Optimizing Heat Pump Systems under Dynamic Electricity Pricing: Sizing Tool and Market Mechanism Analysis

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***Abstract*—In the next years a significant number of heat pumps are expected to be installed in German households. Increasing costs for fossil fuels, new regulatory requirements and the increased awareness of the climate change are the main driver for the change in heat generation technologies in the private sector. Today consumers can already benefit from attractive tariff options for a cost-effective operation of their heat pumps. In this paper an optimization for the sizing of a heat pump system with a storage for a typical household is tested for different tariffs and grid fees followed by a discussion regarding their influence on the low-voltage grid. When designing future heat pump tariffs, attention should be paid to more dynamic electricity pricing by adding flexible grid fees to bring cost optimal heat pump operation in line not only with market constraints, but also with grid constrains.**

***Index Terms*—Flexible electricity pricing, Demand-side integration, Energy cost optimization, Heat pump, Buffer storage**

I. INTRODUCTION

In 2030 six million heat pumps are expected to be installed in Germany [1]. Assuming an average electrical power of 6 kW each the total amount of installed electrical demand would sum up to 36 GW which could result in significant challenges for the low-voltage grids while at the same time offering several opportunities for demand-side integration. The installation of heat pumps including buffer storage systems are an option in residential and commercial heating applications. This paper investigates the interaction between current market mechanisms, specifically flexible electricity prices and reduced grid fees, and their impact on the cost-optimized operation of heat pump systems with buffer storage capacities. This research contributes to the growing body of knowledge on demand-side integration and energy system optimization, offering practical insights for both consumers and energy system planners.

Our research methodology employs a combination of historical market data, heat pump consumption patterns, and optimization algorithms to determine the most cost-effective heat pump operation. We analyze the economic viability of different system sizes and configurations, with a particular focus on minimizing electricity costs through the strategic utilization of periods with favorable electricity supply.

Different approaches to optimize the integration of heat pump systems have been investigated in the literature. In [2] a Model Predictive Control (MPC) algorithm is used with a 48 h weather forecast, 12h/24h/35h day-ahead forecast and a building simulation to achieve a grid-supportive heat pump operation. The validation is done over one month and does not analyze the cost factor of different sizing of heat pumps and buffer storage. Various additional approaches are tested in [3]. With the use of the open source mixed-integer linear program (MILP) pyomo four different types of households are cost-optimized for the day-ahead and intraday-market compared to the base heat pump tariff. The size of the heat pump and storage is varied and tested for a whole year indicating that the intraday market with the same incentives as the base heat pump tariff would be most beneficial. A recommendation for increased storage is not fully researched.

The impact of the widespread integration of heat pumps and photovoltaic and their resulting impact on the electrical grid is analyzed in [4]. The paper concludes that a flexible usage of a heat pump in combination with a thermal energy storage is needed to mitigate the burden on the electrical distribution grid. The influence of market signals is not included in their scope. According to [5] dynamic electricity tariffs that take user behavior into account have an positive impact on the distribution grid.

This paper is structured as follows: Section II introduces the applied method and section III gives an overview about current market mechanisms. In section IV heat pump and buffer storage sizing are outlined. Section V presents the economic optimization with and without dynamic electricity pricing. The results are concluded in section VI.

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TABLE I. SCENARIO OVERVIEW

Scenario	**Input / Parameter**				
	Heat pump electric power	***Buffer storage thermal capacity***	***Grid fee***	***Electricity pricing***	***Optimized operation***
Base1	4 kW	-	Normal	Fixed	No
Base2	4 kW	-	Normal	Flexible	No
Base3	4 kW	20 kWh	Reduced	Fixed	No
Opti1	4 kW	20 kWh	Normal	Flexible	Yes
Opti2	4 kW	40 kWh	Normal	Flexible	Yes
Opti3	8 kW	20 kWh	Normal	Flexible	Yes
Opti4	8 kW	40 kWh	Normal	Flexible	Yes

II. METHOD

The method involves scenario definition, data preparation, and partly an optimization for an example heat pump application for a house with a 10 kW heat demand at -10°C ambient air temperature which is typical for a German single-family house from the 1990s.

Table I shows a scenario overview of three baseline scenarios without optimization and four sub-scenarios with market-optimized power consumption to minimize the operation costs. The optimization aims to minimize operational costs of the heat pump system with buffer storage under flexible electricity pricing conditions (Opti1 to Opti4). The primary inputs for all scenarios are Time series of electricity prices of the day-ahead market as well as time series of ambient temperature both with a 1-hour resolution and from the year 2023.

Equation (1) is derived from a heat pump data sheet [6] and is used to calculate the heat pump efficiency based on the ambient air temperature. Equation (2) describes the relation between ambient air temperature and heat demand [7].

$$\eta_{\text{heat pump}} = T_{\text{ambient}} \cdot 10\ \%/°\text{C} + 350\ \% \tag{1}$$

$$Q_{\text{demand}} = T_{\text{ambient}} \cdot (-\,0.33\ \text{kW}/°\text{C}) + 6.66\ \text{kW} \tag{2}$$

Fig. 1 shows (1) and (2) illustrating the negative correlation between heat demand and heat pump efficiency. This relation leads to an exponentially shrinking flexibility potential with decreasing ambient air temperature. For a situation with -10°C ambient air temperature, a heat pump with 4 $\text{kW}_{\text{electric}}$ has no flexibility, since it can supply exactly 10 $\text{kW}_{\text{thermal}}$ at this operational point.

The three baseline scenarios do not apply an optimization. Base1 and Base 2 have no buffer storage so that the heat pump has to cover the hourly heat demand. Base3 considers a heat pump system with heat pump tariff, which allows the grid operator to reduce power consumption [8]. This tariff requires a buffer storage (see III). Base3 therefore has additional heat losses compared to Base1 and Base2.

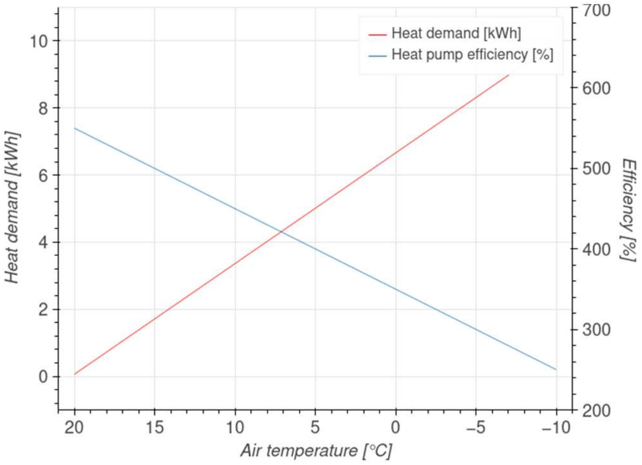

Figure 1. Inlet temperature, heat pump efficiency and heat demand

The four optimization sub-scenarios differ by varying two critical components: Heat pump power (in $\text{kW}_{\text{electric}}$), and buffer storage volume (in $\text{kWh}_{\text{thermal}}$). Base3, Opti1 and Opti2 consider a buffer storage with a thermal storage capacity of 20 kWh and a (simplified) dditional heat loss of 0.10 $\text{kW}_{\text{thermal}}$ per hour. Opti3 and Opti4 consider buffer storage with a thermal storage capacity of 40 kWh and a (simplified) additional heat loss of 0.12 $\text{kW}_{\text{thermal}}$ per hour [9].

The optimization problem can be formulated as a mixed-integer linear programming (MILP) problem, which is solved by using optimization libraries in Python [10]. The optimization process is subject to the following constraints and steps:

1. Minimum buffer storage energy content must be twice the heat demand of the coldest hour of the day or at least 50 % at the end of each day.

2. Maximum thermal power of the heat pump is determined by its electrical power and efficiency at a given ambient air temperature by (3):

$$Q_{\text{thermal supply,max}} = P_{\text{heat pump,electric}} \cdot \eta_{\text{heat pump}} \tag{3}$$

3. Minimum thermal power of the heat pump can be zero or it is determined by 10 % of its electrical power and efficiency at a given ambient air temperature by (4):

$$Q_{\text{thermal supply,min}} = 10\ \% * P_{\text{heat pump,electric}} \cdot \eta_{\text{heat pump}} \tag{4}$$

4. The optimization is aiming to minimize the electricity costs for heat pump operation. The process involves the following:

a. Calculate the heat demand based on the ambient temperature and heat loss for each hour of the day.

b. Determine the available flexibility in the buffer storage over the day.

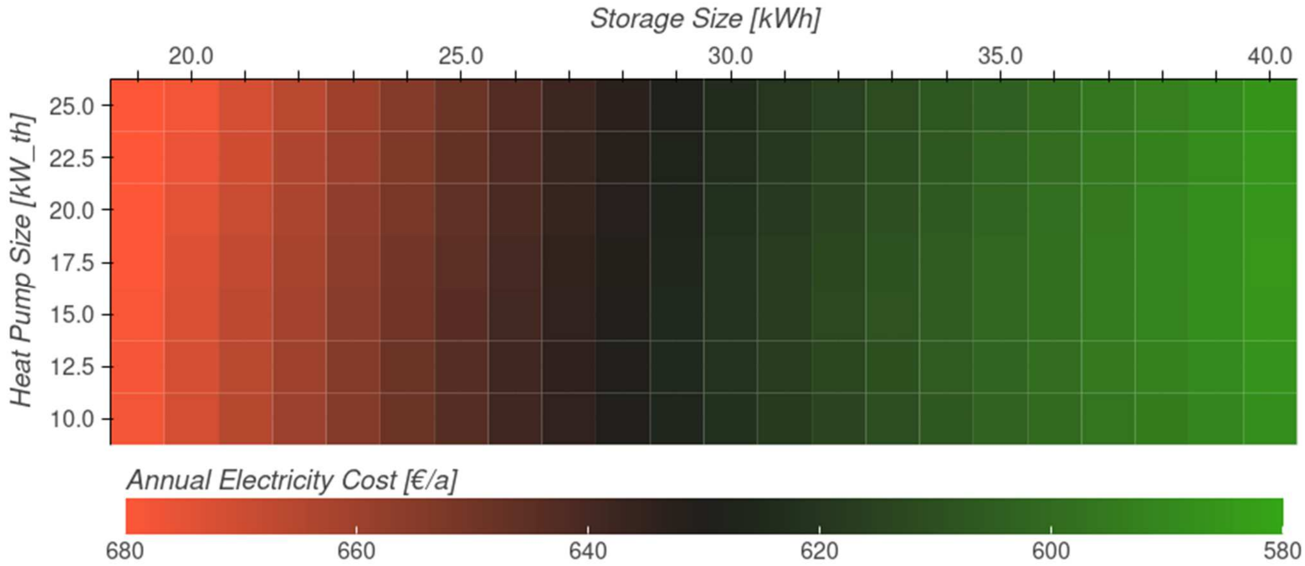

Figure 2. Sensitivity of annual electricity cost [€/a] to heat pump (HP) size [$kW_{thermisch}$] and buffer storage size [kWh]

c. Optimize the heat pump operation schedule to minimize electricity costs while meeting the heat demand and respecting all boundary conditions.

d. Calculate the total daily electricity costs.

5. Aggregation of the daily results to obtain annual performance metrics for each optimization scenario, such as annual electricity costs and electricity consumption.

The results from the optimization sub-scenarios are compared to evaluate the impact of heat pump and buffer storage size on annual electricity costs. This analysis focuses on the optimal sizing for maximizing the benefits of flexible electricity pricing in heat pump systems. The presented analysis has the following limitations and simplifications, which require future research: No dynamic buffer storage losses, no dynamic buffer storage energy content (fixed value, not according to delta between inlet temperature and buffer storage temperature). Other optimization problems for potential future model extensions are the integration of PV systems, electric heating element, domestic hot water and (bidirectional) charging of electric vehicles.

III. MARKET MECHANISMS

This section provides an overview about the underlying market mechanisms which are currently applied to heat pump systems in Germany. The tariffs differ in various aspects that influence their economic viability and incentives for operational flexibility.

A. Base1: Household tariff

Many households with heat pumps operate under standard electricity tariffs without a separate meter for the heat pump. These tariffs typically include fixed pricing: A single rate is applied to all electricity consumption. Base1 considers the price of a household tariff without additional monthly costs and considers a heat pump system without buffer storage consuming the needed electricity to meet the heat demand of each hour of the year within a current household tariff of 0.378 €/kWh [11].

B. Base2, Opti1-Opti4: Flexible Electricity Pricing:

Base2 as well as Opti1 to Opti4 apply flexible electricity pricing. The costs for each hour are calculated by considering the electricity prices in 1-hour resolution and additional 0.250 €/kWh grid fees and tax [12]. This tariff is based on wholesale market prices (day-ahead market), which change dynamically on an hourly basis during the day. The tariff applies for all electricity consumption without a separate meter for the heat pump systems. The prices are published at 1 pm at the day before consumption. Pricing is without additional monthly costs for metering since no additional metering is needed for this operation. Opti1 to Opti4 consider flexible heat pump operation.

C. Base3: Heat Pump Tariff

The heat pump tariff in Base3 combines reduced grid fees with a fixed electricity price. The considered grid fees are based on §14 a EnWG [13] Module 2 in the related determination procedure [14]. This heat pump tariff requires the installation of a second electricity meter and buffer storage, which comes with additional costs. The benefit is a 60 % reduction in grid fee for electricity used by the heat pump, which allows the grid operator to reduce power consumption. For Base3 an additional meter is necessary which adds monthly costs of 8.90 €, but a reduced electricity price of 0.274 €/kWh is applied [11].

Module 1 of the determination procedure [14] offers a second option with a flat-rate reduction without a separate meter. An annual flat-rate discount of 100 € to 200 € on grid fees is possible. In return the grid operator is allowed to reduce power consumption. The implementation of Module 3 will offer a third alternative and is expected for 2025 [14]. It is an extension of Module 1 allowing for dynamic grid tariffs to offer different rates, e. g. for peak and off-peak hours.

IV. SIZING HEAT PUMP SYSTEMS

The proper sizing of heat pump systems with buffer storage is crucial for optimal performance and energy efficiency. This section focuses on two key aspects: Heat load calculation according to DIN EN 12831 [7] and buffer storage sizing based on VDI (Verein Deutscher Ingenieure) recommendations [15].

The heat demand of a building in Germany is calculated according to DIN EN 12831. A design considering a minimal ambient temperature of – 10°C is typical for heating systems in northern Germany [7]. Key components to calculate the heat load are transmission heat losses through building elements such as walls, windows, and roofs, ventilation heat losses due to air exchange, an additional heat-up capacity needed to heat the building after temperature setbacks, as well as system losses due to heat distribution, storage and generation. The resulting thermal rating serves as the basis for sizing the heat pump system, ensuring it can meet the building's heating demands under design conditions. The choice between different configurations (e.g., 4 kW or 8kW heat pump with either 20kWh or 40kWh buffer storage) affects both the system's flexibility and its ability to take advantage of variable electricity pricing and reduced grid fees.

Buffer storage tanks play a crucial role in heat pump systems by reducing compressor cycling, providing thermal mass for defrost cycles and enabling flexible operation in response to electricity pricing. By considering both the heat load calculation and buffer storage sizing, houseowners can create heat pump systems that efficiently meet heating demands while providing flexibility for optimizing energy consumption and costs.

V. RESULTS

Installing heat pump system with buffer storage can lead to long-term savings through increased energy efficiency. However, the results show effects on the low-voltage grid.

A. Economic analysis

The results in Table II show how conventional heat pump operation (Base1 to Base3) perform compared to optimized operation (Opti1 to Opti4). The comparison in Table II reveals that the main economic incentive lies in reduced grid fees (Base3), as outlined in §14a EnWG Module 2, rather than in flexibility electricity pricing (Opti1 to Opti4). Fig. 2 shows the sensitivity of Opti1 to Opti4 focusing on annual costs of optimized and market friendly heat pump power consumption.

Fig. 2 illustrate how the sizing of both the heat pump and buffer storage is crucial for system cost-effectiveness. Doubling heat pump dimension itself has a neglectable effect (increase of 5 € to decrease of 2 € costs p.a.) but doubling the buffer storage size from 20 kWh to 40 kWh leads to savings of 93 € to 100 € p.a. A bigger buffer storage increases the benefit of flexible electricity pricing.

For Base1, Base2 and Opti1 to Opti4 grid fees and tax of 25 ct/kWh apply leading to costs of 1726 € to 1764 €. For Opti1 (4 kW, 20 kWh) the total costs sum up to 2434.50 € leading to a weighted final electricity price of 35 ct/kWh (in comparison to 38 ct/kWh without flexible electricity pricing). Opti2 and Opti4 with 40 kWh buffer storage (bigger option) achieve the lowest levelized cost of electricity of 33 ct/kWh except for the heat pump tariff of Base3.

Base 3 as heat pump tariff without flexible electricity pricing benefit from reduced grid fees in exchange for an additional monthly fee for metering. Base3 leads to levelized cost of electricity of 29 ct/kWh, the cheapest option of all scenarios. It turns out, that the special heat pump tariff (without flexible electricity pricing) is the cheaper option compared to a flexible electricity price without reduced grid fee.

TABLE II. SCENARIO RESULTS OVERVIEW

Scenario name	**Output / Results based on 2023 data**				
	Electric cons.	***Grid fee and tax***	***Electric costs***	***Total annual costs***	***Levelized costs for electricity***
Base1	6905 kWh	1,726 €	885 €	2,611 €	38 ct/kWh
Base2	6905 kWh	1,726 €	730 €	2,456 €	36 ct/kWh
Base3	7052 kWh	1,028 €	904 €	2,039 €[a]	29 ct/kWh
Opti1	7052 kWh	1,763 €	671 €	2,434 €	35 ct/kWh
Opti2	7013 kWh	1,753 €	588 €	2,341 €	33 ct/kWh
Opti3	7056 kWh	1,764 €	675 €	2,439 €	35 ct/kWh
Opti4	7014 kWh	1,754 €	585 €	2,339 €	33 ct/kWh

a. Base3 Scenario include additional monthly costs of 8.90 € for metering

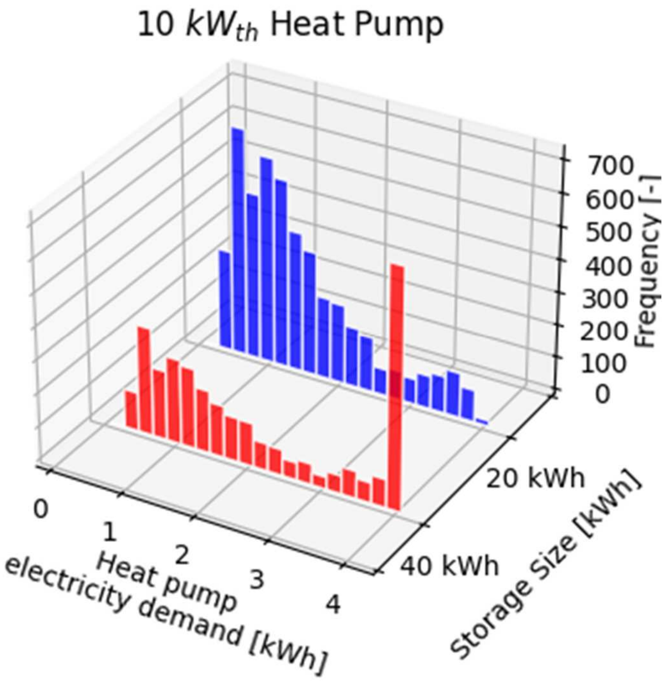

Figure 3. Hourly electricity demand – Opti1 (20 kWh) and Opti3 (40 kWh)

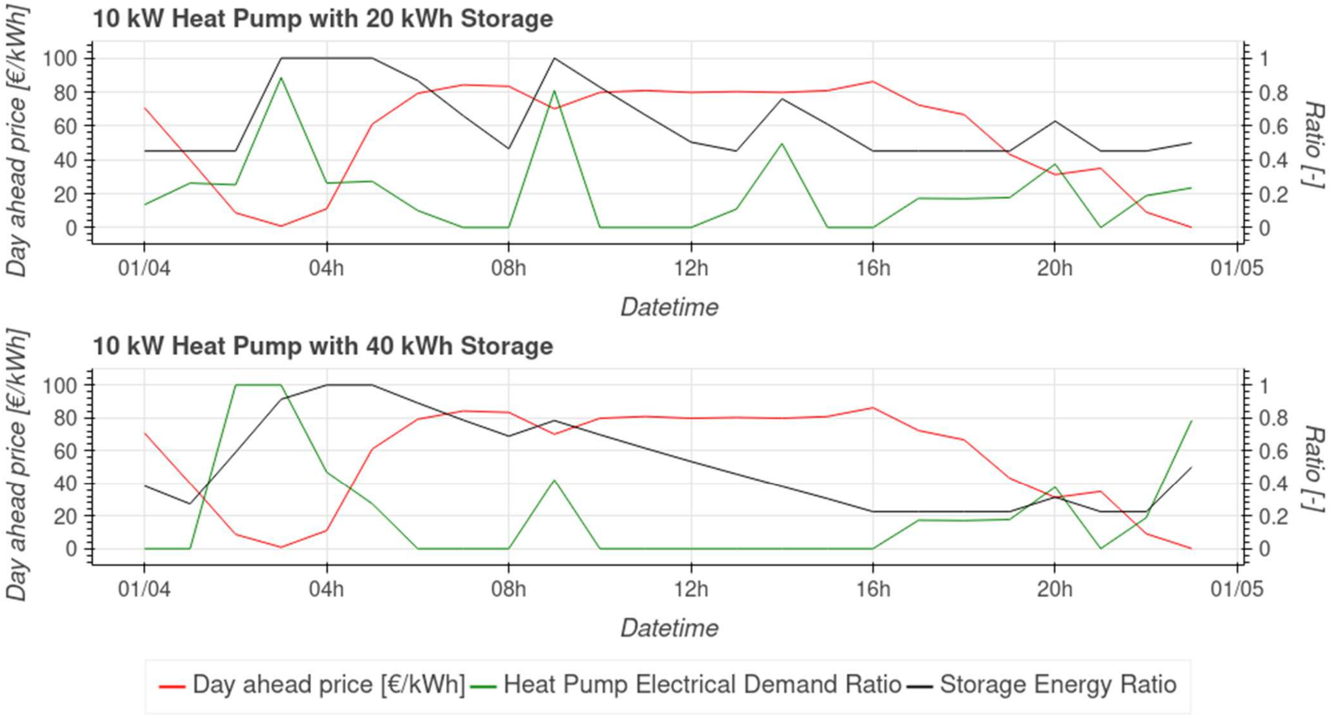

Figure 4. Example day (01.04.2023) - 10 kW heat pump with 20 kWh (Opti1) or 40 kWh (Opti2) storage

B. *Grid effects*

The data analysis shows two potential grid effects with different impacts depending on electricity price dynamics.

1) *Peak Creation During Low-Price Periods*

The simulation results presented in Fig. 3 show that with a higher flexibility potential through a larger storage the hours with full load of the heat pump increase to over 700. The diagram shows how frequent heat pump power consumption occurs. With a smaller storage the heat pump operates more often in partial load then a heat pump with a larger storage.

2) *Peak Reduction During High-Price Periods*

High electricity prices indicate periods with peak demand or limited power generation. The larger storage grants a higher buffer capacity leading to a greater operational flexibility. The smaller storage size cannot avoid power consumption of the heat pump in hours with high electricity prices and therefore fails to reduce the peak-demand in the grid.

Fig. 4 illustrates the underlying behavior of Opt1 and Opti2 on an example day (01.04.2023). With bigger storage size it is possible to benefit from the cheap price in the morning hours around 3 o´clock. The heat pump with 40 kWh storage is running at maximum for 2 hours to fill up the storage. Scaling the first effect could cause overloading in the low-voltage grid, especially in areas with a high number of heat pumps with flexible electricity pricing. The second effect of a bigger storage is a reduced power consumption during periods with high electricity price which reduce the peak-demand in the grid.

Optimized heat pump operation under current market design could 1) lead to peak demand in the low-voltage grid and 2) reduce peak load in the German market at the same day.

VI. CONCLUSION

The results imply that increasing the heat pump dimension has only a small effect on the operational costs and cannot be recommended. Choosing a big buffer storage on the other side can lead to a significant reduction of operational costs.

The special heat pump tariff, which does not include flexible electricity pricing but incorporates reduced grid fees, emerges as the most economical option. This tariff outperforms the flexible electricity pricing scenarios that lack reduced grid fees. Despite being economically advantageous for consumers, the tariff does not unfold all potential benefits of demand response for grid stability and market efficiency.

The study reveals that a bigger buffer storage, when coupled with flexible electricity pricing, can enhance demand-side flexibility. Big storages allow consumers to capitalize on periods of low electricity prices, effectively reducing their overall energy costs. Avoiding operation in periods with high electricity prices can reduce the peak demand in the grid. However, it may also create new demand peaks in the low-volage grid during low-price periods, highlighting the complex relationship between storage size and different grid effects.

Future dynamic grid fees should therefore reflect the local grid situation to effectively reduce grid expansion costs by balancing the low-voltage grid. The implementation challenges include the roll-out of a smart metering infrastructure, the complexity in the tariff design, consumer understanding, and the still evolving regulatory framework. Module 3 of §14a EnWG (expected in summer 2025) could create such a new dynamic electricity pricing when combining flexible electricity pricing and dynamic grid fees.

REFERENCES

[1] Bundesverband Wärmepumpe (BWP) e. V., „Roadmap Wärmepumpe Der Weg zur Dekarbonisierung des Gebäudesektors“. 29. April 2021. [Online]. Verfügbar unter: https://www.waermepumpe.de/fileadmin/user_upload/waermepumpe/07_Publikationen/Sonstige/2021-04-29_BWP_Roadmap_final.pdf

[2] V. Klepic, M. Wolf, und T. Pröll, „Extension of a low-tech Model Predictive Control (MPC) algorithm for grid-supportive heat pump operation“, Energy and Buildings, Bd. 323, S. 114733, Nov. 2024, doi: 10.1016/j.enbuild.2024.114733.

[3] H. Cuzic, „Realizing the flexibility potential of heat pumps on the intraday market as data-driven business model“, Master Thesis, Bd. Faculty of Economics and Social Sciences of the Ruprecht-Karls-University Heidelberg, 2024, [Online]. Verfügbar unter: https://publica.fraunhofer.de/bitstreams/7158fa1d-7fec-4663-a98b-9a8a652db22f/download

[4] N. Tedjosantoso, M. Grasenack, und H. Schäfers, „Analysis of the Impact of Widespread Residential Heat Pumps and Photovoltaics on the Electricity Distribution Grid in Hamburg“, 2024, [Online]. Verfügbar unter: https://reposit.haw-hamburg.de/bitstream/20.500.12738/16565/1/ml_108634_1721055439.pdf

[5] J. Stute und M. Kühnbach, „Dynamische Stromtarife unter Berücksichtigung des Nutzendenverhaltens: Auswirkungen auf das Verteilnetz“, 2021.

[6] WOLF GmbH - ein Unternehmen der Ariston Holding N.V., „Wolf - Varianten der Luft/Wasser Wärmepumpe“. Zugegriffen: 6. Februar 2025. [Online]. Verfügbar unter: https://www.wolf.eu/de-de/produkte/waermepumpe-cha-und-chc-monoblock

[7] DIN Deutsches Institut für Normung e. V., „DIN/TS 12831-1 Verfahren zur Berechnung der Raumheizlast – Teil 1: Nationale Ergänzungen zur DIN EN 12831-1“. April 2020. [Online]. Verfügbar unter: https://www.din.de

[8] Bundesnetzagentur Beschlusskammer 6, „Festlegungsverfahren zur Integration von steuerbaren Verbrauchseinrichtungen und steuerbaren Netzanschlüssen nach § 14a Energiewirtschaftsgesetz“, Nov. 2023, [Online]. Verfügbar unter: https://www.bundesnetzagentur.de/DE/Beschlusskammern/1_GZ/BK6-GZ/2022/BK6-22-300/BK6-22-300_Beschluss.html?nn=877500

[9] Družstevní závody Dražice-strojírna s.r.o., „Kombipufferspeicher 500-1000 Liter mit 140 Liter Brauchwasser ohne Wärmetauscher“. [Online]. Verfügbar unter: https://www.g2-energy-systems.de/speichersysteme/tank-in-tank-puffer-trinkwasserspeicher/ohne-waermetauscher/kombipufferspeicher-500-1000-liter-mit-140-liter-brauchwasser-ohne-waermetauscher.html?srsltid=AfmBOorY_uTe4t7Kn6snxh8jYvTvTE4lUy7vX1o0t_5piyGjxY8u2ZpA

[10] N. Tedjosantoso, F. Doucet, F. Scholl, M. Grasenack, und H. Schäfers, „Optimizing heat pump systems under dynamic electricity pricing : sizing tool and market mechanism analysis“. HAW Hamburg, 2025. doi: 10.48441/41201.2398.

[11] Hamburger Energiewerke GmbH, „Hamburger Energiewerke - Tarif Auswahl“. Zugegriffen: 6. Februar 2025. [Online]. Verfügbar unter: https://www.hamburger-energiewerke.de/

[12] Tibber Deutschland GmbH, „Strompreis bei Tibber“. Zugegriffen: 6. Februar 2025. [Online]. Verfügbar unter: https://tibber.com/de/stromtarif?modal=preisrechner

[13] Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz - EnWG). 2005.

[14] Bundesnetzagentur Beschlusskammer 8, „Festlegung von Netzentgelten für steuerbare Anschlüsse und Verbrauchseinrichtungen (NSAVER) nach § 14a EnWG“, Nov. 2023, [Online]. Verfügbar unter: https://www.bundesnetzagentur.de/DE/Beschlusskammern/BK08/BK8_06_Netzentgelte/68_Para14a_EnWG/BK8_14a_EnWG.html

[15] Fabian Wüllhorst, Christian Vering, Dirk Müller, und Marius Haas, „Thermische Speicher in Wärmepumpensystemen: zu klein, zu groß oder überhaupt notwendig?“ VDI Wissensforum GmbH, 2024.