primary energy use and up to 90% in CO_2 emissions across Europe [80]. Therefore, research is emerging regarding replacing gas boiler with HPs to reduce CO_2 emissions by utilizing their high efficiency and flexibility through EMS.

However, previous studies tend to evaluate buildings on an individual basis, rather than at a district level [47], where collective assessment could yield better and realistic results. Similarly, Patteeuw et al. [46] examined the impact of replacing gas boilers with HPs on CO_2 emissions and DSM, focusing on the benefits across different building types and the influence of renovation levels and HP types on CO_2-abatement costs. However, they focus only on single unit of HPs and do not evaluate the impacts of district energy management system. In addition, although previous studies [48, 49, 50] have highlighted the role of centrally-controlled HPs in DSM and their adaptability to grid conditions and power prices, they often simplify the building sector as a uniform heat sink. Such simplifications overlook factors like thermal inertia and solar gains through windows, which are critical in assessing the benefits of residential HPs.

To address the identified research gaps, this paper provides a comprehensive evaluation of residential HPs and demand-side management at a district level. A bottom-up modeling approach is used that combines detailed building modeling, radiation analysis and model-predictive control to determine emission savings. CO_2-abatement cost is calculated to measure the impact of HPs combined with DEMS on emission reductions.

Contribution

This study significantly enhances our understanding of CO_2 abatement via residential HPs, particularly focusing on both urban and rural district levels. It improves upon prior research by incorporating a broader range of realistic factors, such as electricity levies, maintenance costs and solar gains, into the CO_2-abatement cost calculations. This approach yields a detailed analysis of the costs associated with reducing CO_2 emissions through HPs and underscores the benefits of DLC via DEMS.

Employing a bottom-up model for district energy systems, the study uses model-predictive control within these systems to minimize total cost. It addresses crucial questions regarding the specific CO_2 abatement costs associated with residential HPs in different district settings, demonstrating enhanced efficiency of HPs in CO_2 reduction when controlled by DEMS. The research explores the conditions that make HP deployment most cost-effective for CO_2 reduction.

Key findings indicate that urban districts incur higher CO_2 abatement costs than rural ones, due to differences in housing density and heating demand. Integrating HPs with DEMS leads to significant reductions in CO_2 abatement costs, contributing to improved power grid stability and efficiency. Lower HP investment costs and reduced emissions from electricity production are also identified as key factors in decreasing CO_2 abatement costs.

This research underscores the critical role of DEMS in leveraging the flexibility of HPs and provides important insights for developing cost-effective emission reduction strategies through HP implementation. These insights offer valuable guidance for district-level investments targeting low-carbon goals, especially useful for policymakers and stakeholders in the energy sector.

Cost-effective CO2 abatement in residential heating: A district-level analysis of heat pump deployment

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Manuel de-Borja-Torrejon:	10 %	Software, Resources.
Paulo Danzer:	5 %	Software, Resources
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Cost-effective CO2 abatement in residential heating: A district-level analysis of heat pump deployment

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ABSTRACT

Heat pumps are recognized for their potential to reduce CO_2 emissions in residential heating, particularly when replacing traditional natural gas systems. Their performance can be enhanced when integrated into district-level energy management systems and demand response programs. However, the CO_2 abatement cost, the expense of reducing emissions through the installation of heat pumps, has not yet been fully explored at the district level. This study reveals a substantial disparity in CO_2 abatement costs between typical urban and rural districts, identifying the conditions that make heat pump deployment most cost-effective. Rural districts, with their higher heat demand, emerge as more suitable candidates for the electrification of the heat sector. The research also indicates that district demand-side management not only helps mitigate CO_2 abatement costs but also reduces the negative impacts of a large number of heat pumps. Additionally, a lower emission intensity of electricity could lead to a 50% reduction in CO_2 abatement costs. This research outlines a cost-effective approach to reducing emissions through the use of heat pumps, thereby setting a benchmark for district-level heat pump investments towards achieving low-carbon districts. The findings could provide valuable information that informs strategic decision-making on the replacement of conventional heating systems with heat pumps.

1. Introduction

Heat Pumps (HPs) have been widely advocated as an instrumental technology to mitigate CO_2 emissions associated with space heating in residential properties [1]. A study by the European Heat Pump Association suggests that large-scale heat pump implementation might reduce CO_2 emissions by 35% in the residential space heating sector of certain European countries [2]. Carvalho et al. also suggest that substituting natural gas-based space heating with efficient heat pumps could conserve approximately 60% of primary energy usage and significantly reduce up to 90% of CO_2 emissions in Europe [3]. However, these studies calculate CO_2 emissions based on average values of carbon intensity of the power generation system, a method that has been criticized for several reasons.

Firstly, a strong correlation might exist between the electricity demand of HPs and real-time carbon intensities of the power generation system. This could notably deviate from the average carbon intensity [4]. Second, the surge in electricity demand due to the widespread use of HPs could coincide with the peak electricity demand, stressing the local power grid [5]. Moreover, previous studies often evaluate buildings individually instead of collectively at the district level [6]. Holistic consideration at the district level can significantly enhance results. Consequently, our work employs real-time carbon intensities based on national-level energy mix calculations. Furthermore, constraints on local transformers are imposed and other relevant performance indicators are included to gauge the impacts of a substantial increase in HP on the power grid. To harness the economies of scale, all buildings are modeled collectively at the district level, rather than individually.

This paper provides a thorough assessment of the combined benefits of residential HPs and demand-side management at the district level. Emission savings are determined using a bottom-up modeling approach that integrates detailed building modeling with radiation analysis and model predictive control. Prior studies [7–9] have emphasized the potential of centralized-controlled HPs in demand-side management. They also noted the system's ability to adapt to fluctuating grid conditions and power prices. In addition, such systems can contribute to peak shav-

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Nomenclature

Abbreviations

ASHP	air source heat pump
CAC	CO_2 abatement cost
COP	coefficient of performance
DHW	domestic hot water
DSM	demand side management
EAC	equivalent annual cost
EV	electric vehicle
GB	gas boiler
GII	grid impedance index
HP	heat pump
LOLP	loss of load probability
MPC	model-predictive control
OPEX	operating expense
PV	photovoltaic
RC	resistance capacitance model
SC	self-consumption
SH	space heating
SOC	state of charge
SS	self-sufficiency
TES	thermal energy storage

ing and load shifting, thereby enhancing the reliability of the grid [10]. However, previous studies often simplify the building sector as a heat sink with generic load profiles for large district simulations. This approach overlooks key factors such as thermal inertia in buildings and solar gain through windows, which are crucial in quantifying the benefits of residential HPs.

To measure the impact of installing HPs with demand-side management on emission reductions, we calculate the CO_2-abatement cost — a metric indicating the cost of CO_2 emission reduction. The emission reduction potential of residential HPs has been thoroughly studied. Regarding the CO_2-abatement cost, Kesicki et al. used a long-term energy planning model, UK MARKAL, and found that if the CO_2 price exceeds £137 per ton of CO_2, the use of HPs could become widespread in the UK. However, they did not consider the influences of building types, HP peak demand, demand-side management, and occupant behavior [11]. Patteeuw et al. examined the effects of replacing condensing gas boilers with HPs for residential space heating in the context of CO_2 emission reduction [12]. Their research focused on determining whether all building types derive equal benefits and, hence, should be given equal priority for deployment. Their findings indicated that the CO_2-abatement cost is primarily determined by the renovation level of the building and the type of HP installed.

Our current study expands on these works by computing the CO_2-abatement cost at a district level and taking into account the diversity of building types in both urban and rural districts. More realistic factors, such as the levy for electricity import, maintenance cost, and solar gain, are also taken into account. Considering that CO_2-abatement costs are sensitive to assumptions on parameters such as fuel prices or emission intensity, a sensitivity analysis was conducted to understand the findings under varying conditions. Consequently, this study addresses the following research questions:

1. What are the specific costs associated with CO_2 abatement through the installation of residential HPs in urban and rural districts?
2. How does the demand side management (DSM)[1] system enhance HP efficiency for CO_2 reduction?
3. Under what conditions does HP deployment achieve the maximum CO_2 reduction in a cost-effective manner?

The organization of this paper is as follows: Section 2 details our modeling approach, including buildings, energy systems, and optimization methods. In Section 3, we present the design of our case study and describe the input data used. Section 4 then presents the results derived from the case study settings. The discussion in Section 5 elaborates on important aspects of our findings and responds to the research questions previously proposed. Section 6 shows the limitations of our research. Finally, main conclusions are presented in Section 7.

2. Methods

Fig. 1 presents a schematic overview of the district energy system. The district employs a central controller for DSM, with the objective of minimizing energy costs throughout the district. The central controller utilizes a model predictive control (MPC)[2] strategy to optimize the operating plans of controllable energy devices, thereby achieving minimal energy costs. This process necessitates comprehensive information from households, which covers the characteristics and operational states of energy devices, the state of charge (SOC) of the Thermal Energy Storage (TES), household demands, and current room temperature. In addition, the optimization process needs forecast data for energy prices and emission factors provided by forecasting services.

In this context, buildings serve as the primary units in the district, with all energy devices affiliated with a particular building. Each building comprises multiple zones, each referred to as a home. Energy balances and room temperatures are computed at the zone level. To meet the energy demand within the district, a variety of energy commodities are imported, primarily electricity from conventional and renewable sources and natural gas. These commodities can be used directly or converted to meet user demands. When calculating energy costs and CO_2 emissions, only energy commodities imported from outside system boundaries are taken into account.

The following sections will elaborate on the MPC and optimization problem, the modeling of buildings and the energy system, and the performance indicators.

2.1. Model-predictive control

The MPC used in this study is a control strategy that employs a district model to anticipate future system behavior over a finite prediction horizon. In our study, this horizon is set to 24 hours. On the basis of these predictions, the control signals that minimize energy cost are computed. To avoid high computational burden, operating plans of energy devices are updated every 12 hours, meaning only the control signals of the first 12 hours of the prediction horizon are sent back to households in the buildings. After 12 hours, this prediction, computation, and communication process is repeated with a moving or receding horizon. This entire MPC process is visually represented in Fig. 2.

The optimization problem employed within the MPC to identify cost-optimal control signals for energy devices is formulated as follows, using three indices:

[1] Demand side management refers to strategies implemented to modify consumer demand for energy, often to encourage energy conservation or shift usage to off-peak periods.

[2] Model predictive control is a control strategy that uses a mathematical model to predict future system behavior and computes control actions by optimizing a certain objective over a prediction horizon.

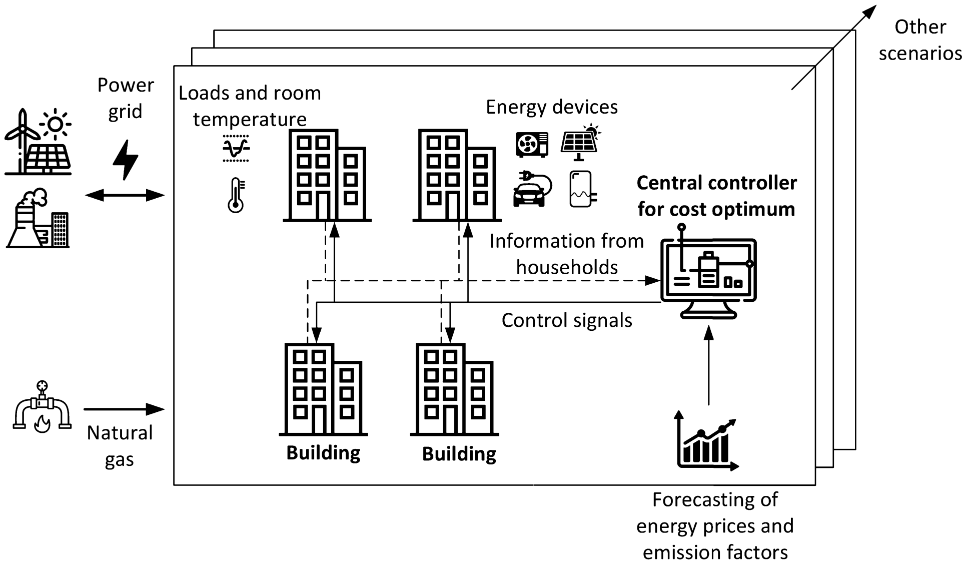


Fig. 1. Schematic overview of the energy system in the district.

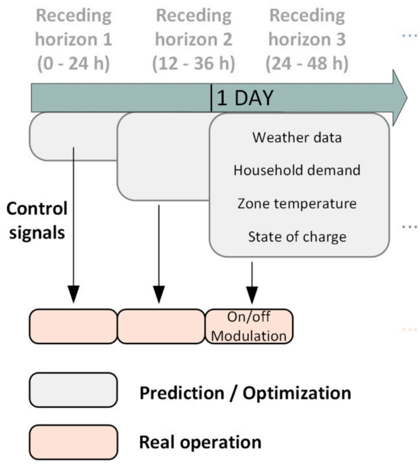


Fig. 2. MPC control.

- Index t stands for a time period.
- Index b denotes a building.
- Index e stands for an energy commodity, which can be either "elec" (electricity) or "heat".

The equations are defined as follows:

$$\min_x \sum_t \sum_e (c^e_{t,in} P^e_{t,import} - c^e_{t,out} P^e_{t,export}) \tag{1}$$

$$s.t. \sum_b (P^e_{t,b,in} - P^e_{t,b,out}) = P^e_{t,import} - P^e_{t,export} \tag{2}$$

$$P^{elec}_{t,b,in} - P^{elec}_{t,b,out} = D^{elec}_{t,b} + P^{elec}_{t,b,hp} + P^{elec}_{t,b,ev} - P^{elec}_{t,b,pv} \tag{3}$$

$$S^{heat}_{t,b} + P^{heat}_{t,b,hp} + P^{heat}_{t,b,gb} = D^{heat}_{t,b} \tag{4}$$

$$|\sum_b (P^{elec}_{t,b,in} - P^{elec}_{t,b,out})| \le cap^{elec} \tag{5}$$

Equation (1) describes the objective in optimization. In this equation, $P^e_{t,in}$ and $P^e_{t,out}$ represent the import and export of energy commodities over the district boundary, respectively. The total energy costs for the entire district are obtained by multiplying them by the import and export prices of the commodities $c^e_{t,in}$ and $c^e_{t,out}$, respectively. x is the variables representing control signals for flexible energy devices such as HPs and Electric Vehicles (EVs). $P^e_{t,b,in/out}$ represents energy import or export for a single building. The sum of the input and output of energy commodities from all buildings must be in line with the total energy import or export of the whole district (Equation (2)).

Equation (3) and Equation (4) ensure energy balance at the building level for electricity and heat, respectively. Equation (3) establishes that the power flow across the boundary of a building is equal to the energy consumed by the fixed load $D^{elec}_{t,b}$, HPs $P^{elec}_{t,b,hp}$ and EVs $P^{elec}_{t,b,ev}$, less the power generated by Photovoltaic (PV) $P^{elec}_{t,b,pv}$. Similarly, Equation (4) states that the heat generated by HPs $P^{heat}_{t,b,hp}$ or Gas Boilers (GBs) $P^{heat}_{t,b,gb}$, adjusted for thermal energy system $S^{heat}_{t,b}$ discharging or charging, should match the heat demand $D^{heat}_{t,b}$. Finally, Equation (5) imposes a constraint on the local transformer, ensuring that the maximum import or export power does not exceed its capacity.

The MPC has the potential to improve demand side management by coordinating the operation of HPs in periods when electricity prices are low. Alongside this cost-optimal control approach, a benchmark control is established to represent a control similar to the conventional rule-based control strategy. In this strategy, the price of commodities in Equation (1) is changed to one unit. This implies that the controller lacks awareness of the variability in electricity prices and operates the HPs solely based on their Coefficient of Performance (COP) over the next 24 hours.

2.2. Buildings

The building modeling process comprises two main steps: preparing building data and creating a thermal model of the building. Initially, the district model is constructed using Rhinoceros 3D, a commercial computer-aided design software [13]. Within this application, relevant geometric parameters are defined for a building, including zones, floors, and window areas. These geometric data are then exported for subsequent calculations. In addition, Ladybug tools are used to assess solar radiation and generate rated PV production data [14]. Fig. 3 shows an example of how radiation data for building faces in a rural district are obtained. The specifications of the building components are sourced from the TABULA library, which provides comprehensive data sets for the physical attributes of walls, windows, ceilings, and floors, all with detailed layering information [15].

After obtaining the necessary building-related data sets, a 2nd order thermal network model developed by [16] is utilized. This model, also known as a Resistance-Capacitance-model (RC-model), simulates the thermal behavior of zones within buildings, as shown in Fig. 4.

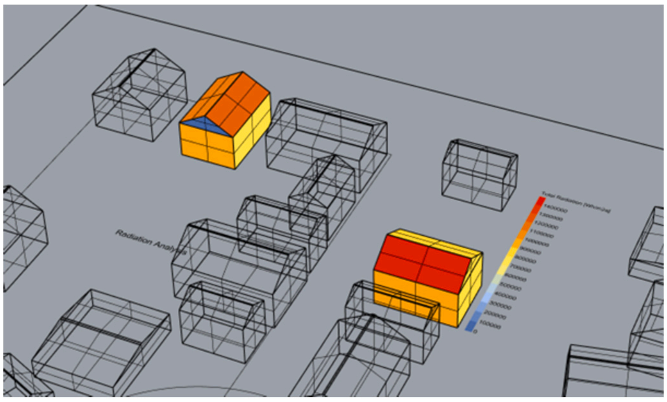


Fig. 3. Radiation analysis.

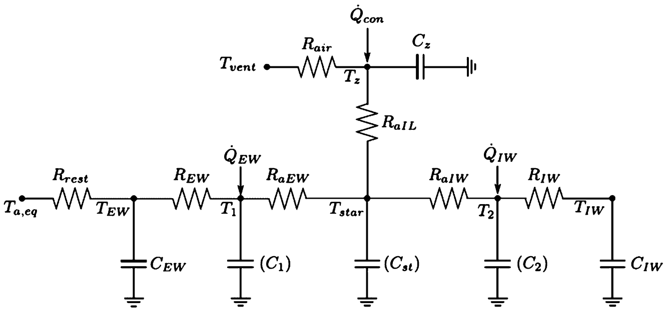


Fig. 4. RC-model of one zone.

They offer an optimal choice for district analysis due to their simplicity. In particular, these models consider changes in wall temperature, which is crucial for maximizing the flexibility offered by the thermal mass of the building. Equations (6) - (10) show more details of this RC model.

$$C_{EW}\frac{\Delta T_{EW}}{\Delta t}=\frac{T_{a,eq}-T_{EW}}{R_{rest}}+\frac{T_1-T_{EW}}{R_{EW}} \tag{6}$$

$$C_{IW}\frac{\Delta T_{IW}}{\Delta t}=\frac{T_2-T_{IW}}{R_{IW}} \tag{7}$$

$$C_z\frac{\Delta T_z}{\Delta t}=\frac{T_{vent}-T_z}{R_{air}}+\frac{T_{star}-T_z}{R_{aIL}}+\dot{Q}_{con} \tag{8}$$

$$C_1\frac{\Delta T_1}{\Delta t}=\frac{T_{EW}-T_1}{R_{EW}}+\frac{T_{star}-T_1}{R_{aEW}}+\dot{Q}_{EW} \tag{9}$$

$$C_2\frac{\Delta T_2}{\Delta t}=\frac{T_{IW}-T_2}{R_{IW}}+\frac{T_{star}-T_2}{R_{aIW}}+\dot{Q}_{IW} \tag{10}$$

$$20\,^{\circ}C\leq T_z\leq 25\,^{\circ}C \tag{11}$$

Dummy capacitors C_1, C_2 and C_{st} are introduced to simplify the equation formulation and the problem solving process. These dummy capacitors are set to values several orders of magnitude smaller than the actual capacitors. If these dummy values are sufficiently small, the resulting dynamic behavior exhibits a very short time constant and, therefore, does not affect the overall results. Currently, a value of 1 is assigned to the dummy capacitors. Equation (11) restricts the indoor temperature to ensure the comfort of the user to be satisfied.

For residential buildings, an apartment-based zoning approach is adopted. Consequently, larger residential structures are represented by multiple RC-models, each equivalent to an apartment. This method facilitates a precise evaluation of both flexibility and environmental factors. The environmental factors include shading, reflection of short-wave radiation, long-wave radiation exchange, and microclimate temperatures and are incorporated into the RC-model through the equivalent outdoor temperature $T_{a,eq}$ and the radiation gains (included in the heat gains in the internal components Q_{IW} and the external components Q_{EW}). Although detailed modeling of the environmental context necessitates additional computational efforts, it results in more realistic results.

2.3. Energy system

Our study incorporates two types of heat generators within the energy system: condensing GBs or Air Source Heat Pumps (ASHPs). The GB represents the traditional heating system that consumes fossil energy resources, whereas the HPs signify the electrification of the heat sector. Therefore, they are modeled in detail to accurately reflect their operational characteristics, which includes their energy consumption and heat generation.

The HP is modeled using hplib [17], which is based on measurements from various manufacturers and provides functions of electricity demand and thermal power of HPs that correspond to the measurements. A generic model of ASHPs is used and it is assumed that they can modulate between 0% and 100%. The thermal power and the COP are calculated using the following equations:

$$P^{elec}_{t,b,hp}=x^{hp}_{t,b}cap^{hp}_{t,b} \tag{12}$$

$$P^{heat}_{t,b,hp}=x^{hp}_{t,b}cap^{hp}_{t,b}COP_{t,b} \tag{13}$$

$$COP_{t,b}=COP_{ref}(f_1T_{amb,t}+f_2T_{out,b,l}+f_3) \tag{14}$$

$$cap^{hp}_{t,b}=cap_{ref}(f_4T_{amb,t}+f_5T_{out,b,l}+f_6) \tag{15}$$

Here, $COP_{t,b}$ and $cap^{hp}_{t,b}$ are the COP and the rated electricity consumption given the ambient temperature $T_{amb,t}$ and the supply temperature $T_{out,b,l}$. COP_{ref} is the reference COP of HPs, similar to $cap^{hp}_{t,b}$. f_i are parameters fitted using manufacturer measurements. The thermal power $P^{heat}_{t,b,hp}$ depends on the modulation rate $x^{hp}_{t,b}$, which can vary from 0% to 100%. The COP remains constant during modulation. $P^{elec}_{t,b,hp}$ is the actual electricity consumption of the HP.

The GB is powered by natural gas. The rated fuel power and combustion efficiency are defined as cap^{gb}_b and $\eta^{gb}_{b,l}$, respectively:

$$P^{gas}_{t,b,gb}=x^{gb}_{t,b}cap^{gb}_b \tag{16}$$

$$P^{heat}_{t,b,gb}=x^{gb}_{t,b}cap^{gb}_b\eta^{gb}_b \tag{17}$$

The TES is assumed fully mixed. The TES can be charged by heat generators or discharged to supply the heat demand for Space Heating (SH) or Domestic Hot Water (DHW). Depending on the operation, the SOC of the TES evolves every time step, as shown in Equation (18):

$$SOC_{t,b}=\eta^{sd}SOC_{t-1,b}+\frac{P^{heat}_{t,b,sto}\Delta t}{cap^{sto}_b} \tag{18}$$

$$P^{sto}_{t,b,sto}=\begin{cases}\eta^{char}S^{heat}_{t,b} & S^{heat}_{t,b}\geq 0\\ S^{heat}_{t,b}/\eta^{disc} & S^{heat}_{t,b}<0\end{cases} \tag{19}$$

$$|S^{heat}_{t,b}|\leq S^{heat}_{b,max} \tag{20}$$

$$0\%\leq SOC_{t,b}\leq 100\% \tag{21}$$

where $\eta^{e,sd}$ indicates the self-discharge rate, while $\eta^{e,char}$ and $\eta^{e,disc}$ represent the charging and discharging efficiency.

Building-specific details such as location, orientation, roof area, and potential shading factors form the basis for estimating sunlight availability at a particular location, which is accomplished by using the Ladybug tool as outlined in Section 2.2. The next step requires calculating the usable roof or facade area of the building. Here, a minimum radiation threshold is considered. A PV system will be installed if this threshold is exceeded for the building. The photovoltaic potential obtained from the aforementioned steps is denoted as $rad^{pv}_{t,b}$. The electricity generation from solar energy can then be calculated as follows:

$$P^{elec}_{t,b,pv}=x^{pv}_{t,b}rad^{pv}_{t,b}\eta^{pv} \tag{22}$$

where η^{pv} represents the efficiency of PV system, and $x^{pv}_{t,b}$ indicated the modulation rate or curtailment.

To reduce modeling complexity and exclude the flexibility on the demand side provided by EVs, all EVs from the same buildings are aggregated and simplified as a load profile. Thus, the EV is controlled to fully charge within 4 hours after arriving home instead of advanced smart charging.

$$Dis_{t,b,n} = \begin{cases} \text{Distance driven}, & \text{for } t = t_{n,a} \\ 0, & \text{otherwise} \end{cases} \tag{23}$$

$$P^{ev,char}_{t,b,n} = \frac{-Dis_{t,b,n} \cdot k^{ev}}{4} \qquad \forall t \in [t_{n,a}, t_{n,a}+3] \tag{24}$$

$$P^{elec}_{t,b,ev} = \sum_n P^{ev,char}_{t,b,n} \qquad \forall n \in b \tag{25}$$

where $t_{n,a}$ represents the arrival time of the n-th EV. On arrival, the distance driven by the n-th EV is known, allowing us to calculate the charging power by dividing the remaining energy required for a full charge by 4 hours. This remaining energy for a full charge is obtained by multiplying the distance driven by k^{ev}, which represents the electricity consumption of EVs in kWh/km. Finally, Equation (25) aggregates the charging power of all EVs that belong to the same building.

2.4. Performance indicators

To calculate the CO_2-abatement cost, a baseline system must be established. Given that GBs are commonly used in Germany, a district heated by GBs is used as our baseline system. For comparison, an identical district is constructed, but the GBs is replaced with HPs. The installation of HPs usually incurs higher costs in terms of investment, energy, and maintenance, but simultaneously results in lower CO_2 emissions. Therefore, the abatement cost is derived by dividing the additional cost incurred by HPs by the amount of emission savings. In our study, the Equivalent Annual Cost (EAC) is used to describe the yearly cost of owning, operating, and maintaining GBs or HPs over their lifetimes.

$$EAC = \frac{C_{inv}}{a^{20}_{0.035}} + C_{OPEX} \tag{26}$$

$$a^n_i = \frac{1-(1+i)^{-n}}{i} \tag{27}$$

$$C_{OPEX} = C_{energy} + C_{maintenance} \tag{28}$$

$$CAC_{hp} = -\frac{EAC_{hp} - EAC_{gb}}{e_{hp} - e_{gb}} \tag{29}$$

where a^n_i is the annuity factor. The lifetimes of GBs and HPs are assumed to be 20 years and the discount rate is set to 3.5%. EAC is calculated by dividing the investment cost by this annuity factor and adding the Operating Expense (OPEX) as shown in Equation (26). The OPEX comprises energy costs and maintenance costs, which are accounted for annually, as shown in Equation (28). The CO_2 abatement cost (CAC) is then calculated by dividing the difference in EAC by the difference in emissions as shown in Equations (29). A "minus" sign is added to convert the value to positive.

Regarding the power grid, the following metrics used in [18] are used in our study to evaluate the impacts of the large-scale HP rollout on the distribution infrastructure.

$$P^{elec}_{t,b,load} = D^{elec}_{t,b} + P^{elec}_{t,b,hp} + P^{elec}_{t,b,ev} \tag{30}$$

$$f_{SS} = \frac{\sum_t \sum_b min(P^{elec}_{t,b,pv}, P^{elec}_{t,b,load})}{\sum_t \sum_b P^{elec}_{t,b,load}} \tag{31}$$

$$f_{SC} = \frac{\sum_t \sum_b min(P^{elec}_{t,b,pv}, P^{elec}_{t,b,load})}{\sum_t \sum_b P^{elec}_{t,b,pv}} \tag{32}$$

$$f_{LOLP} = \frac{\sum_t \alpha_t}{\sum_t 1} \tag{33}$$

$$\alpha_t = \begin{cases} 1, & \text{for } P^e_{t,import} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{34}$$

$$f_{GII} = Std.Dev\left[\frac{P^e_{t,import} - P^e_{t,export}}{max|P^e_{t,import} - P^e_{t,export}|}\right] \tag{35}$$

In essence, the Self-Sufficiency (SS) f_{SS} represents the fraction of the electrical demand on site met by on-site generation. A high ratio is desired as this would mean that the community could meet most of its demands without importing from the electrical grid. The Self-Consumption (SC) f_{SC} represents the fraction of production on site that is used to meet demand on site. The Loss Of Load Probability (LOLP) f_{LOLP} represents the fraction of time when on-site generation is insufficient and energy must be imported from the grid. Finally, the Grid Interaction Index (GII) f_{GII} represents the variability of the energy flow with the grid, normalized with the maximum net flow of electricity.

2.5. Measurement of CO_2 emissions

Multiple methods exist for measuring CO_2 emissions. In this study, a widely accepted approach is employed to evaluate direct and indirect CO_2 emissions related to energy production and consumption, specifically those emissions directly released into the atmosphere. This method aligns with established works such as [11,12,19]. However, [20] introduces a new metric, CO_2 emission responsibility, which differs from standard CO_2 emission measurement techniques. The author argues that certain technologies, even when using exclusively renewable energy, destroy high amounts of exergy and result in high CO_2 emission responsibility. Hence, he proposes to measure CO_2 emission responsibility in relation to a benchmark energy system that maximizes exergy efficiency. While considering the exergy efficiency of technologies is certainly useful, we decided to stick to the more conventional approach of directly measuring CO_2 emissions due to the following reasons:

- In contrast to direct and indirect CO_2 emissions, CO_2 emission responsibility cannot be readily measured, which complicates comparisons between different technologies. In [20], the author states that "the main difficulty of recognizing and metricating ΔCO2 (CO_2 emission responsibility) is the fact that it cannot be observed and measured onsite of the process. Only the direct emissions, CO_2 may be observed and measured onsite, like from the chimney of a boiler."
- Defining an exergy-minimal benchmark system is challenging, as it involves all energy providers and consumers. Thus, an analysis limited to a neighborhood as done in this paper would no longer be possible. In [20], the author states that "a second difficulty (of metricating CO_2 emission responsibility) is the fact that some destroyed exergy could be offset outside the city limits. This needs to expand the analysis to the world, which is not practical."
- The most exergy-efficient system is not always feasible due to practical considerations such as energy source availability and high investment costs, which are explicitly accounted for in our study.
- By 2050, HPs are predicted to operate primarily during times of electricity surplus that would otherwise require curtailment. This significantly reduces CO_2 emission responsibility resulting from the electrification of residential heating by HPs.

3. Case study

In this section, the design of our case study will be introduced. It comprises two parts: calculation of CO_2-abatement through the installation of residential HPs and sensitivity analysis to find the most cost-effective way to reduce CO_2 emissions.

In the first part, scenarios are built with either GBs or HPs, wherein all households are heated by these devices. While the scenario with GBs is always equipped with rule-based control, the scenario with HPs is simulated with either rule-based control or MPC. Here, MPC represents

Table 1
Scenarios in the case study.

Scenario	Heating device	Controller
GB	Gas boiler	Rule-based
HP (no DSM)	Heat pump	Rule-based
HP (DSM)	Heat pump	MPC

the use of a district central controller and the energy management system described in Section 2.1. For an overview, the information for the scenarios is summarized in Table 1.

In the second part, a variety of conditions are examined in terms of their influence on CO_2 abatement cost. For each condition, simulations of the scenarios described above will be performed to obtain the results. The parameters to be investigated include levies, emission intensity, renovation standard, PV capacity, TES size, and HP investment cost.

The simulation year is fixed for 2045, as this is the year that Germany is going to become greenhouse neutral. The UrbanReNet results are used to define the different types of district [21]. UrbanRetNet uses the “method of Typification” to research and analyze existing typologies of settlements and open spaces to identify common characteristics and patterns of urban and rural districts. Based on this, apartment blocks of different sizes and single-family detached buildings are chosen for urban and rural districts, respectively. A mixture of buildings is sampled to reflect the real situation. The size of the districts is determined on the basis of the number of households connected to a local transformer. Therefore, 110 households are assumed for both the urban and rural districts. For the energy standard, KfW-70 is chosen for all buildings, signifying that the primary energy consumption of these buildings is just 70% of the reference building as defined in the German building energy act. This standard is set by one of the largest national investment banks “Credit Institute for Reconstruction” in Germany [22].

Based on the representative districts described above and the modeling methodology described in Section 2, a year-long simulation is conducted for each scenario presented in Table 1. The simulations operate at a time resolution of one hour. Details on the input parameters can be found in Section 3.1 to 3.4.

Indicators in Section 2.4 are calculated based on the data to compare performance between different scenarios. CO_2 abatement cost is compared between GBs and HPs associated with both rule-based control, and it can be determined how much benefits the electrification of the heat sector by introducing HPs can bring. In addition, by comparing the results of HPs with and without DSM, the benefits of using HP flexibility can be quantified in terms of cost and emission savings. Subsequently, the influences of HP on the local power grid will also be analyzed with the help of appropriate indicators.

3.1. Emission factor and commodity prices

The emissions for natural gas remain constant throughout the year. However, the electricity emission factors are dynamic and fluctuate across different seasons. To obtain the hourly emission factors of electricity, the data set of research on hourly CO_2 emission factors was implemented, providing values at 1-hour resolution based on a mix method [23].

To calculate the cost of electricity for end users, four price components must be taken into account: wholesale prices, retailer sales, network charges, and taxes. Time series data from [23] was used to represent price fluctuation in wholesale markets, resulting in an annual weighted average of 75 €/MWh. For the other components, for simplicity, the costs for retail sales, network charges, and taxes are assumed to be the same as the current values. They cost consumers 20, 78, and 82 €/MWh, respectively, as reported in [24]. The current prices of natural gas for end users consist of generation costs and other fees, which are 90 €/MWh. However, the prices of natural gas in 2045 are expected to rise due to an increase in the CO_2 price. Given a CO_2 price of 5.4 €/MWh in 2023, the natural gas prices will increase to 100 €/MWh using the same assumption of a price increase 5% p.a. as in [11]. The prices for natural gas are assumed to remain constant for one year.

Table 2
Emission factors and commodity prices for electricity and natural gas.

	Electricity	Gas
Emission factor [g/kWh]	84	199
Commodity price [€/MWh]	255	100

Table 3
Sizing parameters for the urban and rural district.

Energy device	Urban	Rural
Gas boiler/ Heat pump [kWth/HH]	10	23
Thermal energy system [kWh/HH]	40	40
Photovoltaic [kWp/HH]	2.9	7.5
EV penetration [%]	38	100
Transformer [kVA]	630	1200

Table 4
Investment costs.

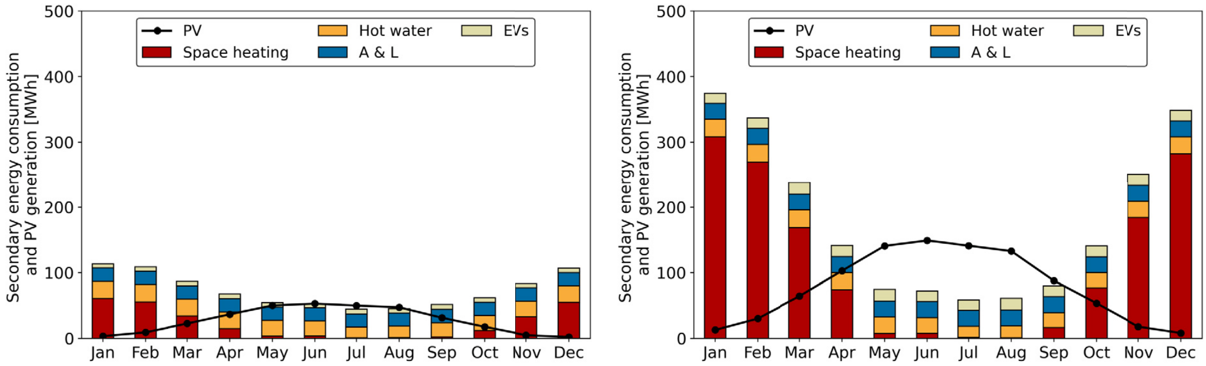
Asset	Fixed	Variable
Gas boiler	3200 €/HH	-
Heat pump	9450 €/HH	385 €/kW_{th}
DSM (district)	10000 €	1000 €/HH

Table 2 provides a summary of the emission factors and the load-weighted prices for end-users, including both electricity and natural gas.

3.2. Sizing energy devices

The thermal power for the heating system must be precisely sized. For scenarios with GBs or HPs, their thermal power is assumed to be the same to ensure comparability. The sizing process is carried out by a prior simulation study, which is an iterative process to find the minimum thermal power needed for each building. It starts with small values and increases by an interval in each iteration until the heat demands are satisfied over one year. This process results in thermal power of 9.8 kW and 31.5 kW on average needed for each household in the urban and rural districts, respectively. The TES capacity is assumed to be 40 kWh for each household, which presents a typical value. The installation of PV is dependent on the potential roof area and the solar irradiance. Only roof areas where solar irradiance exceeds 700 kWh/m^2/a are considered for installing PV panels. This leads to a 2.9 kWp and 7.5 kWp each household for the urban and rural districts, respectively.

To determine the penetration level of EVs in 2045, a dataset from the report [25] revealing the future development of electric vehicles' numbers is used. Using the number of households in Germany (41 million) [26] and an urbanization rate of 78%, the penetration level of EVs is calculated in 2045. Our results are validated by comparing them with those in [27]. Based on research from [28], the transformer for the districts in our study has a power rating of 630 and 400 kVA for the urban and rural districts, respectively. However, through prior simulation, the current transformer in the rural district is not sufficient for the large amount of HPs, PVs and EVs. Therefore, the transformer in the rural district is enhanced to approximately 1200 kVA by a sizing process similar to the heat generator. The power factor of the local grid is assumed to be 0.9 for both districts. The size parameters are shown in Table 3.



(a) Urban

(b) Rural

Fig. 5. Seasonal distribution of energy consumption for the urban and rural district (A & L: appliances and lighting).

3.3. Investment cost

To complete the calculation of the abatement cost introduced in 2.4, the investment cost of GBs and HPs must be determined. According to the literature [29], the fixed cost and variable cost for HPs are 9450 € and 385 €/kW$_{th}$. For GB, 3200 € fixed cost is assumed without variable cost. In the case of HPs with DSM, the additional cost of DSM is incorporated, consisting of 10000 € for the central controller and 1000 € per household for other communication infrastructure such as cables and sensors [30]. The other investment cost is not considered because they are the same for both scenarios and will be offset in the calculation of abatement cost. Table 4 shows a summary of investment costs.

3.4. Weather data and demand profiles

For weather data, the predicted EPW data for 2050 are used, specific to the location in Potsdam. The EPW weather data format has been adopted as a standard format by many other building simulation tools. The data for fixed electrical demand and internal gains are derived from a Residential Electricity Demand Model (REM) [31]. The REM employs activity-based modeling to predict residential electricity demand. This involves modeling individual end-use components across various load categories, enabling the accurate simulation of large numbers of individual household profiles with a high time resolution as fine as one second. This level of detail is useful for developing and evaluating energy efficiency measures in the residential sector.

The demand for DHW was obtained from DHWcalc [32]. DHWcalc is a computer program that generates DHW demand profiles based on statistical data. SH demand is calculated based on the RC-model introduced in Section 2.2. In this study, perfect prediction is assumed for system disturbances. Therefore, the results presented here represent the highest possible operational and CO_2-emission savings.

4. Results

4.1. Energy consumption

In this section, the disparity in energy consumption patterns between urban and rural districts is demonstrated, which forms the basis for our subsequent investigation and analysis. In our monthly assessment of energy consumption patterns in these two types of districts, five key categories are examined: space heating, domestic hot water, electric vehicles, appliances and lighting, and photovoltaic, as shown in Fig. 5. Distinctive differences in consumption and production between the two districts were observed.

The rural district exhibits significantly higher consumption in the category of "space heating" compared to the urban district. This increase can be attributed to the larger living areas and less efficient heating systems typically found in rural homes. On the contrary, due to the wider availability of space and increased exposure to sunlight, the rural district can generate nearly triple the amount of photovoltaic energy compared to urban districts. This significant photovoltaic energy production partially compensates for their higher space heating consumption. Although the consumption related to electric vehicles in the rural district is higher than in the urban district, the consumption for domestic hot water and fixed electrical load is almost the same in both types of districts.

4.2. Power flows and energy balance

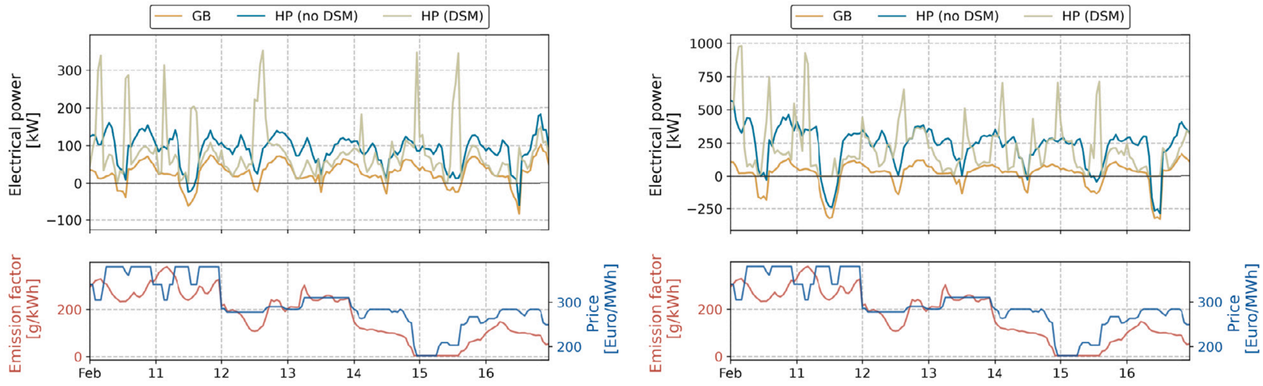
When comparing the power flows of the local transformer in different energy systems, different patterns emerge based on various heating scenarios: GBs, HPs without DSM, or HPs with DSM, as shown in Fig. 6.

The energy system powered by GBs primarily demonstrates a base load profile with limited flexibility, as there are no resources available for demand response. This results in the lowest power flows on the transformer, indicative of a more steady and predictable energy consumption pattern. On the other hand, the scenario with only HPs shows a similar pattern to the one with GBs, but with a greater magnitude. This is because HPs operate continuously to keep the indoor temperatures nearly constant and their power consumption is added on top of the fixed loads.

In contrast, scenarios that use HPs with DSM exhibit highly volatile power flows on the transformer. This combination provides an added advantage by being sensitive to fluctuations in the price of electricity. This allows the system to strategically adjust its operations in response to price changes, thereby optimizing costs through dynamic consumption. It can be observed that the scenario with HPs and DSM tends to schedule the operation of HPs more at night, taking advantage of lower-priced electricity provided by abundant wind energy, or around midday, leveraging the high efficiency of HPs at higher ambient temperatures.

It is important to note that while the basic patterns of urban and rural districts are similar, there are notable differences in the magnitudes of their fluctuations. Rural districts exhibit greater fluctuation, reflecting higher demand peaks and larger power feed-ins. This underscores that the geographical location of the district also significantly influences these patterns.

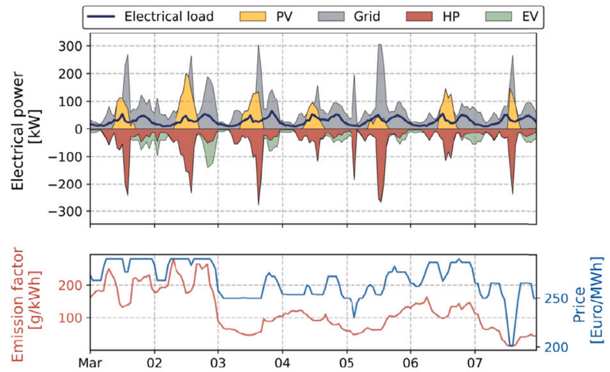
In our analysis of 7-day power and thermal balances in March, results from scenarios with both HPs and DSM are demonstrated. In addition, the corresponding zone temperature courses are presented in urban and rural districts. The balance of power is influenced by several power flows, including fixed electrical load, photovoltaic generation, import or export from the grid, HP operation, and EV charging (Figs. 7(a) and 7(b)). Among these, fixed-load, HPs, and EVs are consumers of power. When demand exceeds local photovoltaic production, electricity



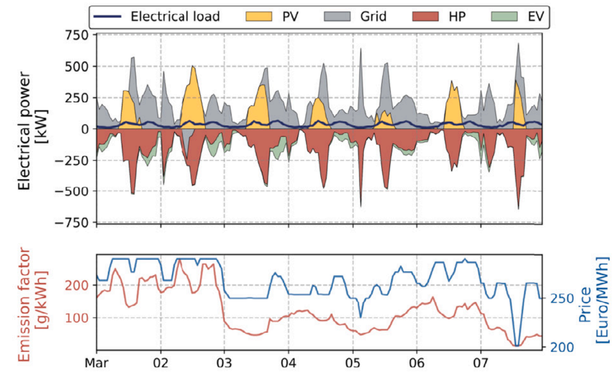
(a) Urban

(b) Rural

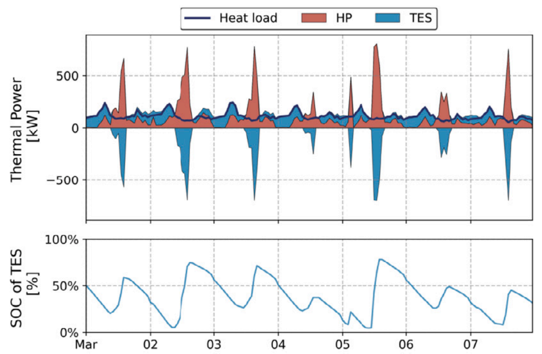
Fig. 6. Comparison of power flows on the transformer.



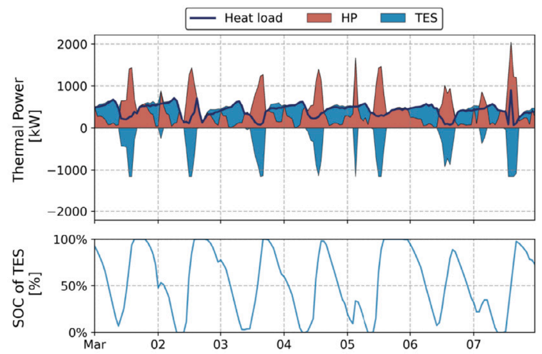
(a) Power balance of the urban district



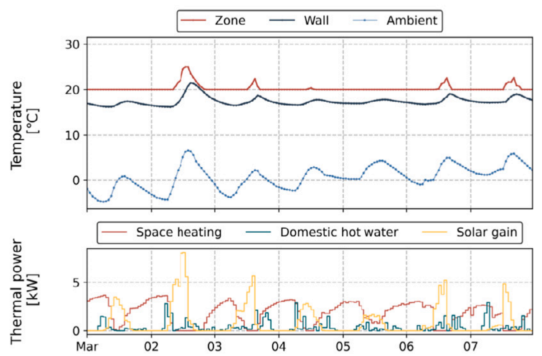
(b) Power balance of the rural district



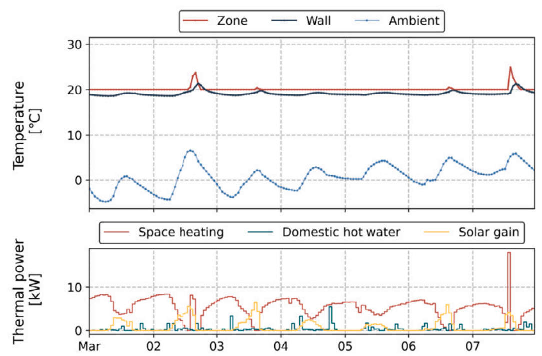
(c) Thermal balance of the urban district



(d) Thermal balance of the rural district

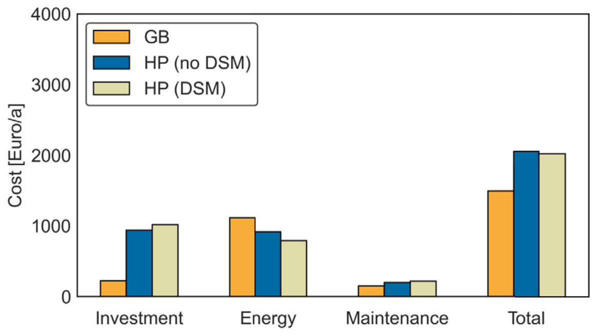


(e) Temperature and heat gains of one zone in the urban district

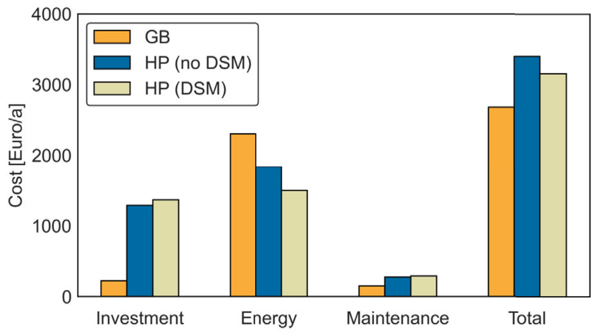


(f) Temperature and heat gains of one zone in the rural district

Fig. 7. Energy system operation in the urban and rural district.



(a) Urban



(b) Rural

Fig. 8. Equivalent annual cost per household.

Table 5
EAC, emissions and CO_2-abatement cost per household.

District	Case	Equivalent annual cost [€/a]	Emission [kg/a]	CO_2-abatement cost [€/ton]
Urban	GB	1492	1415	-
	HP (no DSM)	2060	290	504
	HP (DSM)	2028	236	455
Rural	GB	2683	3657	-
	HP (no DSM)	3404	513	229
	HP (DSM)	3159	392	146

is imported from the external grid. In contrast, excess photovoltaic generation is exported back to the grid. The fluctuation of emission factors and electricity prices (wholesale price + levies) is provided as background information.

The thermal balance, on the other hand, is maintained by HPs and the TES, which provides charging or discharge capabilities to address thermal surpluses or deficits (Figs. 7(c) and 7(d)). The combined thermal output of these systems should meet the heat load from space heating and domestic hot water consumption. The SOC indicates the aggregated values of the entire district. Daily zone temperature variations are illustrated in Figs. 7(e) and 7(f) to show how zone and wall temperatures change depending on factors such as ambient temperature, thermal power for space heating, and solar gain.

Despite large photovoltaic production, most is absorbed by HPs through DSM, minimizing the need for excess power to be fed into the external grid. HP operations are scheduled primarily around noon to take advantage of higher ambient temperatures and often lower electricity prices, maximizing efficiency and cost-effectiveness. On the contrary, although electricity prices are lower at night, HPs rarely run during these times. This is because the COP of ASHP is very sensitive to ambient air temperature. The lower electricity prices at night do not offset the efficiency losses of HPs running during these times. Furthermore, it is observed that optimizations to minimize costs usually result in lower emissions, as CO_2 emission factors are somewhat correlated with electricity prices during this season.

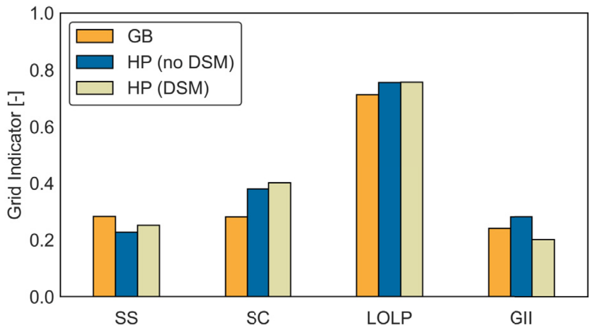
The thermal energy system plays a key role in the flexibility of the system, being frequently fully charged around noon when free photovoltaic sources are available. It provides essential balance to the thermal load and prevents the inefficient operation of HPs at night. In rural districts, with larger heat loads, the thermal energy system undergoes a greater depth of discharge, indicating potential benefits from a larger TES.

In contrast, the thermal inertia of the building offers less flexibility to the energy management system than TES, as its utilization often leads to increased zone temperatures and hence more heat losses. This is particularly notable in urban districts, where zone temperatures mostly remain at 20 degrees, except for times with large solar gain. However, an interesting demand response in rural districts was observed at noon on the 7-th day, with a clear power spike due to the fully charged thermal energy system and extremely low electricity prices. Only in this situation was zone overheating by DSM a worthwhile trade-off between cost and efficiency.

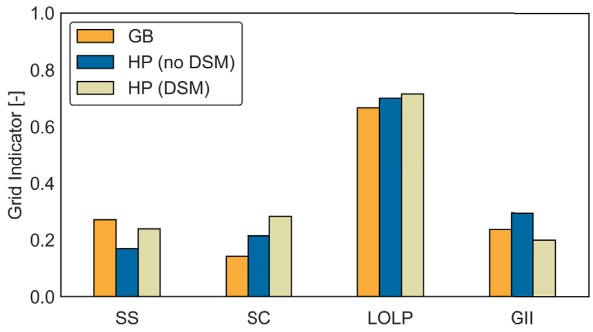
4.3. CO_2-abatement cost

The CO_2 abatement cost is calculated using the method introduced in Section 2.4, with investment costs outlined in Section 3.3. It should be noted that the investment costs for HPs far exceed those of GBs. Despite this, the energy cost after HP installation falls to about 80% of the cost of GBs due to the higher efficiency of HPs and the relatively high prices of natural gas. The relatively small cost savings are primarily attributed to high electricity prices, which are driven by levies such as CO_2 prices, taxes, and network surcharges. Although maintenance costs differ significantly between systems, they constitute only a small fraction of the total cost and, as such, have a limited impact on the EAC. Figs. 8(a) and 8(b) show more details of this calculation process.

This EAC and CO_2 emissions are demonstrated in Table 5, followed by the CO_2-abatement cost. In urban districts, the scenario with only HPs results in a CO_2-abatement cost of 504 €/ton. When DSM is added to the system, the CO_2-abatement cost increases to 455 €/ton, due to higher energy cost and emission savings. In contrast, in rural districts, the CO_2-abatement cost is significantly lower than in urban areas. This is due to the higher heat loads and the associated high initial emissions of the GB heating system in these areas. By replacing the emission-intensive natural gas with emission-free electricity (primarily sourced from renewables), significant CO_2 savings can be achieved, which substantially reduces the CO_2-abatement cost. Indeed, in rural districts, the scenario integrating DSM exceeds the performance of the scenario without DSM more markedly than in urban districts. This suggests that DSM yields greater benefits in an energy system with a higher heat load, as it offers a greater potential for reductions in energy costs and CO_2 emissions.



(a) Urban



(b) Rural

Fig. 9. Performance indicators for power grid.

4.4. Impacts on power grid

Increasing the penetration of HPs within the energy mix has implications not only for the reduction of carbon emissions but also for the stability of the power grid. There is the potential for an increase in electricity consumption and residual peak demand, which could pose stability risks to the local power grid.

Performance indicators have been calculated, as discussed in Section 2.4, to understand the impact of such scenarios (Fig. 9). Notably, it was found that self-sufficiency decreases as HPs are incorporated due to an increase in electrical consumption. However, when DSM is added to the energy system, this decrease in self-sufficiency is mitigated. This can be attributed to the fact that DSM facilitates better utilization of local photovoltaic power, counterbalancing the effects of the increased electricity demand. With regard to self-consumption, the integration of HPs can significantly increase the utilization of local PV power, as they can absorb excess PV power that would otherwise be exported to the grid. In addition, DSM can amplify these effects, resulting in an even higher self-consumption rate.

LOLP, which provides the probability that local generation will not meet local demand, does not increase substantially in scenarios with a large HP deployment in both urban and rural districts, despite their additional electricity demand. This is because HPs are primarily scheduled to operate during times of abundant solar availability, thus minimizing the need for significant electricity imports from the external grid and mitigating potential load issues within the district. The GII, which measures the variability of the residual peak demand and the maximum feed-in power, experiences an increase with the integration of heat pumps. In contrast, the introduction of DSM leads to a decrease in GII.

4.5. Sensitivity analysis

The conditions under which HP deployment achieves optimal CO_2 reduction in a cost-effective manner can be complex. They may depend on numerous factors such as building renovation standards, available PV resources, investment costs, etc.

A sensitivity analysis was implemented to assess the impacts of various factors, including electricity levies, emission intensity, renovation standards, PV penetration, district size, and the costs of HPs and DSM on the CO_2-abatement cost (Fig. 10). Variants and their definitions are provided in Table 6. This analysis not only tests the robustness of the results against the uncertainty of these input parameters but also provides information on the conditions under which transitioning to HPs is cost-effective. It is important to note that costs associated with PV, TES, or building insulation are omitted in this analysis, as they are assumed to be pre-existing.

A reduction in the electricity levy results in a considerable decrease in the CO_2-abatement cost. For example, a 50% reduction in the levy equates to a decrease in the CO_2-abatement cost by 100 €/ton. Analysis of emission intensity suggests that a higher emission intensity impedes the CO_2 mitigation potential of HPs, as HPs consume significant amounts of electricity. CO_2-abatement costs in well-insulated buildings are found to be much higher than in buildings with moderate or poor insulation, which can be attributed to the limited abatement potential in these highly energy-efficient buildings.

A decrease in PV penetration leads to an increase in CO_2-abatement cost, probably due to fewer PV systems and less local generation. A smaller TES size, which implies less flexibility potential, also results in a modest increase in CO_2-abatement cost. Reducing the costs of HPs and DSM can significantly lower the CO_2-abatement cost, with a 50% cost reduction that could lead to a negative CO_2-abatement cost due to the large proportion of HP investment cost in the EAC.

The benefits of additional DSM alongside HP become more significant in scenarios with high emission intensity, compared to the reference scenario. However, changes to other parameters have minimal or even negative impacts on the added value provided by DSM.

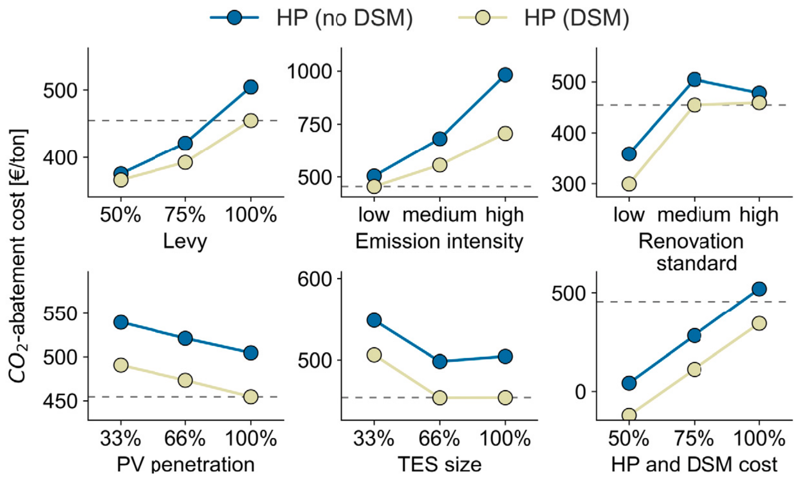
The results of the sensitivity analysis are summarized in a performance map (Fig. 11), showing both the abatement cost (represented by the slope as a dashed line) and the abatement potential (represented by the value of the y axis). Generally, scenarios with a larger slope and higher values on the y-axis represent more viable conditions, as replacing GBs with HPs in these scenarios brings about more abatement potential and is also cost-effective. Compared to the urban district, the rural district not only shows a higher abatement cost but also a greater abatement potential.

5. Discussion

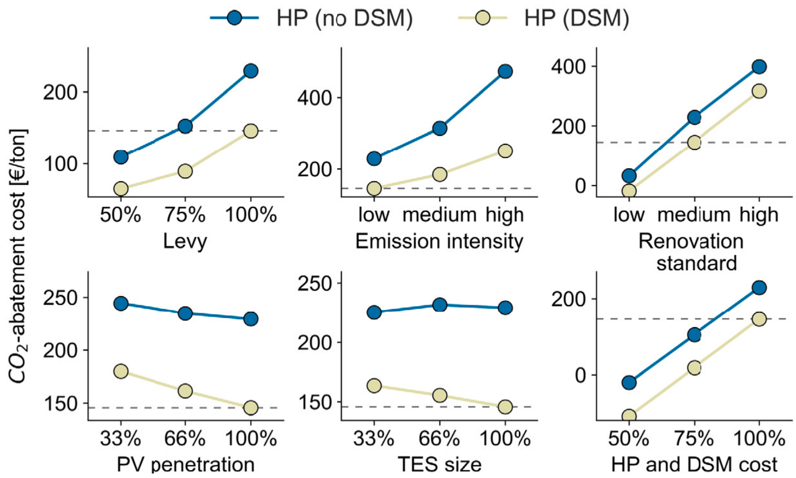
The specific costs associated with CO_2 abatement through the installation of residential HPs can vary significantly between urban and rural districts. In urban districts, the CO_2-abatement cost reaches 504 €/ton. This is because concentrated housing in urban areas could lead to a potential reduction in heat consumption and lower CO_2 emissions heated with GB. Therefore, this results in lower abatement potential through electrification of the heat sector. This lower potential for emission savings, combined with the high investment cost of HPs, results in a high CO_2-abatement cost. On the contrary, in rural areas, the CO_2 abatement cost is considerably lower, reaching a more modest 229 €/ton. This can be mainly attributed to the dispersed nature of housing in rural districts, which require higher heat production and therefore result in higher CO_2 emissions when using traditional GBs. Therefore, the transition to HP results in a more substantial reduction in CO_2 emissions in rural areas. Finally, despite a higher investment cost than in the urban district, greater emission savings in the rural district lead to a lower CO_2 abatement cost. Therefore, rural districts tend to be more favorable environments for cost-effective HP deployment as a CO_2 abatement solution. The insights of this analysis underline the

Table 6
Scenarios in the sensitivity analysis.

Scenario	Abbr.	Explanation
Reference	ref	Scenario used in the analysis from Section 4.1 to Section 4.4
Levy cost of electricity	levy	100% for ref; 75% and 50% means scenarios with levy reduction
Emission intensity	emi	“low” for ref; “medium” uses emission intensity in 2030, “high” in 2020
Renovation standard	revo	“medium” for ref; “low” for no renovation and “high” for KfW-40 standard
PV penetration	pv	100% for ref; 66% and 33% mean less households are installed with PVs
TES size	tes	100% for ref; reduced to 66% and 33% of the reference size
Cost of HPs and DSM	hp	100% for ref; 75% and 50% indicate less fixed and variable cost



(a) Urban



(b) Rural

Fig. 10. Sensitivity analysis of CO_2-abatement cost. The dashed lines indicate the value in the reference scenario (HP+DSM).

importance of location-specific considerations when planning and implementing residential heating decarbonization strategies.

The DSM systems show great potential to improve the HP efficiency for CO_2 reduction. With the adoption of DSM, the centralized controller is aware of the fluctuations in electricity prices and therefore able to schedule the operation of HPs during times of lower electricity prices, thus reducing CO_2 abatement costs. As demonstrated in Section 4.2, scenarios that include DSM tend to schedule the operation of heat pumps more frequently at night, leveraging the lower-cost electricity provided by the abundant supply of wind energy, or around midday, taking advantage of the high efficiency of heat pumps at higher ambient temperatures. Therefore, DSM can maximize the potential of fluctuating electricity prices and COPs of HPs. Furthermore, DSM brings significant advantages to the power grid side. As described in Section 4.4, DSM can compensate for most disadvantages caused by a large number of heat pumps, particularly in terms of power variability.

Sensitivity analysis suggests that rural districts and buildings with lower energy efficiency standards are prime candidates for the deployment of HPs to replace GBs. These locations not only offer lower abatement costs but also a high potential for CO_2 reduction. However, one critical factor that was not taken into account is the increased peak load burden and the necessary cost of improving the grid that could arise from a significant increase in the heating capacity of HPs.

As for other conditions, the HP investment cost is the most crucial factor, although this is unlikely to decrease significantly in the future. An early transition to HPs under conditions of high electricity emission intensity could result in double the abatement cost. On the contrary, the deployment of HP with larger TES could help reduce the abatement

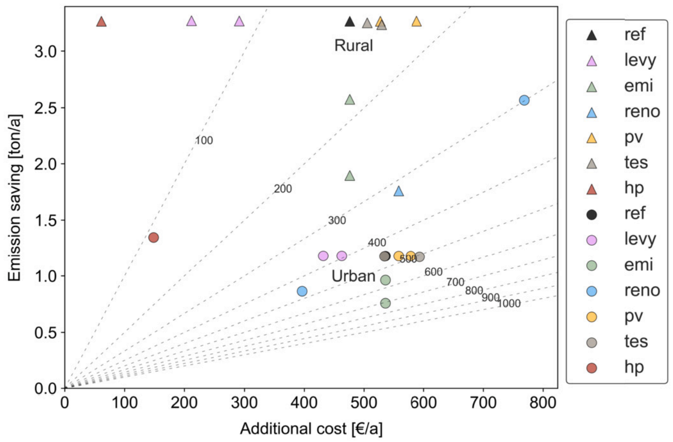


Fig. 11. Performance map of CO_2-abatement for all scenarios. Emission savings and additional costs are given per household. Dashed lines indicate CO_2-abatement cost. Points with negative additional costs are not shown. The point of rural "low" renovation standard is omitted because it is far from other points.

cost. Interestingly, local PV penetration does not play a significant role if the nationwide electricity emission intensity is low.

Therefore, these findings underscore the need for a strategic approach to promote the electrification of the heating sector. Given the wide-ranging impacts of different conditions on both CO_2-abatement costs and potential, policy interventions should be carefully tailored to specific contexts. Examples of these interventions could include, for example, targeted incentives for HP adoption in rural areas or buildings with lower energy efficiency standards, as well as investments in DSM or advanced energy storage technologies to accommodate the increased peak load resulting from HP deployment.

The research carried out by Patteeuw et al. [12] shows varying results when implementing scenarios with air source HPs and radiators. They found that the CO_2 abatement cost ranges from 250 to 600 €/ton for thoroughly renovated detached and terraced buildings by 2030. For "mildly" renovated buildings, these values increase to 700 to 1700 €/ton. This difference is due to their inclusion of the investment in extra electric peak power capacity due to the nation-wide deployment of HPs, where the extra electric peak power is covered by open cycle gas turbines, the most expensive variant. However, our study omits these additional supply-side costs. This stems from our assumption that, by 2045, there would be a higher penetration of renewable energy and advanced energy storage technology, which would reduce the necessary additional peak power capacity. Furthermore, the anticipated surge of EVs and PVs would lead to more investment in power infrastructure, but the additional investment in network infrastructure should not be solely attributed to HPs. Based on this, poorly insulated buildings deserve greater attention for decarbonizing heat demand, because they demonstrate lower abatement costs and higher abatement potential, assuming the costs of new power plants are ignored. Regarding DSM, less advantages are found in our scenarios compared to theirs. This is because these values are computed from the perspective of end consumers, while they incorporate the effects of DSM on peak power reduction and its impact on investment savings in peaking power plants. Differences in methodology can significantly affect the economic benefits perceived from DSM.

The research from [20] introduced a novel method to account for CO_2 emission responsibility that is not directly recorded within a specific energy system and cannot be measured directly or indirectly via CO_2 emission factors. Such emissions are associated with exergy destruction during energy conversion. For instance, employing electricity for residential heating via HPs results in considerable exergy losses compared to utilizing low-temperature energy sources, making them a sub-optimal technology from this perspective. This leads to a greater responsibility for exergy-related CO_2 emissions, even if the electricity consumed comes from renewable sources. This is because more exergy-efficient technology would have consumed fewer energy resources in total. Therefore, these CO_2 emissions are calculated in relation to a benchmark energy system that maximizes exergy efficiency. However, defining such a system poses challenges, as it requires the definition of an exergy-minimal energy system that encompasses all energy providers and consumers. Thus, a localized analysis as conducted in this paper becomes unfeasible. Furthermore, the most exergy-efficient system might not always be viable due to practical constraints like energy source availability and investment costs, which we specifically address in our study. Another point to note is that by 2050, HPs are anticipated to operate predominantly during periods of electricity surplus, considerably diminishing the CO_2 emission responsibility associated with electrifying residential heating. As a result, our study focuses on measurable direct and indirect CO_2 emissions.

6. Limitation

Our study focuses on direct and indirect CO_2 emissions associated with energy production and consumption. Due to reasons outlined in Section 5, CO_2 emission responsibility arising from exergy destruction during energy conversion is not considered.

7. Conclusion

Our research used a bottom-up model of the district energy system to study the costs of reducing CO_2 emissions by installing residential HPs in urban and rural districts. Model-predictive control was used for the demand side management to minimize costs and to calculate the overall cost of setting up HP systems with the equivalent annual cost method.

The key findings of this work are: (i) urban districts face higher CO_2 abatement costs (504 €/ton) compared to rural districts with lower costs (229 €/ton) due to differences in housing density and heat demand, (ii) integrating DSM with HPs leads to significant reductions in CO_2 abatement costs: 10% in urban and 36% in rural areas, also aiding in power grid stability, (iii) lower HP investment costs and the electricity emission factor play crucial roles in substantially lowering CO_2 abatement costs.

This study underscores a cost-effective strategy for reducing emissions through heat pumps, establishing guidelines for district-level investments that target low-carbon objectives. The findings provide key insights for the transition from conventional heating systems to heat pumps, helping policymakers craft informed policies. Further studies could expand to a wider range of building types and climatic conditions to encompass diverse district patterns and regions.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Chapter 4

Discussion

This chapter provides a concise summary of the advantages and disadvantages of three strategies for harnessing the flexibility of residential HPs. It focuses on their economic benefits and their role in promoting smart and sustainable energy consumption. Finally, the chapter positions this research within the existing body of literature, underscoring its substantial contribution and relevance to the field.

4.1 Economic advantages

As discussed in Chapter 3.1, participating in LEMs offers economic benefits to districts, primarily through reduced electricity costs and better feed-in tariffs. Notably, with a 40% HP and 50% PV penetration, a single household has experienced a 5.1% energy cost reduction of approximately 1200 euros annually, although this varies based on the number of HPs and PVs involved in LEMs.

The profitability from ancillary service in local flexibility markets depends greatly on flexibility pricing and the grid operator's demand for flexibility, as elaborated in Chapter 3.2. Depending on the pricing strategy, potential revenues from flexibility trading could be about 10% of the original electricity costs, equivalent to roughly 3 cents per kWh of provided flexibility [76]. The flexibility demand, influenced by renewable energy capacity and infrastructure, is another critical factor. While exact data on flexibility demand is sparse in existing literature, rough estimates suggest daily revenues per household could range from 9 to 30 cents (33 to 110 euros annually), assuming an average daily flexibility demand of 3 - 10 kWh. For an urban household with an annual energy cost of 1200 euros, this equates to an energy cost reduction between 2.8% and 9.2%.

DLC programs also result in substantial cost savings. As mentioned in Chapter 3.3, implementing a DEMS in an urban district can lead to a 17% reduction in energy costs. It's important to note that this case study assumes full HP installation in every household and PV panels on every building within the district.

Table 4.1 summarizes these cost savings. Price-based DRPs through LEMs offer a considerable 5.1% cost reduction, demonstrating notable savings potential even at medium HP and PV penetration levels. Flexibility provision through HEMS presents moderate revenue potential, but trading in local flexibility markets carries a significant risk: if ancillary services are seldom requested, savings could diminish. Flexibility via DEMS and DLC yields the highest savings. However, these values depend on the specific configurations of each case study and should only be viewed as preliminary guidelines or references.

DRP	Application	Energy cost saving	Remarks
Real-time pricing	LEM	5.1%	40% HP, 50% PV
Ancillary service	HEMS	2.8% - 9.2%	3-10 kWh flexibility demand
Direct load control	DEMS	17%	100% HP, 100% PV

Table 4.1: Energy cost saving percentage with various DRPs: Note that configurations vary for each case study. "40% HP" indicates scenarios where only 40% of households have installed HPs

4.2 Smart and sustainable energy consumption

Three distinct DRPs contribute to smart and sustainable energy consumption in unique ways, as detailed in Chapter 1.2. This section compares these DRPs, assessing their strengths and weaknesses based on experiences gained during the investigation.

DLC shows the most promise in terms of balancing energy generation and consumption. System operators can directly regulate HP operations, optimizing timing to alleviate grid congestion. The control over the duration and intensity of interventions is precise. DRPs as ancillary services also aid energy balance within a market-based framework, though limited by flexibility bids from end-users. Real-time pricing in LEMs, however, is less reliable due to the unpredictable nature of its trading process.

For user comfort, HEMS and LEMs perform better by allowing users to manage their energy systems with comfort as a priority. In contrast, DLC can lead to discomfort due to the external control of HPs, potentially causing unwanted temperature changes.

In interconnectivity, DLC, typically supported by a DEMS, can aggregate extensive data for optimal device coordination. This facilitates coordination and communication among flexible devices and optimizes energy flows and consumption. Real-time pricing in LEMs can also facilitate indirect device communication via price signals and offer limited interconnectivity. Ancillary services focus on individual HPs, lacking broader interconnectivity.

DRPs with DLC shows the best performance in integrating renewable energy, utilizing comprehensive forecasting data for optimal use of RES. Real-time pricing can encourage renewable integration through pricing incentives, but not as effectively as DLC. Ancillary services is aimed at balancing energy generation and consumption and can therefore indirectly support renewable integration but have a lesser impact.

Concerning environmental impact, real-time pricing in LEMs and ancillary services in local flexibility markets both contribute to CO_2 emission reduction by encouraging renewable energy use. However, due to pricing incentives, LEMs may outperform ancillary services. DLC can further reduce emissions by integrating real-time national electricity emission factors, making it more effective in minimizing CO_2 emissions.

Economically, as described in 4.1, DRPs that utilize DLC through DEMS result in the highest cost savings. This efficiency stems from the near-perfect control over flexible loads, like HPs, in response to spot market prices, though it may come at the cost of end-user privacy and comfort. Real-time pricing in LEMs offers moderate and consistent cost savings. Conversely, the savings potential from ancillary services in local flexibility markets is relatively lower, with increased risks due to fluctuating flexibility demand. To enhance the appeal of this approach, it may be necessary to increase the prices offered for providing flexibility.

In terms of feasibility, DLC relies heavily on robust communication infrastructure and advanced smart grid technology. Delays or inaccuracies in data transfer can adversely affect the effectiveness of this method. Additionally, DLC demands significant real-time data processing, necessitating considerable investment in data centers and potentially impacting its scalability. As a result, DLC may not be the most viable option for larger districts or regions where such extensive infrastructure is challenging to implement.

In contrast, real-time pricing in LEMs does not necessitate a centralized EMS. Instead, it requires smaller-scale EMS for each end user and needs only a certain level of digitization for market platform, which collects bids and clear the market at regular time intervals. The scalability of LEMs is more practical than DLC due to their lower computational requirements. Additionally, households already equipped with an EMS can join LEMs without incurring extra investment costs.

Providing flexibility through ancillary services requires a moderate level of communication infrastructure – more than what is needed for LEMs but less than for DLC. This is primarily due to the validation processes essential for settling delivered ancillary services. Similar to LEMs, this approach also requires a small-scale EMS in each household for the provision of flexibility.

In summary, the three DRPs for offering flexibility each have their own unique advantages and disadvantages. To provide a clear and comprehensive overview, their evaluation across various criteria is visually depicted in Table 4.2. The suitability of a specific DRP greatly depends on the context and requirements of the scenario in question. For example, DLC implemented via a DEMS is particularly effective for integrating a higher proportion of renewable energy and achieving significant reductions in CO_2 emissions. On the other hand, LEMs stand out for their straightforward implementation and their ability to maintain user comfort.

DRP Application	Real-time pricing LEM	Ancillary service HEMS	Direct load control DEMS
Energy balance	+	++	+++
User comfort	+++	+++	+
Interconnectivity	++	+	+++
Renewable sources	++	+	+++
Environmental impacts	++	+	+++
Economic advantages	++	+++	+
Feasibility	+++	++	+

Table 4.2: Evaluation of DRPs based on aspects related to smart and sustainable energy consumption. Ratings are indicated as "+++" for good performance, "++" for medium performance and "+" for poor performance.

4.3 Research contributions in relation to existing literature

Participation in LEMs has been observed to reduce participants' energy costs by approximately 5.1%, which is notably lower than the 16% - 32% savings reported in previous studies [36, 60, 61, 62, 63]. This difference may be attributed to two main factors: the components of energy pricing and the types of the flexible loads used in the model. In the current LEM configuration, fixed levies like taxes and network charges, which constitute over two-thirds of the total electricity cost, are factored in. This limits the influence of market-based mechanisms and subsequently the potential for cost savings. Additionally, the LEM model exclusively considers HPs as the flexible loads, in contrast to existing studies that include a variety of flexible loads like batteries and EVs. The seasonal dependency of HP flexibility, particularly their limited use in summer, results in lesser cost savings compared to models with a more diverse range of flexible loads.

The LEM case study shows a peak load reduction of around 30% when daily demand charges are applied to all end-users. This outcome is still less than the 40%-50% reductions documented in other research [63, 64], a disparity attributed to our study's focus solely on HPs. However, achieving a 30% reduction with just HPs remains a notable contribution, highlighting their potential in alleviating grid congestion through flexibility.

This study with LEMs sheds light on the essential role of HPs in LEMs concerning cost savings and peak load reduction. By focusing exclusively on HPs as flexible loads and treating other potential loads as fixed, the study provides a detailed assessment of the impact of HPs. It also introduces more realistic components into the energy pricing model, such as taxes and network charges, leading to outcomes that likely reflect real-world scenarios more accurately. The study goes further to examine the distribution of economic benefits among different types of users and the seasonal variations in the effectiveness of HP demand-side flexibility. It suggests that integrating HPs with other flexible loads could improve overall system performance in LEMs. Drawing from these insights, the study proposes a tailored regulatory framework, emphasizing adjustments in levies and monetary compensation, to more effectively exploit flexibility within LEMs.

The second study significantly advances the quantification of flexibility for ancillary services by introducing a novel three-stage method: establishing a reference schedule, generating alternative schedules and validating them against specific technical constraints. The technical constraints are further divided into three categories: switch points, remaining capacity and available regeneration time. This approach differs from [81], which evaluates flexibility in response to various penalty signals like price and CO_2 emissions, by employing a bottom-up approach. This study views flexibility as a collection of alternative operational plans, making it more appropriate for communications with system operators.

Furthermore, this study takes a different path from [36], which employs complex control strategies for flexible loads that require significant computational resources. Instead, it adopts a more streamlined process that facilitates quick communication with trading platforms in local flexibility markets. In contrast to [82], which concentrates on grid-friendly operations for small-scale HPs without considering flexibility trading and overlooks user comfort, this research integrates these crucial aspects.

The methodology of this dissertation encompasses a holistic view, taking into account bottom-up flexibility quantification, user comfort and market considerations. This comprehensive approach not only enables accurate quantification of flexibility but also enhances its practical application within local flexibility markets, thus filling the gaps identified in previous studies. This robust methodological framework is promising to make significant contributions to the field, particularly in the practical utilization of flexibility in local flexibility markets.

The third study in this dissertation explores the advantages of using DEMS to harness the flexibility of HPs. In terms of energy cost savings, the study observes reductions of 13% in urban districts and 18% in rural districts. These are somewhat lower than the 25.6% average savings reported in [49], which also compared costs with and without EMS. This discrepancy largely arises because this dissertation considers only HPs as flexible loads, whereas other studies typically include a variety of flexible loads. Nevertheless, these findings suggest that HPs alone could contribute to approximately half of the potential cost savings through DEMS.

Regarding emission reductions, the study finds savings of 19% for urban districts and 24% for rural districts, surpassing the 15% average reduction achieved through active demand responses for HPs as reported by [46]. This increased efficiency is likely due to the use of a future emission factor for the year 2045, as opposed to the 2020 factor used in the referenced research. With an anticipated rise in renewable energy sources, the future emission factor of electricity is expected to be much lower than current values, thereby amplifying the impact of shifting HP operations.

This study advances beyond existing literature by implementing a detailed building model for calculating heat consumption, moving away from the generic load profiles commonly used in studies such as [48, 49, 50]. This method accounts for additional flexibility provided by building materials and also considers the effect of solar gains through windows on heat demand and the flexibility potential of HPs. Furthermore, this research examines the flexibility of HPs at the district level, rather than the individual building level, acknowledging the benefits of community-level energy consumption coordination. Lastly, the study conducts a comprehensive parameter analysis, considering various factors influencing the flexibility of HPs and offers recommendations on optimizing the use of HPs' flexibility through DEMS.

Chapter 5

Conclusion and future research

This dissertation thoroughly investigates how the flexibility of residential HPs can be harnessed to promote smart and sustainable energy consumption. It explores a variety of DRPs, including real-time pricing within LEMs, ancillary services through HEMS and DLC implemented through DEMS. By examining these diverse programs, the dissertation offers a comprehensive and insightful study into the field of demand-side management. It underscores the significant role that residential HPs play in enhancing energy management practices, thereby contributing to a more efficient and sustainable energy system.

5.1 Conclusion

This dissertation presents various case studies to scientifically investigate HP flexibility. The findings are analyzed in terms of economic, environmental and grid-related factors. Based on these analyses, the impacts of DRPs on smart and sustainable energy consumption are comprehensively assessed, addressing the research questions posed in Chapter 1.4:

RQ#1 explores how combining residential HPs with LEMs can reduce energy costs and diminish residual demand peaks. The analysis indicates that LEMs with a high penetration of HPs can achieve an average annual cost saving of 5.1%. A key discovery is LEMs' role in grid balancing – the implementation of daily demand charges within LEMs has been found to decrease residual demand peaks by up to 25%. However, the benefits of LEMs with HPs are subject to several influencing factors. Balancing costs and levies, which form a major part of total costs, are not influenced by market trading and thus negatively influence the relative savings achieved through LEMs. Additionally, seasonal variations limit the effectiveness of HPs in LEMs, with reduced flexibility in summer due to lower heating demand. Currently, the majority of the benefits of LEMs are experienced by users with HPs, indicating the need for more equitable participation rules. Furthermore, regulatory adjustments are essential to tackle challenges like high balancing costs and uneven benefit distribution, ensuring the optimal functioning and wider adoption of LEMs. In summary, this study demonstrates that LEMs can effectively harness the flexibility of HPs through real-time pricing. However, the success of this approach is heavily reliant on the regulatory framework in place. Despite this dependency, the role of LEMs and residential HPs in enhancing local energy balancing and facilitating coordination among various energy devices remains a significant contribution.

RQ#2 tackles the challenge of quantifying the flexibility of residential HPs in the context of providing ancillary services. The study introduces an innovative, decentralized energy management approach, empowering end users to actively manage their energy use while offering flexibility. Key to this method is a novel three-stage process: establishing a reference schedule, creating alternative schedules and validating them against specific technical constraints. These constraints are categorized into three groups: switch points, remaining capacity and available regeneration time. A critical component of this approach is the integration of a capacity reservation method for thermal energy storage, ensuring optimal system performance alongside maintaining user comfort. Simulations using this method reveal promising results, with an average of only 2.5 minutes of unsatisfactory time per day and a maximum temperature drop of no more than 2.3 °C. This approach fosters smart and sustainable energy consumption by enhancing local energy balancing and the integration of renewable energy, while providing increased user comfort and economic benefits.

RQ#3 delves into the potential of HPs to reduce CO_2 emissions and the added benefits of their flexibility under a DEMS. This research reveals significant disparity in CO_2 abatement costs between urban and rural districts. In urban areas, with higher housing density and heat demand, the costs associated with installing HPs are significantly higher compared to rural areas. However, integrating HPs with a DEMS can lead to marked cost reductions. In urban areas, the adoption of a DEMS results in 17% lower energy costs and 10% less CO_2 emissions, while in rural areas the reductions are 17% in energy costs and 35% in CO_2 emissions. The study emphasizes the importance of factors such as the investment costs of HPs and the electricity emission factor in determining the overall effectiveness and cost-efficiency of the DEMS. Lower investment costs and reduced electricity emission factors can greatly decrease CO_2 abatement costs, enhancing the attractiveness of HPs for emissions reduction. The insights provided by this study are comprehensive, illustrating how residential HPs, when centrally managed through DLC in a DEMS, can offer a cost-effective strategy for reducing emissions while promoting smart and sustainable energy consumption. These findings are particularly useful for district-level investment decisions and policy formulation, supporting a strategic shift from traditional heating systems to more sustainable HP solutions in both urban and rural settings.

This dissertation thoroughly addresses its research questions, offering a detailed analysis of HP flexibility and its impacts on economic, environmental and grid-related aspects within various DRPs. It delves into key factors influencing end-user participation, like economic benefits and thermal comfort. The study successfully fills existing research gaps, providing critical insights that aid in advancing energy practices and guiding policy development.

5.2 Future research

Building on the findings and insights from this dissertation, I propose the following avenues for future research:

Impacts of local flexibility on power grid

This dissertation successfully quantifies and analyzes the flexibility potential of residential HPs, covering various aspects. However, it lacks in-depth evaluation of specific impacts, particularly in terms of power grid congestion relief and investment cost savings from DRPs. The primary challenge lies in obtaining detailed flexibility demand data from system operators. To thoroughly explore these areas, future research needs to conduct larger-scale simulations, which should encompass both residential and commercial sectors within a defined geographical area and consider the local power grid topology.

Understanding these specific impacts is vital for shaping future energy policies and economic decisions, including infrastructure investments and the implementation of targeted subsidy policies. Therefore, future research efforts must focus on these critical and practical aspects of HP flexibility, ensuring alignment with the dynamic requirements of the energy economy.

Benefits of local energy markets with proposed regulatory framework and diverse renewable energy sources

This dissertation presents various proposals for a regulatory framework to support LEMs, but their real-world impact requires further validation through simulation studies or field tests.

Future research could compare LEMs, particularly those with lower balancing costs and levies, with the model in this study. Such comparative analysis would help validate the effectiveness of the proposed regulatory frameworks. Additionally, it's essential to explore the financial implications of adapted regulations for system operators, especially regarding financial source for compensating the reduced levies. Addressing these economic aspects is crucial for the practical implementation of these regulatory measures.

Investigating LEMs that integrate diverse renewable energy sources would also provide valuable insights. Markets that align with the seasonal characteristics of HPs could offer a more comprehensive approach to energy management.

The ultimate goal of these future research directions is to thoroughly confirm the benefits of LEMs, contributing to their development from theoretical models to essential tools in enhancing energy flexibility.

Comparison and prioritising among flexibility solutions of residential heat pumps

This dissertation investigates three strategies for using residential HP flexibility but does not compare them under the same conditions, largely due to their varying geographical scales. Additionally, acquiring detailed flexibility demand data for a thorough quantitative assessment of the flexibility trading approach proves challenging.

Nevertheless, a study comparing all three methods within the same district context would be valuable. This comparison would assess each strategy's economic and environmental impact and their effectiveness in grid management. Each approach likely has unique strengths in specific scenarios. Future research comparing these strategies could clearly identify their respective advantages and ideal applications. Such comprehensive analysis would significantly enhance understanding of the most effective utilization of residential HP flexibility, informing suitable methods for different energy systems at national or regional levels.

Appendix A

List of publications

A.1 First-authored publications

1. Z. You, S. D. Lumpp, M. Doepfert, P. Tzscheutschler, and C. Goebel. "Leveraging flexibility of residential heat pumps through local energy markets". In: Applied Energy 355 (2024), p. 122269. ISSN: 03062619. DOI: https://doi.org/10.1016/j.apenergy.2023.122269.
2. Z. You, M. Zade, B. Kumaran Nalini, and P. Tzscheutschler. "Flexibility Estimation of Residential Heat Pumps under Heat Demand Uncertainty". In: Energies 14.18 (2021), p. 5709. DOI: https://doi.org/10.3390/en14185709.
3. Z. You, M. de-Borja-Torrejon, P. Danzer, A. Nouman, C. Hemmerle, P. Tzscheutschler, and C. Goebel. "Cost-effective CO2 abatement in residential heating: A district-level analysis of heat pump deployment". In: Energy and Buildings 300 (2023), p. 113644. ISSN: 03787788. DOI: https://doi.org/10.1016/j.enbuild.2023.113644.
4. Z. You, B. Kumaran Nalini, M. Zade, P. Tzscheutschler, and U. Wagner. "Flexibility quantification and pricing of household heat pump and combined heat and power unit". In: 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe). 2019, pp. 1–5. DOI: https://doi.org/10.1109/ISGTEurope.2019.8905594.

A.2 Co-authored publications

1. M. Zade, Z. You, B. Kumaran Nalini, P. Tzscheutschler, and U. Wagner. Quantifying the flexibility of electric vehicles in Germany and California — A case study. Energies, 13 (21): 5617, 2020. DOI: https://doi.org/10.3390/en13215617.
2. B. Kumaran Nalini, Z. You, M. Zade, P. Tzscheutschler, and U. Wagner. "OpenTUM-Flex: A flexibility quantification and pricing mechanism for prosumer participation in local flexibility markets". In: International Journal of Electrical Power and Energy Systems 143 (2022), p. 108382. ISSN: 01420615. DOI: https://doi.org/10.1016/j.ijepes.2022.108382.
3. B. K. Nalini, M. Eldakadosi, Z. You, M. Zade, P. Tzscheutschler, and U. Wagner. "Towards Prosumer Flexibility Markets: A Photovoltaic and Battery Storage Model". In: 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe).

IEEE, 29.09.2019 - 02.10.2019, pp. 1–5. ISSN: 978-1-5386-8218-0. DOI: https://doi.org/10.1109/ISGTEurope.2019.8905622.

A.3 Open-source repositories

1. Z. You, M. Zade, and B. Kumaran Nalini. OpenTUMFlex. [Computer software]. URL: https://github.com/tum-ewk/opentumflex, 2020.
2. S. D. Lumpp, M. Zade, M. Doepfert and Z. You. lemlab. [Computer software]. URL: https://github.com/tum-ewk/lemlab, 2021.

Appendix B

Acronyms

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