Realizing the flexibility potential of heat pumps on the intraday market as data-driven business model

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Affidavit

I hereby confirm that I have written this thesis independently and without unauthorized external assistance and that all passages taken verbatim or in spirit from publications in this thesis have been individually identified and the source cited.

Kassel, 04.06.2024

(Name, Signature)

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Abstract

Recently, as a reaction to the energy crisis fueled by Russia's aggression against Ukraine, the EU launched the REPowerEU plan in 2022 to use more renewable energy, reduce energy consumption and diversify the energy supply (European Commission 2024a). One key focus area for decarbonization and energy saving is the private heating sector. Heat pumps take a central role in the heating system's flexibilization and decarbonization. In essence, the aim of this study is to assess heat pump´s flexibility potential, specifically concentrating on the intraday market by comparing it against other pricing mechanisms and examining different setups across various household heat profiles. To determine optimal load shifting schedule on intraday market, the study employs Mixed Integer Linear Program (MILP) optimization model. Model generates potential yields on intraday market, as well as for dynamic day-ahead and flat heat pump tariff, for data available for years 2022 and 2023. By comparing revenue streams, this study points to the flat heat pump tariff as most attractive pricing mechanism in terms of cost reduction. After further consideration, where financial incentives granted to flat heat pump tariff were isolated, the study settles on intraday market as best solution for private households offering flexibility with heat pumps. Positive outcome for intraday market can be attributed to the market´s high volatility, especially effective among households with high energy demand. To conclude, the research fills a gap in previous studies by providing insights into heat pumps offering their capacities on intraday market in comparison to other pricing mechanisms and proves intraday market´s high suitability due to its the high volatility.

Introduction

While the European Union (EU) has agreed to reduce greenhouse gas emissions by at least 55% by 2030, this requires a high share of renewable energy and greater energy efficiency. Having set such an ambitious target is part of a broader strategy to achieve net CO2 emissions by 2050, as outlined in the European Green Deal announced in 2019 (European Commission 2024b). In May 2022, the EU introduced the REPowerEU plan in response to the energy crisis aggravated by Russia's aggression against Ukraine, which emphasizes the use of renewables, reducing energy consumption and diversifying the energy supply. In March 2023, the EU increased its renewable energy target for 2030 up to at least 42.5%, with the aim of achieving 45% share of total energy mix.

The European Green Deal and the "Fit for 55" package in particular are at the very core of these efforts, because they set binding targets for emissions reduction and the use of renewable energy. Together, these measures stress the need to transition from conventional to renewable energy sources, in spite of the intermittent nature of supply from sources like wind and solar. In response, the Energy Transition Expertise Centre (EnTEC) has been researching digital solutions to address the power system flexibility that is essential to balancing these fluctuations (European Commission 2023a).

This study considers the role of heat pumps in private households when it comes to contributing to the flexibility of the energy system and its decarbonization. Apart from electrifying heat generation, heat pumps also increase the flexibility of the electricity grid, making them a crucial component in the transition to sustainable energy system. Based on this, this study assesses the absolute potential of heat pump flexibility on the energy market and examines different arrangements, such as varying storage capacities and residential thermal load profiles.

Examining the more general aspects of energy system flexibility has been the subject of existing studies and reports, among others by the European Commission and EnTEC. That said, there is a need for more in-depth research on the specific contribution of heat pumps to energy flexibility from a household´s perspective. This research fills this gap by providing insights financial attractiveness of heat pump flexibility, highlighting the use of intraday market compared to other pricing mechanisms.

To address the aim of this study, similar existing studies will first be reviewed in Literature Review. Relevant technical requirements for energy flexibility, as well as economic context will be further explored in Techno-economic Framework. Chapters Methodology and Model Input and Parametrization will introduce the model used to assess the flexibility potential of heat pumps. Finally, results will be presented (chapter Results) and further analyzed in chapter Discussion. Limitations will reflect on study´s scope while suggesting possible improvements for future research. Conclusion and Outlook will summarize findings and consider future scenarios.

Literature Review

This section will provide context for the thesis topic within the current literature on the economic value of flexibility. It will identify existing research gap and highlight how this research aims to address and contribute to closing this gap.

Flexibility is of great importance in dealing with the growing share of intermittent renewable energy sources, which pose a threat to the stability of the electricity grid (European Commission 2023a). A wide range of literature addresses various flexibility approaches, ranging from the implementation of different technologies to the adoption of various business models. Amidst these approaches, electric vehicles (EVs) are a prominent technology that offers significant potential for demand-side management through bidirectional charging, more commonly known as the vehicle-to-grid (V2G) model. The flexibility potential of EVs has been investigated in several countries, namely China, Austria and Singapore, with results showing that it is a cost-effective solution (Hu et al. 2024; Horak et al. 2024; Bartolini und Hug 2023). Some other leading solutions, like electric batteries, are proving to be an important source of flexibility, whether they are used as stand-alone units or integrated with other consumer systems, as proven by Saldarini et al. (2023) and Rivera-Durán et al. (2023).

Ultimately, heat sector flexibility is certain to increase, especially as heat pump technology becomes more widespread. This is highlighted by recent studies like those by Fernández Bandera et al. (2023) and Li et al. (2023), which emphasize the importance of optimizing self-consumption in prosumer households equipped with photovoltaic systems and heat pumps. The authors point out the advantages of cost reduction, load shifting and grid relief at peak hours. Meanwhile, Wilczynski et al. (2023) and Banaei et al. (2024) explore incentive-based models for heat pump flexibility, in which they focus on improving service quality for end users through different electricity tariffs. Their work centers on promoting demand flexibility among new users and helping policy makers design attractive incentives. In sharp contrast to the single household approach, Petrucci et al. (2023) and Pinto et al. (2021) consider residential communities as flexibility units and introduce the aggregator as the central entity responsible for data-driven, coordinated energy management. Although these studies provide insights into different flexibility optimization models, they do not include the analysis of different electricity tariffs and their impact on households with heat pumps.

Expanding on existing research, Corinaldesi et al. (2020) argue for a two-step optimization strategy that considers both the day-ahead and intraday energy markets. In this approach, they try to exploit the short-term flexibility and higher price volatility of the intraday market. Building on this new framework further, Golmohamadi et al. (2021) add a balancing market on top of intraday trading, further refining the optimization process. Empirical evidence from both studies, which were conducted in Austria and Denmark, show a significant reduction in electricity costs when offering flexibility, further confirming the value of short-term electricity markets. On the other hand,

Marijanovic et al. (2022) only use a single-stage optimization approach, focusing on the intraday spot market in Germany.

Nevertheless, recent studies have shown that there is a research gap regarding the suitability of using the intraday market as the most effective solution for households, especially in comparison to alternative pricing models such as flat tariffs or other dynamic pricing schemes. The purpose of this study is to assess the absolute potential of heat pump flexibility on the intraday market and to investigate set-up variations such as storage capacity and household thermal demand profiles. By examining the financial attractiveness of intraday market participation compared to alternative pricing mechanisms, this study aims to uncover the revenue streams within the data-driven energy value chain. In addition, it provides insights into the optimal configuration for households seeking to maximize the economic gains of heat pump flexibility.

Techno-economic Framework

This chapter will address the complex nature of flexibility in the energy sector while exploring its essential role in ensuring the efficient operation and security of electricity grid during the ongoing energy transition. In addition, chapter reviews regulatory measures and market mechanisms aimed at promoting flexibility, including the ability to respond to market signals. The focus lies on the emerging role of intraday trading in promoting flexibility services. Continuing, the chapter examines recent developments in EU initiatives such as Gaia-X and the Common European Energy Data Space, highlighting Germany's efforts to address energy market flexibility by introducing digital economy solutions to the energy sector.

Flexibility

Flexibility is defined as *" the change in feed-in or withdrawal in response to an external signal (price signal or activation) with the aim of providing a service in the energy system."* (BNetzA 2017). In the context of the energy transition, it is often stated that there is an increasing need for flexibility in order to efficiently guarantee security of supply Babatunde et al. (2020). Ensuring the secure operation of the electricity system requires a continuous balance between generation and consumption to maintain a grid frequency of 50 Hz. This balance is achieved through flexibility in electricity trading and balancing markets. The electricity market has rules that mandate balance responsible parties to manage their balancing groups within 15-minute intervals. Economic incentives ensure these parties balance feed-in and consumption effectively. Electricity prices, influenced by supply and demand, drive efficient allocation. Flexible generators and consumers can adjust their activities based on price signals, avoiding high costs or negative prices. This flexibility is crucial due to the variability of renewable energy sources. There exist different types of flexibility as seen in Figure 1.

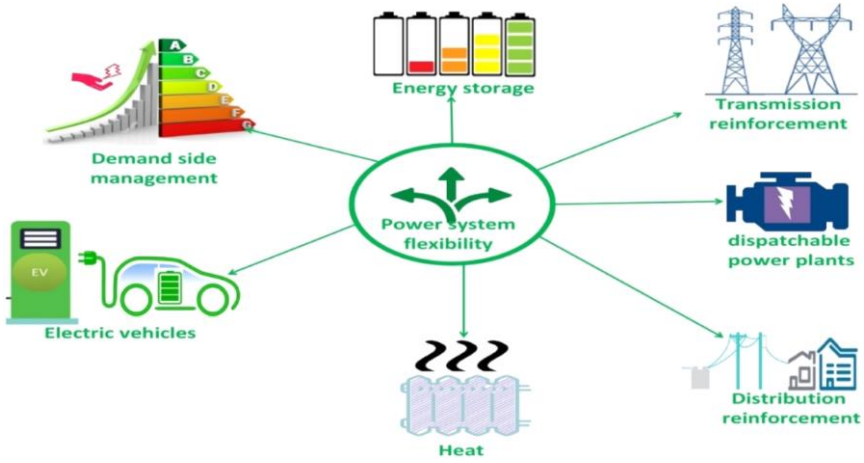

Figure 1: Sources of power system flexibility (Babatunde et al. 2020)

Grid flexibility is essential as increased renewable feed-in and slow grid expansion cause congestion. Transmission network expansion is planned through complex procedures, but grid flexibility remains necessary. Redispatch measures manage physical bottleneck situations. Distribution networks are starting to use grid flexibility more, such as peak shaving, to reduce expansion needs. To effectively address congestion, categorization approach was implemented, namely the traffic lights approach. In the green phase, market actors operate freely with minimal network intervention. In the yellow phase, network operators use market-related measures like redispatch. In the red phase, operators take direct measures, including feed-in management, to ensure grid stability, often without prior agreement or compensation. Distribution networks, with limited redispatch potential, often move directly from green to red in case of congestion.

According to the discussion paper written by the Federal Network Agency, enhancing market-related measures and incentives at the distribution level could improve congestion management efficiency, leading to a more flexible and resilient electricity system capable of accommodating the growing share of renewable energy while maintaining stability and efficiency (BNetzA 2017). Opening up the balancing markets to new suppliers could address the interaction problem between the balancing market and the electricity wholesale market. Additional participation from flexible providers like those with flexible loads or storage facilities could replace conventional plants' balancing capacity reserve. However, past attempts, like the Interruptible Loads Ordinance (AbLaV), faced challenges with a small provider group and lack of competition. Amendments aimed to increase participation, but their effectiveness remains uncertain.

Currently implemented mechanisms for promoting renewable energy, often based on kilowatt-hour compensation, constrain flexibility by not responding to market conditions and ignoring market signals. For instance, fixed feed-in tariffs and market premiums prevent renewable installations from adjusting to price signals, resulting in overproduction even at negative market prices. Alternative support schemes based on quantity rather than purely on price per kilowatt-hour could offer a less damaging impact. Although it is important to mention, current regulatory measures designed to increase flexibility, such as the "use don't curtail" concept, rely heavily on payments from transmission system operators.

Privileges granted to users who practice self-consumption, in form of energy-related levies and grid tariffs exemption, encourage investment in self-generation plants and hinder flexibility and market response. Special tariffs additionally hinder flexibility because they reward steady consumption behavior that ignores market signals. The grid tariff system's barriers i.e., peak load assumptions and special tariffs, affect inflexible consumption behavior. Regulatory treatment of grid flexibility measures may further hinder efficient network operation. In summary, addressing these barriers requires reevaluating support mechanisms, tariff structures, and regulatory incentives to promote flexibility and responsiveness to market signals in the electricity sector.

Proposed actions include (BNetzA 2017):

1. Network Tariffs and Flexibility: Allow distribution system operators flexibility in offering tariff reductions, with clear criteria to prevent discrimination.
2. Remuneration for Flexibility: Consider reducing network tariffs or direct payments within incentive regulation schemes to remunerate flexibility.
3. Linking Network Tariffs to Grid Interests: Structure network tariffs to reflect network usage costs separately from energy supply/demand to encourage efficient flexibility use.
4. Special Network Tariffs: Revise special tariff arrangements to incentivize grid-beneficial behavior and remain administratively manageable.
5. Cellular Models: While valuable for certain consumers, caution against implementing local energy balancing as the system-wide principle due to security and efficiency concerns.
6. Flexibility from Storage: Consider electricity storage alongside other flexibility options, ensuring a level playing field and addressing challenges in market participation and grid support.

Since the study by Federal Network Agency was conducted in 2017, several policies have been implemented to promote demand-side flexibility, including The Energy Industry Act (EnWG) §14a that allows the Federal Network Agency to issue nationwide regulations under which operators of electricity distribution grids and energy suppliers, end consumers and grid connections are obliged to agree to arrangement on the grid-oriented control in return for reductions in grid charges in accordance with the specifications provided by the Federal Network Agency. These regulations cover prioritizing economic incentives, scaling control based on application, monitoring and digitizing the grid, defining controllable consumption facilities and network connections, and determining grid charges. Until the establishment of uniform national regulations, operators of electricity distribution grids shall charge a reduced grid fee to those suppliers and end consumers in the low-voltage sector with whom they have entered into grid usage contracts. Controllable consumption facilities include heat pumps, electric vehicle charging points, refrigeration systems, energy storage, and night storage heaters. Controllable consumption devices should have a separate metering point, namely smart metering systems, with specific requirements outlined in the Act on Metering Point Operation (MSB).

Recent research that was conducted in context of Kopernikus projects sponsored by Federal Ministry of Education and Research (BMBF 2024b) focuses on flexibility solutions (BMBF 2024a) that examine factors contributing to the flexibility of the power system in 2030 and in 2045. Correlating study by EnTEC emphasizes the growing share of residential heat pumps in final energy demand, highlighting the need for flexibility in heating sector even more (European Commission 2023a).

In conclusion, the promotion of demand-side flexibility, especially in residential heat sector, is crucial for ensuring the efficient operation and security of the transitioning electricity system.

Recent policies, such as The Energy Industry Act (EnWG) §14a, have laid the groundwork for grid-oriented control of consumption facilities and network connections to achieve reduced grid fees. However, addressing regulatory barriers and incentivizing the deployment of flexible technologies will be essential for realizing a more resilient and responsive energy system in the future.

Energy Market

This chapter will explore dynamics of energy trading, investigating various submarkets like long-term contracts and short-term spot markets, mainly day-ahead and intraday market. Additionally, it will discuss the crucial roles of market participants within the market framework and their significance in facilitating flexibility services.

Energy Trading

The electricity market is distinguished from other markets by its unique focus on the trade of electricity as a grid-based product with limited storage capabilities (SMARD 2024d). In order to maintain a balance, the demand for electricity must always align with the supply. Similar to other markets, the price of electricity is determined by the interplay of supply and demand. Due to the fluctuating supply-demand ratio in the electricity market, the price can vary on an hourly or even quarter-hourly basis, depending on the trading platform. For example, during periods of high solar panel electricity generation, the supply surpasses the demand, resulting in lower electricity prices. Conversely, when demand is high and supply is low, the price of electricity increases.

The energy market includes various submarkets offering different products based on the timing of purchase and actual electricity supply (SMARD 2024b), as shown in Figure 2. Long-term contracts, such as futures or forwards, enable buyers to purchase electricity years in advance on the forward market. These contracts appeal to risk-averse customers by providing protection against energy price volatility. More precise volume trading occurs on short-term spot markets, specifically the day-ahead and intraday markets. On the day-ahead market, electricity for the following day is traded, with bids and offers specifying quantity and supply time submitted by midday. The exchange then determines the wholesale price for each hour of the next day. The price set on the day-ahead market is a crucial reference value for electricity trading and is publicly available on EPEX (EPEX SPOT 2024b). The continuous intraday market is the most flexible electricity trading platform, allowing trading up to 15 minutes before delivery. Within the same control area under the same transmission system operator (TSO), trading can occur as close as 5 minutes before delivery, making the intraday market ideal for correcting previously made bids (Amprion GmbH 2024).

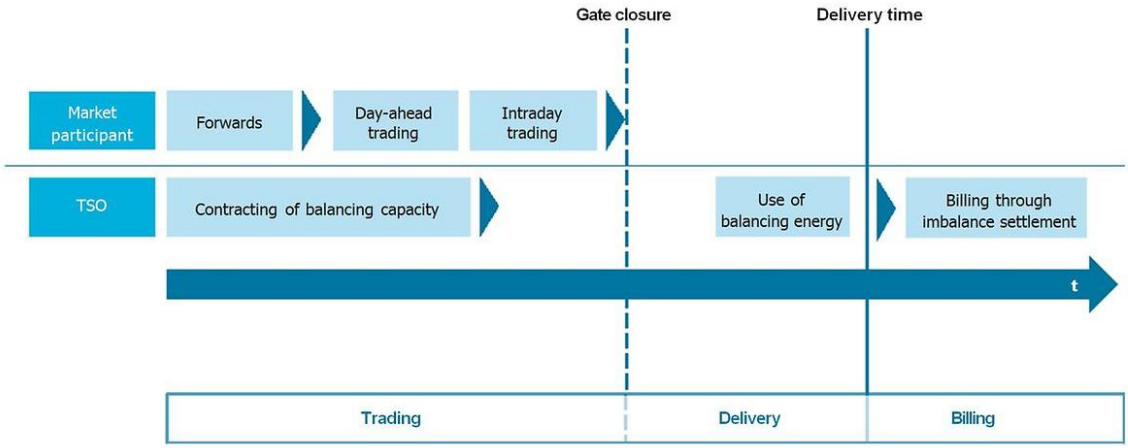

Figure 2:Submarkets of the electricity market in Germany, chronological representation (SMARD 2024d)

Once trading is completed and the gate is closed, TSOs must ensure balance between supply and demand before real-time delivery. In Germany, every consumer and producer of electricity is assigned to a balancing group and must report forecasted electricity consumption or generation. Despite careful planning, imbalances may occur, and TSOs use balancing energy from balancing services to correct the imbalance. Balancing energy is sourced from different types of balancing reserves, which can be available within 30 seconds or up to 15 minutes. The following part will discuss the crucial roles within this market framework.

Important Market Roles

In the electricity system, understanding the interaction between different market participants is crucial for effective market operations, especially in the context of flexibility services. The main roles can be categorized into physical roles, administrative roles, and market roles.

Physical roles involve the technical processes of the electricity system, including production, transport, consumption, and security. Administrative roles are responsible for managing relationships between customers and market or grid operators, which is known as the service market. Market roles pertain to the various market platforms that facilitate services and transactions within the electricity market. The interaction between these roles in the context of flexibility services is illustrated in Figure 3. A detailed explanation of the market roles and their scope of responsibility is provided in Table 1 (TenneT Holding B.V. 2024).

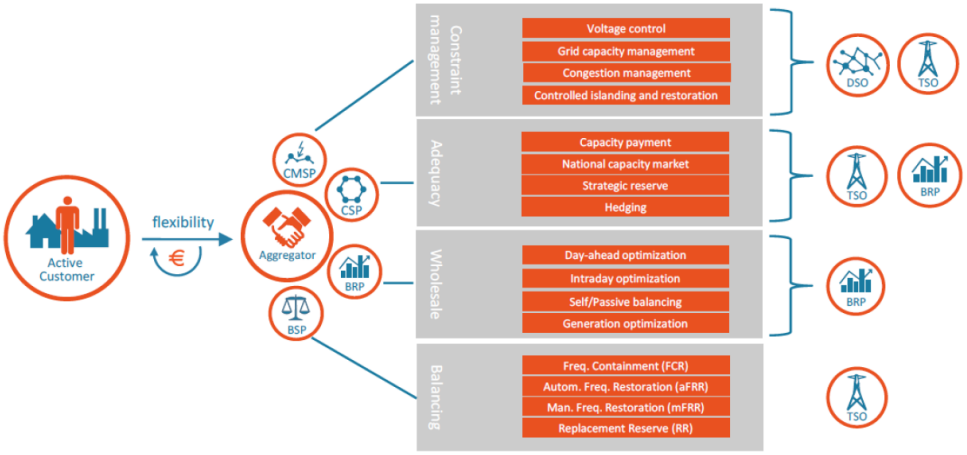

Figure 3: Flexibility services and flexibility roles (Heer et al.)

Table 1: Market participants

Role	
Physical roles	
 Transmission system operator (TSO)	In Germany, there are four main control areas, each assigned to one TSO, namely Amprion GmbH, TransnetBW GmbH, TenneT TSO GmbH, and 50Hertz Transmission GmbH (SMARD 2024c). As stated in Section 11(1) of the German Energy Industry Act (EnWG), the TSO's primary responsibility is to operate and maintain a safe, reliable, and efficient energy supply network. They are also tasked with optimizing, reinforcing, and expanding the network in accordance with requirements and in a non-discriminatory manner. Additionally, in case of fluctuations in system frequency they may utilize balancing services. Moreover, TSOs are part of the European Network of Transmission System Operators for Electricity (ENTSO-E) and are required to notify ENTSO-E about data related to electricity markets, consumption, and generation, as per Regulation (EU) No 543/2013. This regulation ensures transparent development in electricity markets, which is crucial for linking the German network with those of neighboring countries.
 Distribution system operator (DSO)	DSOs operate the regional distribution grid, acting as a vital link between the high voltage grid and end consumers. DSOs are involved in connecting new consumers and producers to the grid, metering the consumption of small consumers, and reporting metered data to suppliers and TSOs. Additionally, DSOs carry out the important tasks of registration, management, and exchange of data to be utilized by market parties.
 Electricity producer	Large producers typically connect to the high voltage grid and assume the role of a balance responsible party, offering their production capacity on the market and providing balance or congestion services. Small producers and consumers connect to the local grid through their DSO or can make independent contracts with aggregators, who bundle flexible assets and offer them on the electricity market.
Administrative roles	
 Balance responsible party (BRP)	Balance responsible parties have the responsibility of reporting forecasts for each imbalance settlement period of 15 minutes to the TSO. These forecasts are used to create a commercial trade schedule, ensuring the efficient operation of the electricity system.
 Electricity supplier	Electricity suppliers directly enter into electricity supply contracts with end consumers. They purchase power on the wholesale market, including forward futures, day-ahead, and intraday markets. Electricity suppliers are also responsible for invoicing end consumers for all costs related to their electricity bills.
 Balance service provider (BSP)	Balance service providers and congestion service providers play a crucial role in the electricity system. They offer balancing energy and capacity to help maintain the supply-demand balance and ensure system stability.

 Congestion service provider (CSP)	Additionally, congestion service providers assist in managing congestion issues within the grid.
 Metering point operator	Performs the task of metering point operation, as well as metering equipment installation, operation, and maintenance.
Market roles	
 Aggregator	Aggregators bundle together multiple small consumers and offer flexibility services on the wholesale, balancing, or congestion markets. They provide a means for smaller consumers to participate in the market and offer their flexibility to support grid operations. As the electricity system evolves, aggregators may also take on the responsibilities of congestion service providers to help alleviate local grid congestion issues.

Overview presented in Table 1 was based on Harmonized electricity market Role Model that was developed to enable smoother communication between market participants from different countries by introducing common terminology (bdew 2022). The model is suitable to describe all important roles used in this study, but it is important to note that German market slightly adjusted the role model for use within the country boarders (bdew 2023a). While European and German model vary in detail, key players mentioned above remain the same.

Day-ahead & Intraday Market

This subchapter will further describe and compare day-ahead and intraday market, starting with day-ahead. Day-ahead trading refers to the trading of electricity for the following day (Next Kraftwerke 2024a). For Germany auction bids for the next day must be submitted by 12:00 noon, with results published at 12:40h each day. From 15:00h, it is already possible to conduct intraday trading for the next day. Typically, trading involves full hourly blocks.

The market clearing price, determined by the intersection of supply and demand, sets the price for all participants for a given product. Commonly known as the merit-order effect, this principle involves ranking electricity generated from different energy sources based on their marginal costs, with preference given to the lowest-cost sources (SMARD 2024b). Renewable energy sources, which typically have very low marginal costs, are often ranked at the top of the list and consumed first. The final electricity price is established at the point where demand matches supply, specifically at the costliest energy source. Negative electricity prices have been observed in the German electricity market in recent years (Khoshrou et al. 2019). These negative prices primarily occur during peak solar and wind energy generation periods when demand is low. The intermittent and volatile nature of renewable energy results in fluctuating electricity prices and an unpredictable energy market. The minimum trade volume is 0.1 MWh, and the price range is between -500 €/MWh and 3,000 €/MWh. Custom-defined blocks can also be traded, with a maximum volume of 400 MW per block and a limit of 100 such blocks per participant per day.

Unlike the day-ahead market's merit-order principle, the intraday market uses a limit order book (LOB) for price formation, resulting in multiple electricity prices for each delivery time (Martin und Otterson 2018). The LOB follows a pay-as-bid system, where participants specify the price and power volume they are willing to trade for each delivery time. Orders are matched with the best available opposite orders at the defined price or a better price (lower for buy orders, higher for sell orders), with transaction volumes corresponding to the minimum volume defined in both orders. If a limit order is not fully executed, the process continues until the order is completely matched, canceled by the owner, or the market closes. For example, a limit order to sell 5 MWh can be fulfilled through multiple buy orders, resulting in several transactions at different prices.

The intraday market also features multiple indices that simplify the bidding process into singular price trading times (EPEX SPOT 2024a). The IDFull index, or Final Index, represents the weighted average price of all continuous trades executed during an entire trading session of any EPEX SPOT continuous contract. This index includes full market liquidity and serves as a primary reference for continuous market prices. The ID3 index is the weighted average price of all continuous trades executed within the last three trading hours of a contract, focusing on the most liquid part of the trading session. This index is crucial for customers to market their offers or assess trading activities. The ID1 index captures the weighted average price of all continuous trades within

the last trading hour of a contract, addressing last-minute imbalance needs and reflecting system balancing flexibility and the increasing impact of renewable energy sources.

Since 2010, there has been notable growth in the continuous intraday market, attributed to the rise in electricity generated from intermittent energy sources (BNetzA 2023b). This market has become appealing for flexibility services like demand-side management (Siano und Sarno 2016), cogeneration (Mitra et al. 2013), and virtual power plants (Wille-Haussmann et al. 2010). Moreover, given its cost-effectiveness compared to traditional balancing power, there has been a shift in volume from the balancing market to this short-term electricity auction market, as illustrated in Figure 4 (Next Kraftwerke 2024b).



Figure 4: Development of flexibility markets in Germany over time (Next Kraftwerke 2024b)

Data Economy

The chapter will explore the scope and rationale of data economy, as well as mentioned EU initiatives to digitalize energy system, among which are Gaia-X and the Common European Energy Data Space. Additionally, it will also discuss Germany's projects that address challenges in the data economy. Finally, the chapter will conclude by mentioning requirements for data-driven business models within the energy sector.

European Strategy for Data Economy and Energy System

The EU action plan on digitalizing energy system (EUR-Lex 2022) aims to reduce dependence on Russian fossil fuels, address the climate crisis, and ensure affordable energy by 2030. Key initiatives include deploying solar panels, heat pumps, zero-emission vehicles, and investing in digital technologies like smart Internet-of-Things (IoT) devices, 5G, and energy data spaces. This

transformation supports the European Green Deal (European Commission 2024b) and REPowerEU (European Commission 2024a), requiring strategic investments, cybersecurity enhancements, and consumer empowerment. A major focus is creating a digital twin of the EU electricity grid to improve efficiency and smartness, supported by initiatives like the TEN-E Regulation and CEF Digital for cross-border projects. Consumer protections will be maintained, and new digital tools will help manage energy use and costs. Energy communities and local energy projects will also be supported. To tap the potential of using data in different sectors, data spaces supported by digital ecosystems were introduced.

Digital ecosystem addressing management and control over electricity system is called the Energy Data Space (European Commission 2023a). Term "data space" stands for a form of data relationship between trusted partners who follow same high-level standards concerning data storage and data sharing within one or many ecosystems. The aim is to provide highest quality raw material that can reinforce European economy, namely high quality data. From automotive to healthcare, agriculture to education, transportation, energy or finance, the ecosystems would be able to collaborate and combine existing solutions in environment with reduced physical barriers and reduced time to market while leveraging distributed intelligence to create additional value for all. By facilitating the seamless exchange of high-quality data, data spaces enable the development of innovative data-driven business models. These models can harness the power of big data analytics and information networks to optimize operations, enhance customer experiences, and create new revenue streams (Sorescu 2017). Businesses can leverage shared data to gain deeper insights, predict trends, and make more informed decisions, thereby driving growth and competitiveness in the European market.

Therefore, European Union is striving to create the Common European Energy Data Space which goal is to facilitate the participation of flexible energy sources and creating new revenue streams. Active customers are operating assets that are relevant to the energy system, either as generating assets (photovoltaics) or with flexible loads (heat pumps). The report written by the EnTEC (European Commission 2023a) under the auspices of the European Union developed a plan to realize the Common European Energy Data Space. The plan includes three high level use cases describing price responsive charging and discharging and balancing services from electric vehicles, smart residential flexibilities and role of virtual power plant (VPP) and aggregators. The main stakeholders in the initial ecosystem system are transmission and distribution system operators, metered data administrators, original equipment manufacturers and resource aggregators, as seen in Figure 5. Furthermore, active consumer assumes a role of data owner who is controlling the use of data in this energy data ecosystem. Access to energy data is enabled by smart metering systems in aspect of European AMI (advanced metering infrastructure) concept, which will be unique feature of the Common European Energy Data Space.

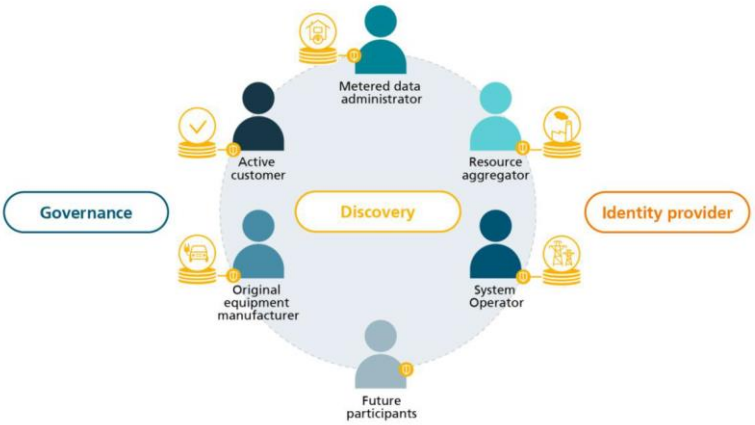

Figure 5: Initial setup of the Common European Energy Data Space (European Commission 2023a)

On the European level, energy organization Gaia-X is striving to establish an ecosystem with federated and secure infrastructure, by organizing the community management and governance of the emerging digital ecosystem where data is shared and made available in a trustworthy environment (Gaia-X European Association for Data and Cloud AISBL 2023). The intention behind the initiative is to give users control back by retaining sovereignty over their data. The federated system would link many cloud service providers and users together in a transparent environment that should drive the future European data economy. Gaia-X started in 2019 as a non-profit association where members define its architecture and rules. Today, association counts more than 1800 contributors and more than 350 members all working toward the same goal of creating trusted decentralized digital ecosystems aligned with EU standards. Germany, while also participating in Gaia-X initiative, has many running projects on data economy and data spaces. Paper published by Büchel und Engels (2022) pointed out the importance of data economy for Europe´s digital strategic autonomy, while also saying that high share of German companies from industrial and industry-related service sector are not data economy ready, which means that they do not possess the ability to store, process, use, and share data securely and autonomously. Therefore, the Federal Ministry for Economic Affairs and Climate Action is funding a total of 21 selected projects in the Smart Data Economy (BMWK 2024b). The aim is to develop and test solutions such as data products and systems, data services derived from them and data-based business models. In the digital age, data is a significant economic factor and resource for creating economic value.

Energy Data and Data-driven Business Models

Current economy is experiencing express digitalization with a growing number of innovative and data-based business models. As stated in European Strategy for Data Economy and Energy System, that trend has hit power system that is currently undergoing transition to a more digital ecosystem. Vital factors for the advancement of data-driven business models in the energy

sector are energy data collection and its analysis. In order to address this issue, German government decided to deploy smart meters, which would help digitalize the energy system and improve data accuracy (Die Bundesregierung 2023). However, as identified by a study conducted by EnTEC (European Commission 2023a), challenges persist in ensuring secure and efficient data sharing. Leading challenges in data sharing within the EU energy sector include warranting uniform data formats across countries, addressing access barriers due to data ownership by multiple stakeholders, ensuring compliance with data privacy regulations like General Data Protection Regulation (GDPR), and mitigating cybersecurity risks to safeguard business operations.

Collaborative efforts are essential in order to harness the full potential of data. Projects like the "Incentives and Economics of Data Sharing" (IEDS) focus on designing mechanisms which offer incentives to organizations for participation in open data networks (Fraunhofer ISST 2024). By aggregating and sharing data with stakeholders, these digital ecosystems generate value added (European Commission 2023b) (Sestino et al. 2023). On the other hand, ensuring data quality is crucial for efficient digital energy systems. Methods such as the one developed by the Institute for Energy Environment Forecast Analysis (EEFA) aim to accurately determine energy consumption in sectors not covered by official statistics (BMWK 2024a). This approach helps improve energy balance and supports data-driven decision-making in the energy sector by utilizing extrapolations and data from energy cost billing firms.

In summary, EU initiatives like Gaia-X and the Common European Energy Data Space aim to enhance data-sharing ecosystems and drive innovation in the energy sector. Germany's projects, funded by the Federal Ministry for Economic Affairs and Climate Action, address challenges in the data economy to promote value creation. In the upcoming section, we'll delve into a model heavily dependent on data quality within the energy sector.

Methodology

After laying out the context and rationale in the previous section, next step involves the calculation of potential aggregator profits to address the research question. This section will detail the methodological approach by referencing methods used in similar studies, then outlining the analysis framework, and finally, explaining the steps taken to calculate the profits. Additionally, this study will discuss alternative electricity tariffs available to households as reference points to better assess the realized flexibility potential on the intraday market.

Optimization Approach to Model Heat Pump and Storage Capacity on Spot Market

The model draws upon prior research conducted by Marijanovic et al. (2022), the open-source "FlexIndex" model by (CF Flex Power GmbH), and the simulation program “Microscope” developed by Fraunhofer IEE. Similar to Marijanovic et al. (2022) and FlexIndex, this study employs storage modeling for realizing flexibility on energy market. Flexible operation of the heat pumps is characterized by deviations from thermal-driven operation, represented by the household's load profile L_t, which is the energy required to always cover household’s thermal consumption. Deviations from thermal-driven operation occur due to price fluctuations on the spot market. In terms of heat pump capacity control, it is assumed that heat pump operation promptly follows the signals sent by the agent, which could be either the household itself or an aggregator. Consequently, additional revenues are generated on the spot market by reducing heat pump consumption during periods of high prices and increasing it during periods of low prices. When the heat pump is curtailed, it operates below the L_t level, with thermal storage fulfilling the heat demand. Conversely, when the heat pump is ramped-up, it operates above L_t level, with excess energy stored in the storage system (similarly to the method used by Marijanovic et al. (2022)). To sum it up, aside from supplying thermal demand, the focus of this thesis's heat pump application is on wholesale prices and maximizing additional household profits by exploiting price differentials between electricity buying and selling times.

It is important to highlight that the modeling approach is expanded to analyze potential agent profits, with inputs being diversified within the analysis. Agent profits are primarily influenced by the price spreads and the capacity for energy shifting. Therefore, input variations are made with respect to storage sizing and household characteristics, while also considering two different spot markets, namely day-ahead and intraday.

The next section will formally define the flexibility problem as a mixed-integer linear program (MILP) in hourly time periods for the day-ahead market and quarter-hourly time periods for the intraday market. Subsequently, the model is translated to Python and solved using the open-source software package Pyomo and the GLPK solver.

Mathematical Formulation

Table 2: Equations

(1)	$max \sum_{1}^{T} p_t \cdot (q_t^{dis} - q_t^{ch})$	$\forall\, t \in T$
(2)	$SOC_t = (1-\beta) \cdot SOC_{t-1} + (1-\gamma) \cdot q_t^{ch} \cdot COP_t - (1-\delta) \cdot q_t^{dis} \cdot COP_t$	$\forall\, 1 \geq t \geq T$
(3)	$q_t^{ch} \leq q_{max}^{HP} - L_t$	$\forall\, t \in T$
(4)	$q_t^{dis} \leq SOC_t$	$\forall\, t \in T$
(5)	$0 \leq SOC_t \leq SOC_{max}$	$\forall\, t \in T$
(6)	$SOC_t = 0$	$\forall\, t = 1, T$
(7)	$q_t^{dis} \leq y_t^{dis} \cdot M$	$\forall\, t \in T$
(8)	$q_t^{ch} \leq y_t^{ch} \cdot M$	$\forall\, t \in T$
(9)	$y_t^{ch} + y_t^{dis} \leq 1$	$\forall\, t \in T$

Table 3: Sets, Variables and Parameters

Symbol	Unit	Definition
Set		
$t \in T$	h	Period
Variables		
SOC_t	kWh	State of charge (storage)
q_t^{ch}	kWh	Charged energy
q_t^{dis}	kWh	Discharged energy
y_t^{ch}	[0, 1]	Indicator for charge
y_t^{dis}	[0, 1]	Indicator for discharge
Parameters		
L_t	kWh	Load profile (heat pump)
p_t	€/kWh	Spot price
β	[0; 1]	Stationary loss
γ	[0; 1]	Dynamic loss charge
δ	[0; 1]	Dynamic loss discharge
COP_t	≥ 0	Coefficient of performance factor
SOC_{max}	kWh	Maximum state of charge
q_{max}^{HP}	kWh	Maximum heat pump capacity
M	-	Big M number (1000)

The heat pump flexibility model is defined by a profit maximization objective function subjected to heating system and storage constraints (as seen in Table 2), which is defined with various parameters and variables (as seen in Table 3). Equation (1): Objective function maximizes the net profit, which is calculated based on the energy procured q_t^{ch} and marketed q_t^{dis} on the spot market for the given price p_t. Equation (2): State of charge constraint SOC_t models the dynamics of the storage system, taking into account static (β) and dynamic (γ and δ) losses and the efficiency coefficient COP_t of the heat pump. It ensures that the state of charge of the storage system remains within acceptable limits. Equation (3): Charging limit constraint limits the amount of energy that can be charged based on the existing thermal demand L_t and the maximum capacity of the heat pump q_{max}^{HP}. It ensures that the charging process does not exceed the remaining capacity. Equation (4): Discharging limit constraint ensures that the energy discharged by the storage does not exceed the state of charge at each time step. Equation (5): Storage capacity constraint sets a limit on the storage capacity, ensuring that it does not exceed the maximum capacity SOC_{max}, which will be varied as part of subsequent analysis. Equation (6) & (7): Discharging and Charging big M Constraint introduce binary variables, y_t^{ch} and y_t^{dis}, to control the charging and discharging processes by using the big M method (Bonami et al. 2015). The big M value must be a sufficiently large number to effectively enforce the constraints, and for this study, it is set at 1000. Equation (8): Binary constraint ensures that either charging or discharging (or neither) can occur at each time step.

Furthermore, the model distinguishes between the day-ahead and intraday market optimization cycles. The day-ahead optimization cycle implicitly refers to the optimization cycle of every 24 hours with hourly products, aligning itself with publicly available price data. Conversely, intraday market optimization involves shorter cycles with quarter-hourly products, allowing for higher volatility. A visual representation can be seen in Figure 6.

Upon solving this linear program, the optimal electricity charging and discharging schedule is determined, along with the resulting daily, monthly, or seasonal profit. The visualization of the optimization process, depicting the main inputs, processes, and outputs, is illustrated in Figure 6. The following section will introduce alternative electricity tariffs for the purpose of comparison when evaluating the flexibility potential of the intraday market.

Electricity Tariffs Available to Households

To participate in the intraday market trading, additional prerequisites are necessary compared to more conventional electricity purchase agreements. For instance, the intraday market imposes a minimum requirement on the amount of electricity that can be traded, specifically 0.1 MW (Martin und Otterson 2018). This entry requirement restricts private households from engaging in spot market trading due to their typically lower heat pump and storage capacities, which usually range in the few kW power. Therefore, additional market participants such as aggregators are essential to aggregate multiple households and strive to achieve the best buy or sell price on the spot market.

To accurately assess the potential profits resulting from such a complex operation, it is crucial to put it into perspective and compare it to alternative electricity tariff options.

Figure 6 illustrates four electricity tariffs considered in this study: basic flat tariff, heat pump flat tariff, day-ahead dynamic tariff, and intraday dynamic tariff. The basic flat tariff and heat pump flat tariff are commonly offered electricity tariffs by all major energy providers in Germany. The basic flat tariff is a default household electricity tariff available regardless of the installed metering system or the type of consumption units owned. Conversely, the heat pump flat tariff is designed for households equipped with a heat pump and an attached separate meter, enabling external control of the consumption unit in accordance with Act on Metering Point Operation (MsbG) §19. According to the Act on Electricity and Gas Supply (EnWG) §14a, electricity providers are permitted to offer customers a cheaper electricity tariff with a reduced grid fee upon entering agreements on the grid-oriented control of controllable consumption devices. Such grid-oriented control aims to alleviate pressure on the grid network during peak consumption hours by disconnecting controllable consumption from the electricity grid. Consequently, heat pump flat tariffs are significantly cheaper for operating the heating system than the default tariff. This study models the heat pump flat tariff where it assumes that households opting for the heat pump flat tariff were equipped with storage capacity to fill-in when the heat pump gets disconnected from the grid. The overall model structure mostly remains unchanged, with the exception of the objective function. The objective function, represented as equation (10), aims to minimize charging of storage. Furthermore, equation (11) defines that storage needs to able to cover the difference between the required load profile L_t and the curtailed load profile L_t^{hp}.

$$min \ \sum_1^T q_t^{ch} \tag{10}$$

$$q_t^{dis} = L_t - L_t^{hp} \tag{11}$$

In conclusion, both objective functions aim to minimize costs but employ different methods. Models with dynamic prices seek to maximize profit through market arbitrage, thereby reducing overall electricity expenses. Conversely, the heat pump flat tariff, with its uniform electricity price, cannot leverage price gaps to maximize profit. Instead, it must minimize storage usage to avoid energy losses and achieve the lowest possible price.

Furthermore, households can opt for dynamic electricity tariffs, allowing them to regulate their own consumption based on day-ahead electricity prices provided by electricity providers like tibber (Tibber Deutschland GmbH 2024). Tibber provides services such as a mobile application and necessary technical equipment for consumption regulation in exchange for a small fixed monthly fee (as seen in Table 4). While the mentioned tariff options are already viable for households, the

intraday electricity market has not yet been offered as a solution. This underscores the importance of evaluating its potential compared to existing options.

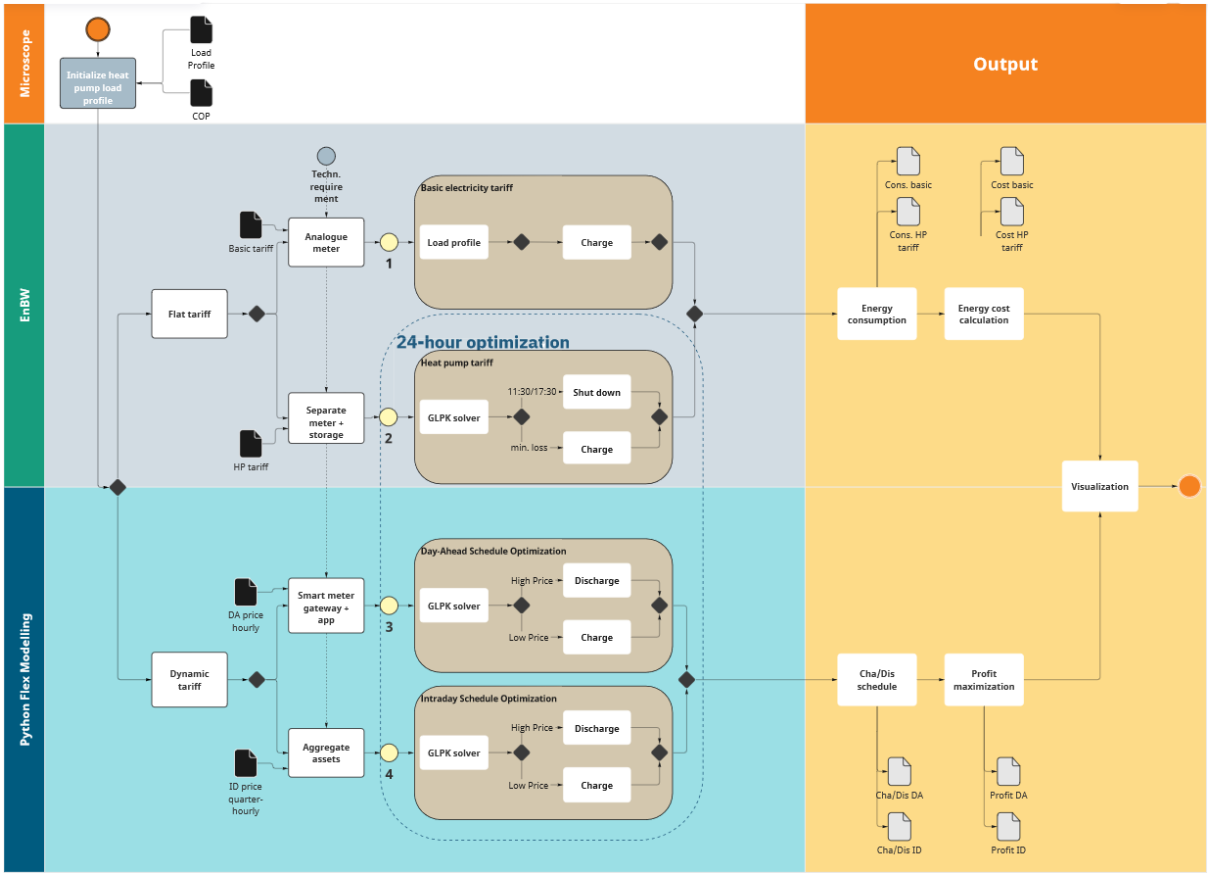

Figure 6: Modelling process (own depiction)

To sum up the models considered in this study, Figure 6 provides an overview of all processes, from initialization to result visualization. The process begins with retrieving input data from the program Microscope, followed by evaluating either the flat or dynamic tariff options, each with different technical requirements. Both the heat pump flat tariff and dynamic tariffs then undergo 24-hour MILP optimization, and finally, all results are visualized, which will be presented in the chapter Results. The following chapter will elaborate in detail on the input data and model parametrization, providing a deeper understanding of the sources, assumptions, and configurations used in the study to ensure the accuracy and relevance of the simulation outcomes. This includes a thorough discussion of the data types, the rationale behind specific parameter choices, and the calibration methods applied to align the model closely with real-world conditions. This detailed elaboration sets the stage for interpreting the results presented in the subsequent chapter.

Model Input and Parametrization

This chapter describes input data obtained from multiple sources. System parameters such as load profiles, coefficient of performance for the heat pump, and loss factors for thermal storage were provided by Fraunhofer IEE. On the other hand, electricity prices were sourced from publicly available web sources (as seen in section Energy Trading).

Electricity Market

This study considers four different electricity prices, as outlined in Table 4. Flat tariffs are based on electricity tariffs offered by Energie Baden-Württemberg (EnBW 2024), while the Day-ahead model utilizes the already available dynamic tariff tibber (Tibber Deutschland GmbH 2024). As depicted in Table 4, all tariffs include a fixed monthly fee and a cost per kilowatt-hour. Flat tariffs have a constant cost per kWh, while dynamic tariffs feature a variable cost. Variable cost for day-ahead dynamic tariff is sourced from the official website of the Federal Network Agency (SMARD 2024a). The dynamic electricity prices pertain to the year 2022 from January to September and whole year 2023.

Table 4: Business models/Tariffs

Business Model	Referent tariff	Monthly fix fee €	Hourly price ct/kWh
Basic-Flat	EnBW	15,51 €	27,77 ct
HP-Flat	EnBW	6,37 €	19,33 ct
DA-Dynamic	tibber	5,99 €	Hourly DA price
ID-Dynamic	-	Aggregator fee	Quarterly weighted average

On the other hand, determining intraday auction prices requires more consideration. The continuous intraday market offers various products with different energy prices, as described in section Day-ahead & Intraday Market. For each time unit, there are multiple buy and sell prices, and the prices of energy depend on the volume being traded. In this study, a small trading volume was assumed, allowing us to achieve prices close to the best buy and best sell that could be expressed as weighted average price for this model. Weighted average price was extracted from intraday price index ID3 in quarter-hourly resolution from (EPEX SPOT 2024b) provided by Fraunhofer IEE.

As seen in Figure 7, the model's two flat and two dynamic electricity tariffs for the years 2022 and 2023 are displayed in both annual (left-hand side) and weekly (right-hand side) time scale in quarterly-hour resolution. The figure clearly illustrates the differences in price volatility between the tariffs and across the years, which will be further discussed in the Results section.

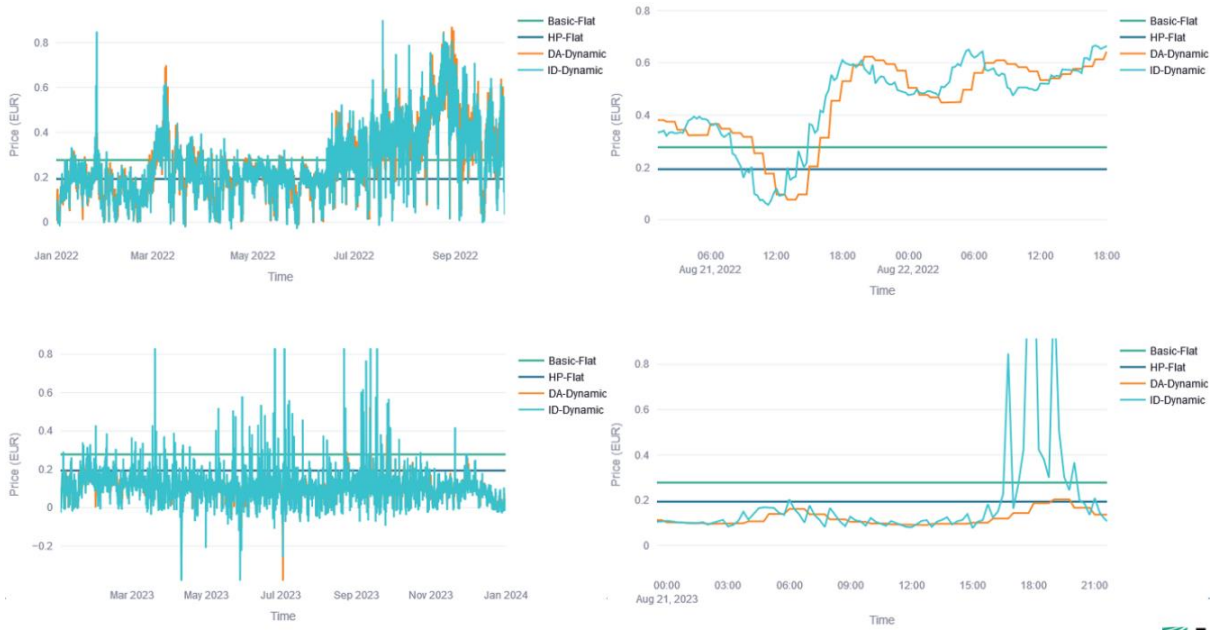

Figure 7: Annual and daily electricity tariff prices for 2022 and 2023

Heat Pump Load Profiles

This section delineates different households and their corresponding load profiles. The study will analyze four distinct load profiles based on the maximum heat pump capacity installed, building type, and year of construction (as depicted in Table 5).

All load profiles feature heat pumps with air-water heat sources installed in single-family homes (SFH) and townhouses (TH). Buildings are categorized based on the year of construction: those constructed after 2016 are considered new, while those built between 1949 and 1978 are classified as old. The selection of load profiles was made with consideration for households' ability to be independent in their electricity choices, hence apartment buildings were not considered. Hence, this study uses four different heat pump load profiles: new and old single-family household with heat pump capacity of 7,1 kW and 10,2 kW respectively, as well as new and old townhouse household with heat pump capacity of 7,2 kW and 5,5 kW respectively.

Table 5: Load profiles[1]

Load profile	HP capacity (kW)	Heat source	Building type	Building standard
New SFH	7,1	Air-water	SFH	New
New TH	7,2	Air-water	TH	New
Old SFH	10,2	Air-water	SFH	Old
Old TH	5,5	Air-water	TH	Old

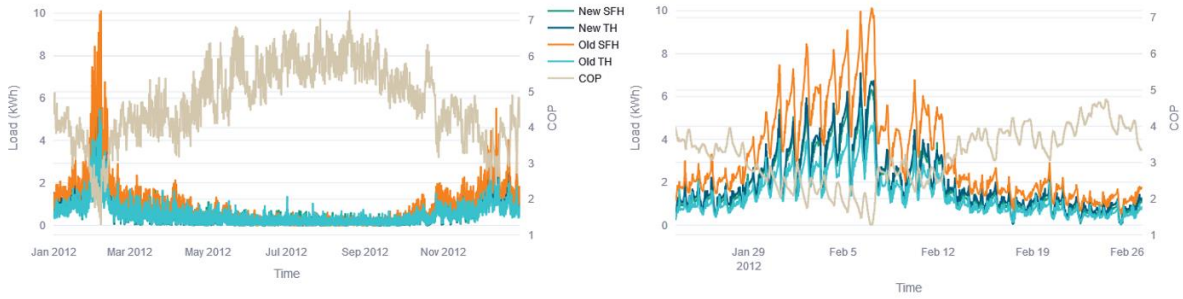

Figure 8: Load profiles & COP – energy demand (annual & 2 weeks in February)

The load profiles were generated[2] according to the test reference year 2012 for Germany (Deutscher Wetterdienst 2024), along with the related coefficient of performance (COP). The coefficient of performance, representing heat pump efficiency, is simulated for different weather conditions. The optimization model considers source temperatures (air inlet) ranging from -20°C to +30°C and desired water outflow from 35°C to 55°C, with COP factors varying between 1,82 and 6,3. As seen in Figure 8, the highest energy consumption across all households occurs during the cold months, reaching a peak in February. As such, full heat pump capacity is seldomly used. Conversely, the COP factor behaves contrary to the energy demand. For example, when the demand is highest in winter, the COP factor is lowest, indicating reduced heat pump efficiency.

Storage

Storage sizing was determined based on the maximum heat pump capacity. A standard storage capacity equivalent to 2 hours of the maximum heat pump capacity was assumed. This aligns with regulations specified in Federal Electricity Tariff Regulations (BTOElt) §7, which allow grid operators to disconnect heat pumps for a maximum duration of 2 hours during peak hours.

[1] Courtesy of Fraunhofer IEE
[2] Courtesy of Fraunhofer IEE

Therefore, the storage capacity serves as an energy source replacement during periods of high electricity demand. Subsequently, this study will vary the storage capacities to assess their impact on flexibility revenue. In addition to the standard two-hour capacity, capacities of four hours and six hours were also considered. Table 6 illustrates the storage capacities corresponding to different load profiles.

Table 6: Storage capacities across tariffs

Load profile	HP capacity (kW)	Storage 2h (kW)	Storage 4h (kW)	Storage 6h (kW)
New SFH	7,1	14,2	28,4	42,6
New TH	7,2	14,4	28,8	43,2
Old SFH	10,2	20,4	40,8	61,2
Old TH	5,5	11,0	22,0	33,0

Lastly, the study assumes a stationary loss of 10%, accounting for energy losses during standstill periods. At the same time, dynamic losses during storage operation were assumed as 0,2% for charging and 0,1% for discharging. The loss values were estimation by Fraunhofer IEE expert on thermal storage systems. This chapter lays the foundation for the subsequent analyses by providing a detailed understanding of the input data characteristics and model parameterization, essential for accurate simulations and interpretations of the results.

Results

This chapter will explore the energy consumption patterns and market dynamics for a single-family household in a newly renovated house throughout the year 2023. Through an analysis of seasonal trading characteristics, weekly consumption schedules, and comparisons across different tariffs, insights into the household's intraday market activities and resulting profits can be gained. The findings reveal seasonal variations in profitability, distinct consumption patterns throughout the week, and the impact of tariff choices on energy usage and cost reductions. Furthermore, comparisons between years 2022 and 2023 highlight shifts in the attractiveness of the day-ahead and intraday markets, while an investigation into varying thermal storage capacities offers insights into optimizing profitability.

Base Case

This chapter will the results of the intraday optimization model, focusing on the base case scenario of a single-family household residing in a newly renovated house (New SFH) for year 2023. The chapter will display energy consumption patterns under different dynamic tariff options and examine seasonal variations in energy consumption. Additionally, the household's seasonal behavior in marketing its energy on the intraday market and the resulted profit is presented.

Time Based Analysis

Time based analysis will consider seasonal variation of results and later delve into specifics connected to average weekdays, highlighting working weekdays, Saturday, and Sunday separately.

Seasonal

This subchapter examines the trading activities of single-family households on the intraday market across four different seasons, as depicted in Figure 9. The analysis considers charging and discharging schedules according to the course of intraday prices, providing insights into the achieved profit per season.

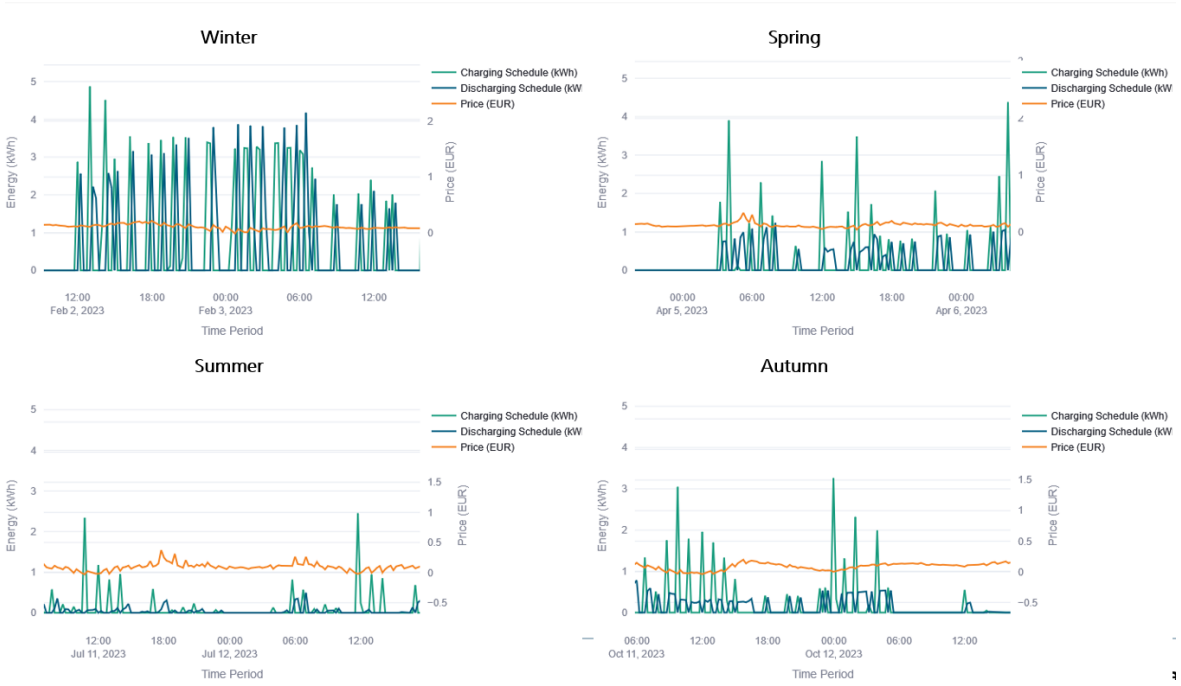

Figure 9: Seasonal trading on Intraday market 2023 (New SFH)

Winter (2nd and 3rd of Feb)

Spring (5th and 6th of Apr)

Summer (11th and 12th of Jul)

Autumn (11th and 12th of Oct)

In the graph, four different days from February, April, July, and October represent four different seasons. The graphs display time periods in quarter-hour resolution on the x-axis, energy charged or discharged in kWh on the left y-axis, and energy price on the intraday market per kWh in Euro on the right y-axis. The green line depicts the charging schedule, the blue line represents discharging, and the orange line illustrates the course of intraday price. Across all four graphs, it is evident that charging and discharging do not occur simultaneously. A dip in energy price results in energy being charged, while a price jump leads to energy being discharged.

Winter emerges as the season with the highest trading volume, directly correlated with the peak energy demand from heat pumps. Additionally, price volatility is relatively low compared to warmer months. In warmer seasons, there is a notable decrease in energy demand, primarily limited to warm water heating, leading to a lower volume of trading. However, it is noteworthy that negative energy prices may occur, likely caused by high energy generation from solar plants. Autumn sees a resurgence in energy volume, indicating a return to higher trading activity.

The disparities in energy trading and price development are most evident in the varying profits observed across winter, spring, summer, and autumn, as illustrated in Figure 10. By far, the highest profit was achieved during the winter months, accounting for approximately one-third of the annual profit generated through heat pump flexibility for a single-family household. Conversely,

despite the lower energy demand, the summer months yielded relatively good profits, attributable to the relatively high price volatility caused by renewable energy sources. For instance, summer yielded the highest revenue per sold kWh of 8,6 eurocents, followed by spring with 5 eurocents, and winter and autumn 2,2 eurocents and 1,9 eurocents respectively. The profits observed in spring and autumn mirror the trend of decreasing energy demand compared to winter and increasing energy demand compared to summer, while also reflecting the occurrence of price jumps relatively well.

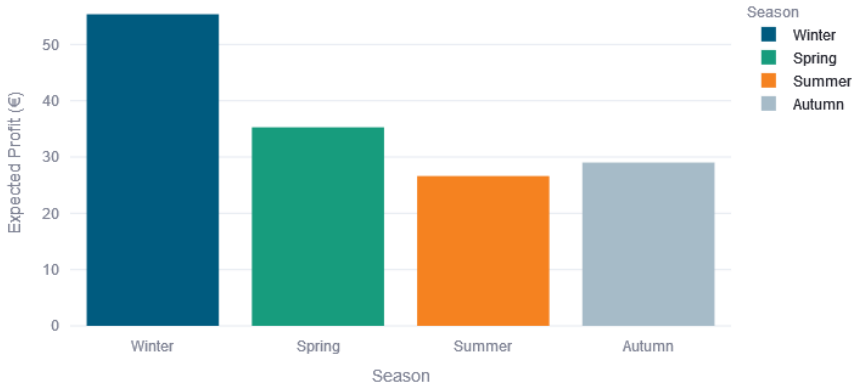

Figure 10: Seasonal profit on Intraday market 2023 (New SFH)

Overall, the seasonality exerts a significant impact on the potential earned profit through heat pump flexibility on the intraday market. The differences observed across seasons, such as variations in energy demand and price volatility, highlight the dynamic nature of the market and underscore the need for tailored strategies to optimize profitability throughout the year.

Weekday

Next, the discussion shifts to the energy consumption patterns throughout the week, as depicted in Figure 11. The week is presented as an hourly consumption schedule for an average weekday, covering Monday to Friday, followed by Saturday and finally Sunday.

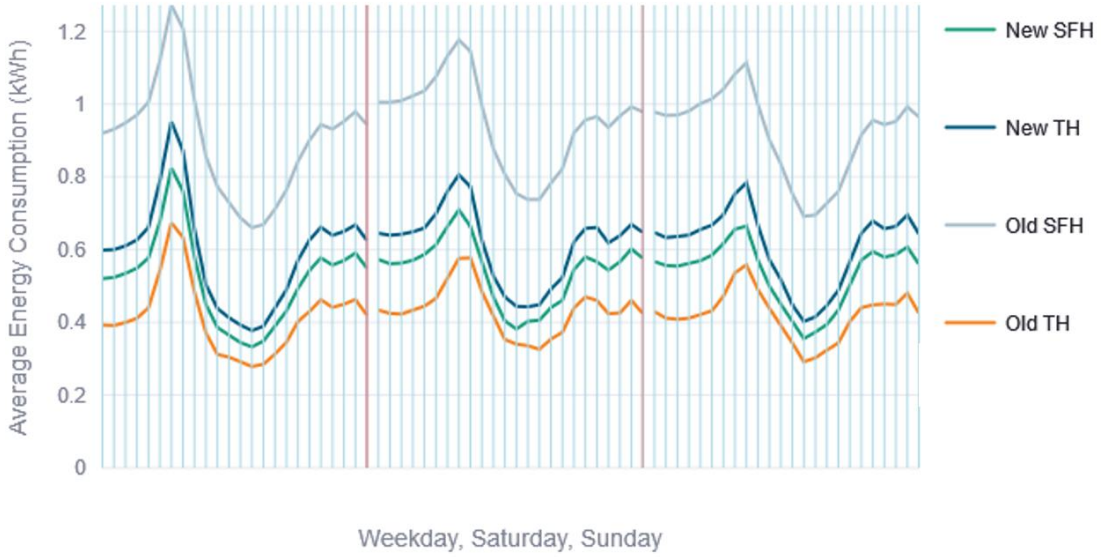

Figure 11: Weekly energy consumption schedule on average

All four energy consumption profiles suggest a similar consumption pattern, varying in volume. The peak consumption typically occurs at 7 in the morning and dips around 2 o'clock in the afternoon. Even in the household profile with the highest consumption, energy consumption rarely exceeds 1 kilowatt-hour. Saturdays exhibit a less extreme consumption pattern compared to weekdays, while Sundays exhibit the lowest overall consumption per day. The energy demand pattern reflects the living habits of the family, suggesting strong energy demand before leaving the house and after returning, while Sundays indicate a day spent outside the house. Furthermore, as illustrated in Figure 12, different days of the week are associated with varying profits as well.

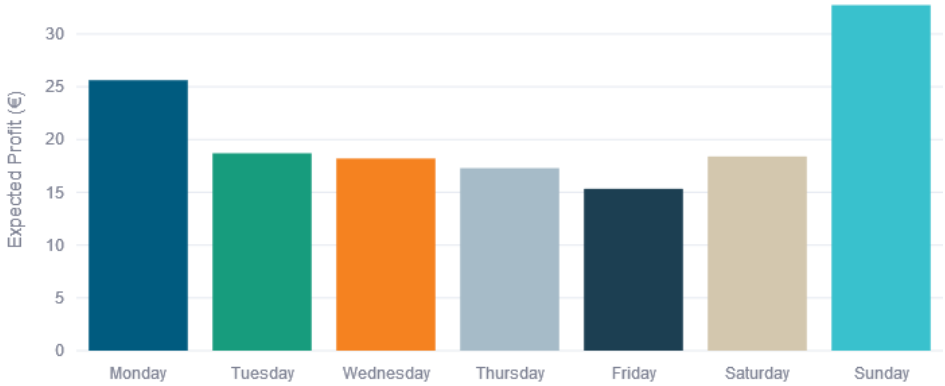

Figure 12: Profit per weekday for a New SFH on Intraday market 2023

In contrast to the lowest energy demand on Sunday, Figure 12 suggests that the highest achieved profit for heat pump flexibility occurs on that day. This difference could be attributed to factors such as price volatility and the availability of more thermal storage capacity for trading on

the market. Overall, weekly patterns serve as an additional factor to consider when discussing flexibility potentials.

Cost Comparison on Household Level

In this subchapter, the analysis focuses on four different tariffs, with the basic flat tariff serving as the baseline. The other three tariffs are presented in comparison to the baseline.

Figure 13 illustrates the annual energy consumption for a single-family household (New SFH) under four different tariff options. Comparing the energy consumption values across the different tariffs reveals notable differences. Under the basic-flat tariff, the household's annual energy consumption was 4598.38 kWh. When compared to this baseline, the HP-flat tariff experiences a slight increase of 2.43%, with an energy consumption of 4709.92 kWh. Further energy consumption increases to were noticed under day-ahead dynamic tariff (DA-Dynamic) and intraday dynamic tariff (ID-Dynamic), namely 5015.37 kWh and 5033.01 kWh respectively. These represent a significant increase of 9.07% and 9.45% compared to the baseline (as seen on right y-axis in Figure 13). Higher energy consumption is caused by storage use and resulting energy losses during load shifting. Therefore, while more dynamic tariffs offer potential benefits in terms of flexibility and cost savings, they also lead to higher energy consumption.

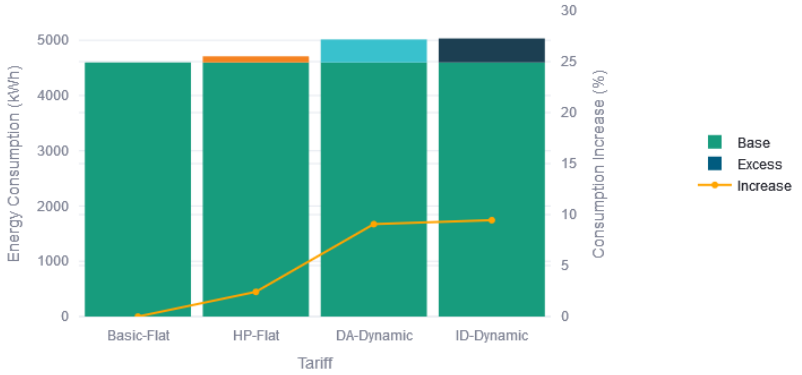

Figure 13: Energy consumption across tariffs (New SFH)

Before presenting cost reduction potentials under different tariffs across all four load profiles, it is important to mention different underlying energy consumption. Among the load profiles, energy consumption ranges from lowest for old townhouse (TH) with 3.659 kWh annual consumption, to highest for single-family house (SFH) in old building with annual consumption of 8.007 kWh. As such, households are associated with different absolute economic potential. Table 7 provides a comprehensive overview of the results for cost reductions across all four load profiles in year 2023 in comparison to the baseline of basic flat tariff. Across all households, the HP-flat tariff consistently offers the most significant cost reductions compared to the basic-flat tariff, with

reductions being around 30%. This makes it an attractive option for households looking to reduce energy costs by abiding to EnWG §14a regulations. However, this statement will be subject to scrutiny in the subsequent Discussion chapter, where the advantageous conditions afforded to heat pump tariffs, such as reduced grid fees and other levies, will undergo closer examination and contextualization. The analysis aims to provide a more comprehensive understanding of the true implications when opting for such incentivized tariffs. In addition, analysis will provide a balanced perspective for households considering their energy procurement options.

When comparing the day-ahead dynamic and intraday dynamic tariff, variations in cost reductions and potential benefits across different load profiles can be observed. Under the intraday dynamic tariff, the cost reductions are generally larger across all load profiles compared to the day-ahead dynamic tariff. For example, while intraday offers cost saving above 20% across all households, day-ahead tariff struggles with cost savings close to 2%. Furthermore, the relative cost reductions under the intraday dynamic tariff vary more significantly across different load profiles compared to the day-ahead dynamic tariff. This suggests that the intraday market offers greater saving opportunities to the households with higher energy demand and bigger storage and heat pump capacities installed.

Table 7: Cost reduction under different tariffs 2023 Jan – Dec

Load profile	Energy consumption	Cost	Cost reduction		
		Basic-Flat	HP-Flat	DA-Dynamic	ID-Dynamic
New SFH	4.598 kWh	-1.277 €	+ 367 € *	+ 31 €	+ 146 €
New TH	5.246 kWh	-1.457 €	+ 442 € *	+ 34 €	+ 159 €
Old SFH	8.007 kWh	-2.223 €	+ 673 € *	+ 46 €	+ 223 €
Old TH	3.659 kWh	-1.016 €	+ 308 € *	+ 26 €	+ 119 €

**HP-Flat tariff contains grid fee and levy reduction*

Comparing the results from January to the end of September 2022 with those from the year 2023, the most significant difference lies in the cost reductions achieved under the day-ahead dynamic and intraday dynamic tariffs (Table 8).

Table 8: Cost reduction under different tariffs 2022 Jan - Seb

Load profile	Energy consumption	Cost	Cost reduction		
		Basic-Flat	HP-Flat	DA-Dynamic	ID-Dynamic
New SFH	2.987 kWh	-829,44	+ 252 €	+ 32 €	+ 22 €
New TH	3.383 kWh	-939,38	+ 286 €	+ 34 €	+ 23 €
Old SFH	5.190 kWh	-1441,25	+ 438 €	+ 46 €	+ 34 €
Old TH	2.405 kWh	-667,84	+ 203 €	+ 26 €	+ 18 €

Despite the significantly lower energy consumption for the year 2022, the cost reduction under the day-ahead dynamic tariff remained relatively consistent between 2022 and 2023. This suggests that the attractiveness of the day-ahead market for offering flexibility services in 2022 was higher than in year 2023. Furthermore, it is noteworthy that the comparison between the attractiveness of the day-ahead and intraday markets reveals a notable difference between the two years. In 2022, the results suggest a higher attractiveness of the day-ahead market compared to the intraday market, which is in contrast to the findings from 2023. Possible reasons for this difference could be difference in volatility in electricity prices or other market conditions.

Sensitivity Analysis

This section examines market volatility and compares the results of the day-ahead and intraday markets for the years 2022 (Jan to Sep) and 2023. The volatility of the electricity prices was determined using a rolling standard deviation calculation.

Year on Year Comparison

Mathematical equation for rolling standard deviation is as follows (12), where σ_t stands for rolling standard deviation at time t. Window size n is set to 7, where p_i stands for energy prices within the rolling window and $\bar{p}_t$ for mean energy price within the window.

$$\sigma_t = \sqrt{\frac{1}{n-1} \sum_{i=t-n+1}^{t} (p_i - \bar{p}_t)^2} \tag{12}$$

As depicted in Figure 14, for the day-ahead market in 2022, the median price was 0,0103 €/kWh, with a mean of 0,0143 €/kWh and a standard deviation of 0,0139 €/kWh. In 2023, these values decreased, with the median at 0,0047 €/kWh, mean at 0,0067 €/kWh, and standard deviation at 0,0075 €/kWh, indicating lower price volatility. In contrast, the intraday market showed a different trend. In 2022, the median was 0,0127 €/kWh, mean 0,0171 €/kWh, and standard deviation 0,0147 €/kWh. These increased in 2023 to a median of 0,0136 €/kWh, mean of 0,0185 €/kWh, and standard deviation of 0,0307 €/kWh, reflecting higher volatility. The maximum price also saw a significant spike in the intraday market in 2023, reaching 1,2845 €/kWh, compared to 0,2059 €/kWh in 2022. This data suggests that while the day-ahead market experienced reduced volatility in 2023, the intraday market became more volatile, presenting both higher risks and potentially greater opportunities for profit.

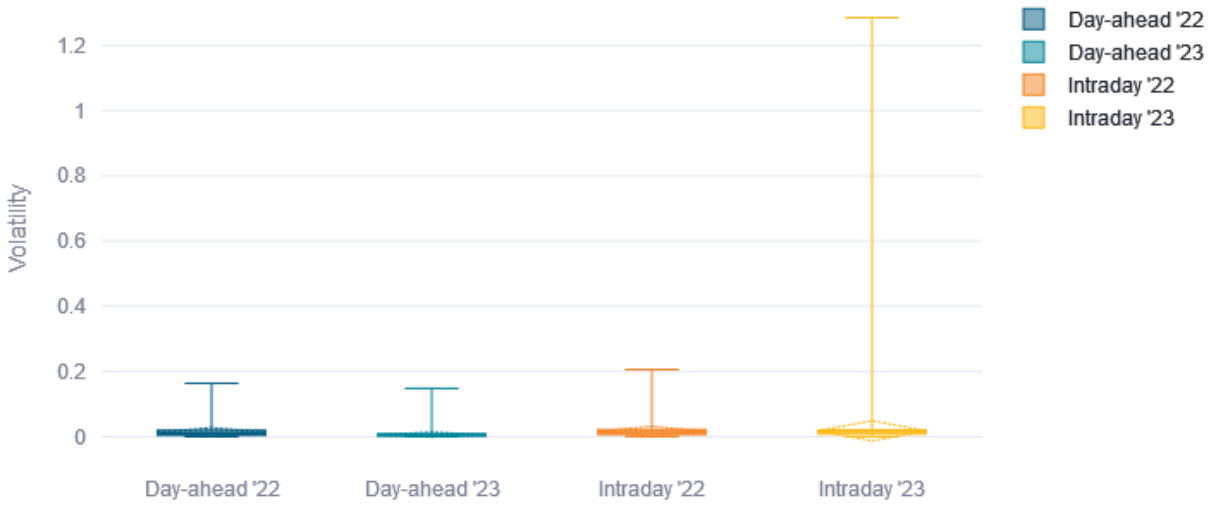

Figure 14 Electricity price volatility for day-ahead and intraday market, year 2022 and year 2023

The upcoming Figure 15 depicts the electricity market volatility for day-ahead and intraday market across all four seasons for the years 2022 and 2023. Comparing the two years, day-ahead market volatility generally decreased from 2022 to 2023. For instance, in winter, the median volatility decreased from 0,00695 in 2022 to 0,00385 in 2023. Conversely, intraday market volatility showed increase in fluctuation between the two years. In winter, for example, the median volatility increased from 0,00924 in 2022 to 0,01174 in 2023. Furthermore, each season displayed specific aspects. Winter exhibited the lowest volatility levels in both years, with generally lower median and mean values compared to other seasons. Spring showed an increase in volatility compared to winter, with a notable rise in both day-ahead and intraday market for median and mean value, as well as extreme markers. Like spring, autumn represented a transition period, with volatility levels falling between those of summer and winter, while still scoring higher than spring, particularly for the intraday market. Across all seasons, summer displayed the highest volatility levels, especially noticeable in the day-ahead market, with substantial increases in median, mean, and maximum values compared to lowest performing season i.e., winter.

Seasonal volatility in electricity markets can be traced back to several factors. Firstly, fluctuations in energy demand across seasons play a significant role in shaping market dynamics and can be attributed to higher heating demand in cooler months. Additionally, weather patterns like temperature extremes and precipitation further influences market volatility by impacting both energy consumption and generation. Finally, on top of seasonal varying of energy demand and weather conditions, the availability and variability of renewable energy sources, like wind and solar, further push seasonal price fluctuations since changes in wind intensity or sunlight hours drive renewable energy output.

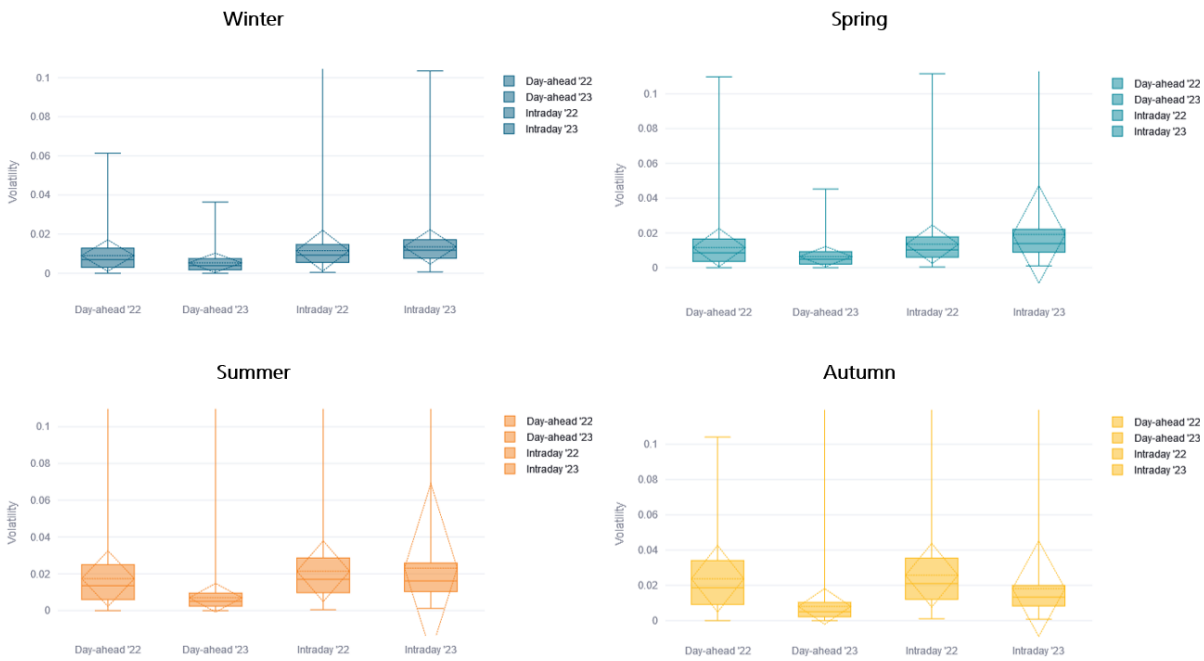

Figure 15: Seasonal electricity price volatility in day-ahead and intraday market

Storage Variation

This subchapter explores the effect of varying thermal storage capacities on the cost reduction in intraday market across different households for the year 2023 (as seen in Table 9), which additionally provides the insight into relationship between storage capacity and market dynamics. Thermal storage plays a crucial role in enabling households to participate in load shifting that optimizes their energy consumption and effectively capitalizes on market volatility. Nevertheless, it is important to assess potential additional benefit of storage increase in order for households to be able to optimize their energy profile before seeking to maximize energy cost reduction with intraday market trading.

For example, in household profile new SFH, increasing the storage capacity from 2 peak hours to 4 peak hours resulted in additional cost reduction of approximately 28 % or 41 €. On the other hand, further expansion to 6 peak hours leads to further cost reduction of around 22 percentage points compared to the base case. Similarly, in case of the new TH, the respective additional relative cost reduction is approximately 27 % and 48 % compared to the base case of 2 peak hours. This trend continues across all household profiles, with larger storage capacities generally leading to higher absolute additional cost reductions on the intraday market. The results imply that expanding thermal storage capacity leads to only marginal cost reduction. For example, when considering the new SFH, despite doubling the storage capacity from 2 to 4 peak hours, the return was only around 27 % higher. This indicates diminishing returns as storage capacity increases. Further cost-benefit

calculation would be necessary to investigate attractiveness of increasing storage capacity while weighing investment cost against the potential higher return on the electricity market.

Table 9: Storage capacity variation

Load profile	HP capacity (kW)	Initial profit	Additional profit	
		Storage 2h (kW)	Storage 4h (kW)	Storage 6h (kW)
New SFH	7,1	146 €	+41 €	+74 €
New TH	7,2	159 €	+43 €	+76 €
Old SFH	10,2	223 €	+61 €	+107 €
Old TH	5,5	119 €	+32 €	+58 €

In conclusion, while increasing thermal storage capacity shows potential for marginally higher profits, the diminishing returns observed underscore the need for careful consideration before making an investment decision. Further consideration of fixed costs and their meaning for investment decision will be discussed in Discussion and Limitations part of this study.

Discussion

This chapter examines the comparative advantages of heat pump electricity tariffs versus dynamic tariffs, focusing on the importance of accurate assessment. The relevance of fixed costs and energy data in data-driven models for energy markets is emphasized. Furthermore, a detailed comparison between day-ahead and intraday dynamic tariffs is conducted, revealing differences and similarities. Additionally, joint marketing strategies on both markets are explored, providing insights into interpreting previous results and uncovering new findings.

Equilibrating Heat Pump Electricity Tariff

This chapter will examine why the initial results show a clear cost advantage for the heat pump electricity tariff compared to dynamic tariffs. The heat pump electricity tariff from energy provider EnBW in year 2024, used in this study, offers a monthly fixed cost of 6.37 euro and a cost per kilowatt-hour of 19.33 ct (EnBW 2024). The cost explanation provided on their website highlights reduced grid usage fees and concession fees for controllable consumption units. As illustrated in Figure 16, the electricity price comprises various taxes, charges, and levies.

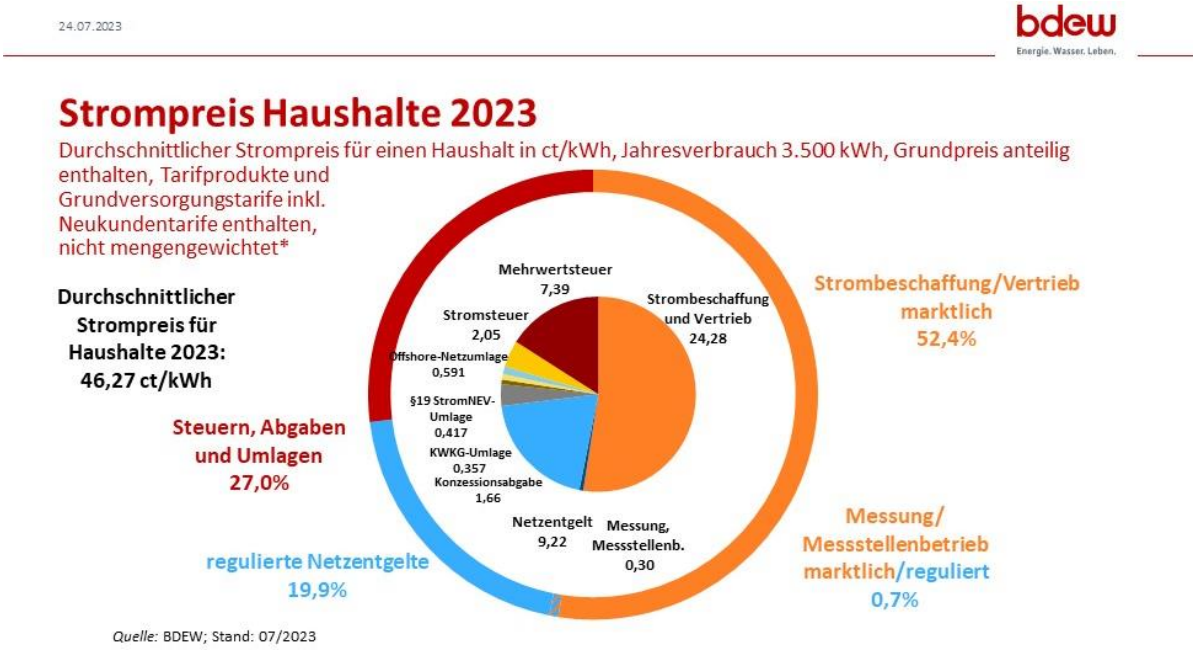

Figure 16: Electricity price components for households 2023 (bdew 2023b)

Further details on which of these extra burdens are reduced can be found on the German Federal Network Agency's website (BNetzA 2024a), which explains the three different modules that can be applied to controllable consumption units and the extent of grid usage fee reduction. Module 2, applicable to heat pumps, reduces the grid usage fee by 60%, which was 9.22 ct per

kilowatt-hour in 2023. Additionally, heat pumps under the heat pump electricity tariff are exempt from the KWKG levy of 0.357 ct, which subsidizes electricity generation from combined heat and power plants (BNetzA 2024b), and the offshore grid levy of 0.591 ct, introduced for possible compensation payments to offshore wind farm operators for delayed grid connections or prolonged interruptions (BNetzA 2024d), according to Federal Grid Agency (BNetzA 2023a).

The dynamic tariffs are not included in the charge reduction program, even though they reduce the burden on the grid by avoiding electricity consumption during peak hours when prices are highest. To ensure a fair comparison across all tariffs, the reduced charges and levies should be added to the heat pump electricity tariff. Specifically, 60% of the grid fee amounting to 5.532 ct, the entire KWKG levy, and the offshore grid levy should be added to the initial price of 19.33 ct, resulting in 25.81 ct/kWh. By recalculating the cost reduction compared to the baseline basic-flat electricity tariff, the heat pump tariff does not emerge as the most cost-effective option, as shown in Table 10.

Table 10: Adjusted heat pump tariff profitability

Load profile	Energy consumption	Cost	Cost reduction		
		Basic-Flat	HP-Flat	DA-Dynamic	ID-Dynamic
New SFH	4.598 kWh	-1.277 €	+ 61 € (+ 367 €)	+ 31 €	+ 146 €
New TH	5.246 kWh	-1.457 €	+ 101 € (+ 442 €)	+ 34 €	+ 159 €
Old SFH	8.007 kWh	-2.223 €	+ 154 € (+ 673 €)	+ 46 €	+ 223 €
Old TH	3.659 kWh	-1.016 €	+ 70 € (+ 308 €)	+ 26 €	+ 119 €

The original cost advantage of the heat pump tariff is expressed in blue brackets below the adjusted cost reduction. As seen in Table 10, the heat pump tariff loses the majority of its initial cost reduction, cutting it down from 367 euros to only 61 euros for a single-family household in a newly rebuilt house. Therefore, when the charge reduction benefits are excluded from the results, the intraday dynamic tariff emerges as the most attractive solution across all types of households for the year 2023. The day-ahead dynamic tariff remains the least attractive solution, offering benefits in the range of only tens of euros, while the intraday dynamic tariff surpasses the second-best heat pump tariff by more than half. This analysis highlights the importance of considering overall charge reduction benefits when evaluating the cost-effectiveness of different electricity tariffs, ultimately demonstrating the superior potential of intraday dynamic tariffs in delivering cost savings across various household types.

Fix Cost

Aside from comparing tariffs solely based on the cost per kilowatt hour, it is also necessary to consider monthly fixed costs and the required technical equipment to participate in different pricing schemes. Firstly, the monthly fixed cost for the baseline tariff is the highest at 15.51 €, while for the heat pump and day-ahead dynamic tariffs, it drops to approximately 6 €. The fixed cost for the intraday dynamic tariff includes the aggregator fee, which can be assumed to be similar to tibber's fixed cost of 5.99 €, as the set of services offered to the household does not differ significantly. Additionally, all tariffs require thermal storage for two peak hours, where one kilowatt of combined storage for warm and drinking water costs 2.03 €/l, according to a study by FfE (FfE 2017). Since one kilowatt can be compared to 50 to 100 liters (ofenseite 2020), one kW can cost between 101.5 € and 203 €. Thus, the cheapest household profile (Old TH) with 11 kW of thermal storage would need an investment ranging from 1,116.5 € to 2,233.0 €. With an annual yield of 119 € from the intraday dynamic tariff, the thermal storage would take between 9 and 19 years to amortize. Hence, base case does not seem very attractive and in case of further storage upscaling, the cost would increase disproportionally in comparison to market profit, making the storage investment even less profitable.

To sum up, since all three tariffs have monthly costs around 6 € and require thermal storage, a significant cost difference could arise from metering requirements. Only the heat pump tariff requires an additional meter to disconnect the heat pump. The normal annual metering cost is 20 € per household, but for controllable units, it can go up to 50 € per year (BNetzA 2024c). This additional annual cost of 50 € for the heat pump tariff is not required for dynamic tariffs. The extra metering cost is not dramatic if grid fee reductions are included, but with the revised cost benefit, this fixed cost could reduce the savings to merely 10 € in some cases.

In conclusion, when evaluating the overall cost-effectiveness of different electricity tariffs, it's essential to consider not only the per kilowatt hour rates but also the associated fixed costs and technical requirements, as these factors can significantly impact the true economic benefits of each option.

Intraday vs Day-ahead

This chapter explores the marketing of heat pump flexibility on the intraday versus the day-ahead market. Initial results for 2023 demonstrate a clear dominance of the intraday scheme. The aim is to investigate the causes of this difference by examining the charging and discharging schedules observed in both markets. Through this analysis, the underlying factors contributing to the superiority of the intraday scheme will be clarified.

Figure 17 illustrates the charging schedule (left-hand side) and discharging schedule (right-hand side) for both the day-ahead market (orange line) and the intraday market (blue line) over a few days in September 2023. This visual comparison provides insight into the operational

differences between the two markets, which will be further analyzed to understand the underlying reasons for the observed performance disparities.

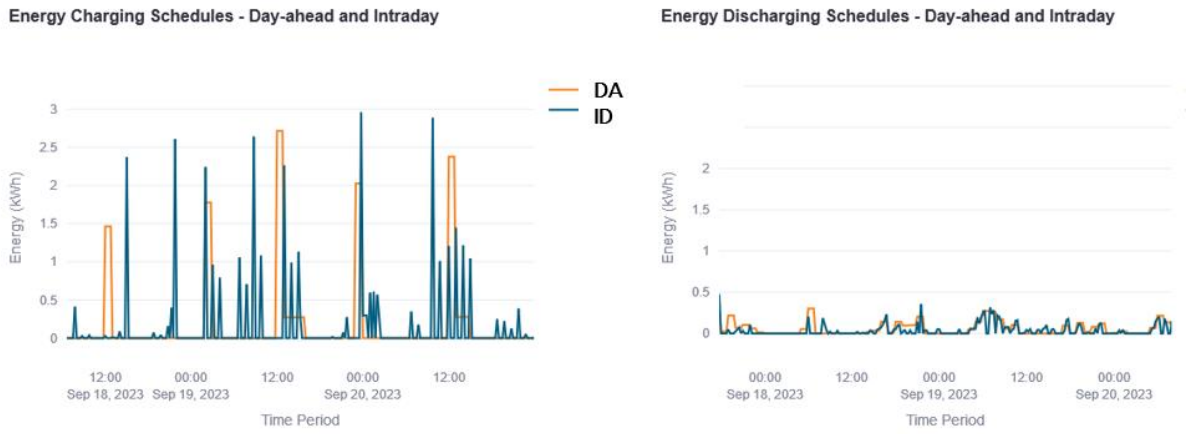

Figure 17: DA vs ID – Charging and discharging (New SFH, 2023)

The comparison between the day-ahead and intraday markets was conducted using a single-family household in a newly built house equipped with a 7.1 kW heat pump and two-hour storage. Despite having the same technical setup, the input data resolution differed: the day-ahead market used hourly data, while the intraday market used quarter-hourly data. Both models optimized over a 24-hour period, resulting in 24 units for the day-ahead model and 96 units for the intraday model. These subtle differences led to significant variations in the frequency of energy charging and discharging between the two markets. For instance, as shown in Figure 17, the intraday model executed multiple actions during periods where the day-ahead model remained passive. The traded energy volume was also higher in the intraday market, with the day-ahead model charging 5,362 kWh in 2023, compared to 6,831 kWh for the intraday model. The same pattern was observed for discharging volumes. The main differences between the two market models lie in input data resolution and price volatility, as discussed in the results section. The model is designed to capitalize on price differences to achieve higher profits, and the intraday model performed better due to its finer input data resolution and greater price volatility.

On the other hand, it would be interesting to consider how the model could be expanded to create a synergy between the two energy marketing strategies. This approach might lead to overall higher profits compared to choosing a single most profitable solution from the beginning. Since this would exceed the scope of this study, it is only possible to consider existing studies with similar intent and attempt to derive possible conclusions. For example, Corinaldesi et al. (2020) consider intraday market trading as purely short-term trading in addition to day-ahead market trading. The results of the study show that intraday trading significantly improves initial results achieved solely on the day-ahead market. But while intraday trading can enhance results initially achieved through day-ahead market trading, it is typically viewed as a complementary approach due to its inherent volatility and instability. The higher risks and shorter trading time frames typically discourage

traders from relying solely on the intraday market. Consequently, it is challenging to conclude from the literature whether sole intraday trading would be superior to a combined trading strategy. Moving forward, the next section will discuss the limitations of the model and input data used in this study.

Impact of Data

This study assessed business models that heavily rely on data. Data quality and continuity are critical for business model optimization, creation of accurate forecasts and submission of credible energy reports. By ensuring accurate and up-to-date data, market participants enable effective operation of energy systems and services. In the context of heat pump flexibility models and energy trading, data inaccuracies due to incomplete or outdated information can be costly for service providers since data has direct impact on revenue stream. For instance, real-life flexibility service providers need to rely on energy demand forecasts for the next day, which depend on historical demand data base. Furthermore, same data base enables optimization of trading model used to generate revenue. Revenue can be further impacted by market regulations in context of energy reporting.

In order to trade on the energy market, achieving the required minimum energy volume is challenging for a single heat pump, necessitating the role of an aggregator. The aggregator, who also acts as an energy and flexibility service provider, aggregates the energy from multiple heat pumps to meet the market requirements. As a direct marketer, the aggregator assumes the role of a balance responsible party (BRP). The BRP is responsible for reporting forecasts for each 15-minute imbalance settlement period to the transmission system operator (TSO) (Next Kraftwerke 2024c). If there is an imbalance, the TSO must activate balancing energy from reserves, which can be expensive due to the high cost of the last activated energy source (see Figure 18). The cost is then

forwarded to BRP group responsible for market imbalance. Thus, incorrect forecasts and reporting can lead to significant penalties and diminish the final profit.

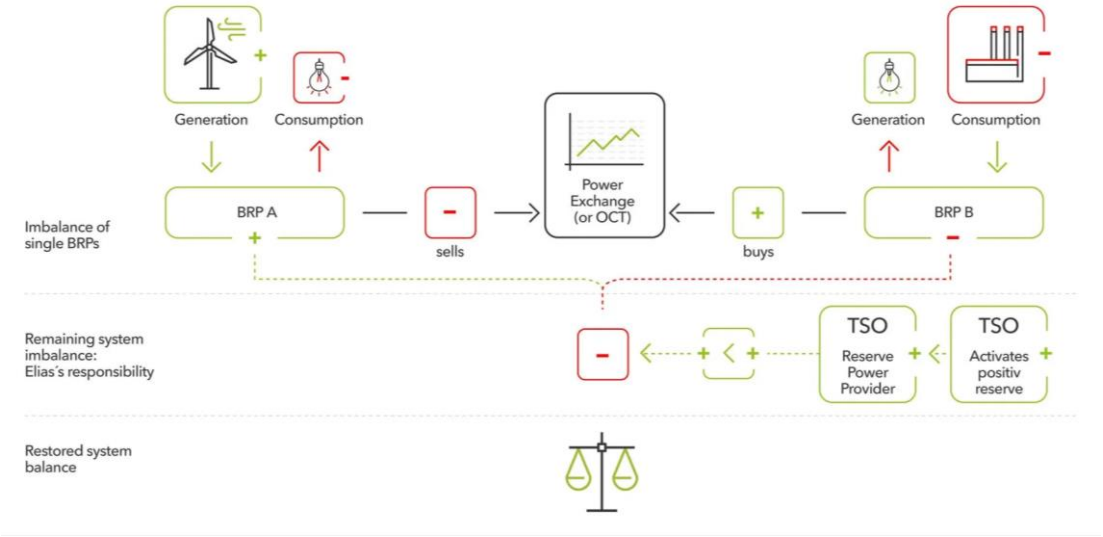

Figure 18: BRPs and Imbalances (Next Kraftwerke 2024c)

Continuous acquisition of the latest consumption data from customers allows energy providers to refine their models and forecasting programs, reducing forecast errors and associated costs. For optimal accuracy, consumption data should be synchronized with databases that include weather data, electricity price trends, technical data of consumption units, and household temporally occupancy schedules. The development and tuning of good data-driven models are characterized by consistent efforts to maintain high data quality and integration. This synchronization would enhance the reliability of flexibility services and improves the overall efficiency of the energy system. Although this study does not quantify the cost implications of forecast errors for electricity providers offering flexibility services, it underscores the critical role of accurate and integrated data in minimizing errors and costs.

Limitations

This chapter will explore limitations related to this study, like input data, model assumptions, model simplifications, and energy market simulation. The consideration of study´s limitation is crucial for understanding the constraints and potential biases inherent to the model, and for identifying areas where future research could improve the accuracy and general applicability of the results. By addressing these limitations, the goal is to provide a broader view concerning factors that could have influenced the outcomes and reliability of the previously presented findings.

The most limiting factor of this study is the input data. Energy demand and the COP factor were based on weather data from the reference year 2012, which resulted in inability to factor potential underlying correlations between temperature, load profiles and energy prices. Additionally, it was not possible to account for geographical variations, which could have provided more accurate load profile evaluations. Furthermore, weather patterns are tending to become more extreme in recent years. Since they are important factor when considering market fluctuations, by excluding them from consideration, the study was unable to accurately depict current state of the energy market.

Furthermore, the study assumed storage capacity based on the duration for which the heat pump could be disconnected from the electricity grid. However, from the perspective of household investment and economics, it would be more sensible to internalize costs and optimize storage capacity accordingly. The sensitivity analysis of storage capacity indicates that the additional revenue gained on the market does not increase linearly with additional storage capacity (as seen in Figure 19). Therefore, it would be prudent to calculate the point at which the relationship between capacity and profit is optimal. Furthermore, the cost of storage capacity could be reduced by incorporating heating temperature elasticity. This would require a model that accounts for both the cost of storage and the flexibility of temperature, necessitating an additional cost and utilization function.

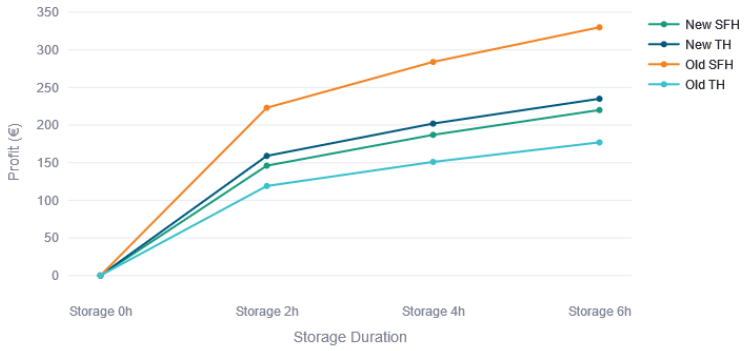

Figure 19: Storage profit curve

The model used in both the day-ahead and intraday markets employs a singular electricity price per time unit, which aligns it more closely with day-ahead trading than with intraday trading. Day-ahead market determines the electricity price in advance, while intraday market operates through a continuous bidding process, where agents can encounter multiple buy or sell prices for traded volumes, regulated by a limit order book (as explained in Day-ahead & Intraday Market). This study utilizes the ID3 index (EPEX SPOT 2024a), a weighted average price of all continuous trades conducted within the final 3 trading hours of a contract, which consequently limits the representation of this intricate and highly dynamic process. Furthermore, it does not account for market liquidity and the volume traded. To effectively train an agent for optimal trading on the intraday market, machine learning e.g., multi-agent approach with reinforcement learning, would offer a much more suitable solution than the simplified model employed in this study. Hence, while the weighted average price employed for the intraday market serves the purpose of comparing heat pump flexibility under varied energy prices, it does not accurately reflect the complexity of real short-term trading. Additionally, future smart consumers may adjust their energy consumption behavior and intensity in response to market signals, making the load profile variable rather than static. Since this model treated load profiles as fixed parameters and did not consider price elasticity, future research would need to address this factor in order to get more accurate picture of future energy systems.

In conclusion, while this study has provided valuable insights into the dynamics of heat pump flexibility in the electricity market, several limitations must be acknowledged. From constraints in input data and model assumptions to the simplified representation of market dynamics, there are areas for improvement and further exploration. Moving forward, the next section will delve into the conclusions drawn from this study and outline potential avenues for future research.

Conclusion and Outlook

This study presents the results of a comparative analysis aimed at determining the suitability of using the intraday market as an effective solution for private households with heat pumps, as opposed to alternative pricing structures such as flat tariffs or other dynamic pricing solutions. Dynamic energy tariffs optimized the household´s consumption schedule by deciding on optimal load shifting according to the market signals. The results revealed the nature of intraday market, highlighting few key findings. One of the key findings deduced from comparison of household load profiles was an increased relative intraday potential among households with higher consumption. Investment in bigger storage capacity was not encouraged. Furthermore, the time-of-year analysis revealed that the summer is the most profitable season per traded kWh due to the high market volatility. Nevertheless, winter achieved the best overall yield due to the large trading volume generated by high energy demand. A further sensitivity analysis comparing the data from years 2022 and 2023 highlighted the importance of market volatility for the final profit generated through arbitrage. An increase in volatility on the intraday market from 2022 to 2023 led to a rise in earnings, while the opposite was true on the day-ahead market that lost its price span.

Moreover, this study argues that the absolute comparative cost advantage of heat pump flat tariff compared to the intraday dynamic tariff was primarily due to regulatory incentives, which were not introduced to intraday trading. Thus, the conclusion of this study is that intraday market proved to be the most suitable option for households seeking to offer flexibility with installed heat pump owing to its high volatility. Moreover, opting for the intraday market would significantly alleviate the burden on the energy network due to its constant load optimization, in contrast to the limited hours of grid disconnection associated with the heat pump flat tariff.

Further research is recommended to determine the effects of a full switch to renewable energy, which could strongly influence the development of energy prices. With renewable energy sources having negligible marginal costs, it is anticipated that energy prices may decrease (Härtel und Korpås 2021). Furthermore, in case of majority of flexible consumers, market volatility could further decrease, potentially impacting the conclusions drawn regarding the high potential of the intraday market for flexibility. Nevertheless, given the substantial potential and increasing acceptance of intraday trading within the market, it earns consideration to extend intraday trading opportunities to private households engaging in flexibility services. Furthermore, innovative business models incorporating refined trading strategies are likely to be developed to include all willing participants as active energy consumers and producers.

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