Real-time pricing for heat pumps: Who pays, who gains?

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Abstract:

The widespread adoption of heat pumps in residential buildings offers a promising opportunity for demand response, particularly with the implementation of real-time pricing (RTP) to encourage flexible electricity consumption. However, the financial impact of RTP on different household and building types with heat pumps remains underexplored. This study investigates the economic implications of heat pump operation under RTP, analyzing how building characteristics, user thermal comfort settings, and local photovoltaic (PV) self-consumption influence electricity consumption and related cost savings or financial burdens. The analysis also includes the financial perspective of heat pump aggregators and their impact on users' costs and benefits. By integrating an agent-based electricity market model, AMIRIS, and a heat pump dispatch optimization model, simulations were conducted for various representative building types in Germany. The results indicate that heat pump users in well-insulated buildings, particularly those with underfloor heating, benefit most from RTP, as electricity consumption can effectively be shifted to low-price periods. When combined with local PV generation, effective heating cost savings can be amplified to up to 50%, with user flexibility in thermal comfort settings enhancing self-consumption rates. Conversely, older, poorly insulated buildings face challenges in realizing financial benefits due to limited flexibility, with electricity cost savings insufficient to offset the cost of enabling flexible heat pump operation with RTP. While the study identifies the building types best suited for flexible heat pump operation under RTP, it also demonstrates that even in the absence of RTP, user flexibility in thermal comfort can enhance energy efficiency and reduce costs for heat pump operation.

Keywords: Heat pumps, Real-time pricing, Flexibility, Building types

1 Motivation

The increasing use of heat pumps in residential buildings presents a significant opportunity for enabling demand response (Roth et al. 2024). Concurrently, real-time pricing (RTP) is being implemented in many countries to promote dynamic electricity consumption via smart meter gateways. RTP incentivizes users to adjust their electricity usage based on market signals, which should confer several advantages for the energy system, including enhanced integration

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of electricity from renewables and reduced peak loads (Kopsakangas Savolainen und Svento 2012). Customers stand to benefit from cost savings (Stute et al. 2024), yet the financial implications of RTP across diverse household and building types equipped with heat pumps remain under-explored.

This study investigates the economic benefits and challenges of heat pump operation under RTP in the future German energy system. A distinctive feature of this research is its holistic approach, which considers variations in building efficiency, user thermal comfort settings, and local photovoltaic (PV) self-consumption, while also accounting for indirect feedback effects from wholesale electricity markets. Specifically, this includes the financial implications of electricity procurement of heat pump aggregators who commercially supply flexible customers with RTP.

The central question addressed is: *who benefits and who bears the costs when heat pumps operate under RTP?* To answer this, four factors are analyzed:

- The impact of building type on heat pumps' electricity consumption and operational costs
- The influence of user flexibility in indoor temperature variations
- The contribution of local photovoltaic (PV) self-consumption
- The impact of aggregator and infrastructure cost for flexible heat pump operation.

This study complements previous research by the authors on the system and user effects of operating heat pumps with RTP (Sperber et al. 2025). The present study provides a more detailed examination of building-level effects, thereby offering new insights into the distributional consequences of flexible heat pump operation under RTP.

2 Methods and assumptions

2.1 Models

This study couples the open agent-based electricity market model AMIRIS (Schimeczek et al. 2023) with a bottom-up residential heat pump dispatch optimization model, focusing on Germany[2].

AMIRIS calculates future wholesale electricity prices endogenously by simulating the strategic bidding behavior of prototyped market actors. A heat pump aggregator serves as an intermediary between the energy exchange and decentralized heat pump users in buildings, commercially supplying its customers at RTP and procuring the necessary electricity on the day-ahead market in response. This RTP is based on forecasted day-ahead electricity prices, which account for inflexible heat pump operation, and include static price components such as regulatory charges, energy taxes, and levies on electricity.

[2] Please find the code related to this study on Zenodo at https://zenodo.org/records/14191160. AMIRIS is openly available at https://gitlab.com/dlr-ve/esy/amiris/amiris.

The GAMS-based heat pump dispatch optimization model (Figure 1) calculates the minimum-cost electricity consumption of heat pumps under RTP. It considers space heating and domestic hot water (DHW) generation in representative single-family houses based on the German building typology (Loga et al. 2015). The model accounts for user thermal comfort by incorporating variable indoor temperature setpoints, while calculating space heating demand according to internal resistance-capacitance-networks of thermodynamics (Sperber et al. 2020). Additionally, it allows for the integration of local PV generation.

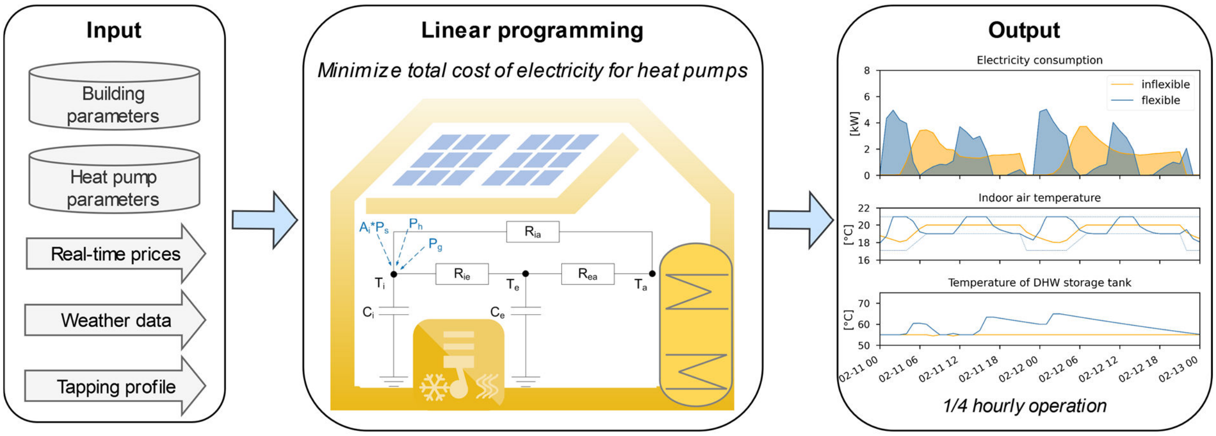


Figure 1: Schematic overview of the heat pump dispatch optimization model

The models are integrated using the FastAPI framework[3], with AMIRIS periodically calling the heat pump dispatch optimization model. AMIRIS transfers RTP as input data for optimization, while the aggregated grid electricity consumption from all heat pumps is fed back into AMIRIS. Subsequently, the heat pump aggregator places its bids on the day-ahead market, and the market is then cleared.

2.2 Scenarios

The simulations are conducted for the German energy market in a 2030 scenario, where renewables account for approximately 80% of electricity consumption. It is assumed that 6 million heat pumps, in line with governmental targets (BMWK - Federal Ministry for Economic Affairs and Climate Action 2022), are installed and operate under RTP.

These heat pumps are assumed to be installed in different building types based on the German building typology, which vary in age, size, and refurbishment level. In the following, the nomenclature is based on the construction period of the building, with the suffix *SQ* referring to the status quo energy condition and *MR* denoting a moderately refurbished building.

Three scenario variants for operating heat pumps with RTP are considered, with differences in temperature setpoints, as outlined in Table 1. During the night, a setback temperature is applied, which is 0.9 times the minimum daytime temperature setpoint. The average temperature remains consistent across all scenario variants.

[3] FastAPI is openly available at https://github.com/tiangolo/fastapi.

Table 1: Characteristics of scenario variants regarding heat pump operation

Scenario variant	Daytime setpoint temperature	DHW storage tank temperature
Inflex	20°C	55°C
ModFlex	20°C ± 1°C	55-70°C
HighFlex	20°C ± 2°C[4]	55-70°C

Additionally, two variants are considered based on the availability of local PV generation: *no PV* and *with PV*. In the *with PV* variant, the remuneration of surplus PV electricity fed into the grid is determined by a fixed feed-in tariff. It is assumed that local PV electricity is consumed at the opportunity cost of this feed-in tariff.

As the objective of this research is to assess the impact of different operational modes of heat pumps across those scenarios, only the variable costs are considered, excluding annuities for the investments in the technical infrastructure required for the operation of heat pumps with RTP. However, the analysis does not take into account the investment costs related to the technical setup, including those for heat pumps, building retrofits, or local PV installations. For all data and assumptions, please refer to Sperber et al. (2025).

3 Results

The results are presented first from the isolated perspective of users (section 3.1), followed by the perspective of heat pump aggregators (section 3.2), and finally, both perspectives are combined (section 3.3).

3.1 The isolated perspective: User's electricity consumption and costs

The following section present the results from the isolated perspective of heat pump users, meaning that no feedback effects from aggregators or associated costs are considered. The user-level effects are shown for the location of Würzburg, Germany[5].

3.1.1 Grid electricity consumption

To provide a general understanding of the impacts of RTP on heat pump operation in combination with user flexibility and PV self-consumption, Figure 3 illustrates these effects. The figure shows the daily electricity consumption from the grid for an air/water heat pump in a moderately refurbished building from the 1960s, displaying heat pump dispatch across hours of the day for all days of the year. The upper plots represent inflexible operation, while the

[4] While the variations in the daytime setpoint temperature are significant, particularly for the HighFlex variant, appropriate clothing can ensure thermal comfort in these cases (Huckebrink et al. 2023).

[5] Results for further locations and also further scenario variants are available on Zenodo at https://zenodo.org/records/14191160.

lower plot shows flexible operation (scenario *ModFlex*). The left plots depict consumption without PV self-consumption, and the right plots include PV self-consumption.

In the *inflexible* mode *without PV*, heat pumps exhibit distinct consumption peaks in the early morning, coinciding with the end of the night setback for space heating. This surge in electricity demand is required to restore buildings to their daytime setpoint temperature, and to replenish the domestic hot water storage tank following morning showers. Apart from this, inflexible heat pump consumption closely follows heating demand and, consequently, ambient temperatures.

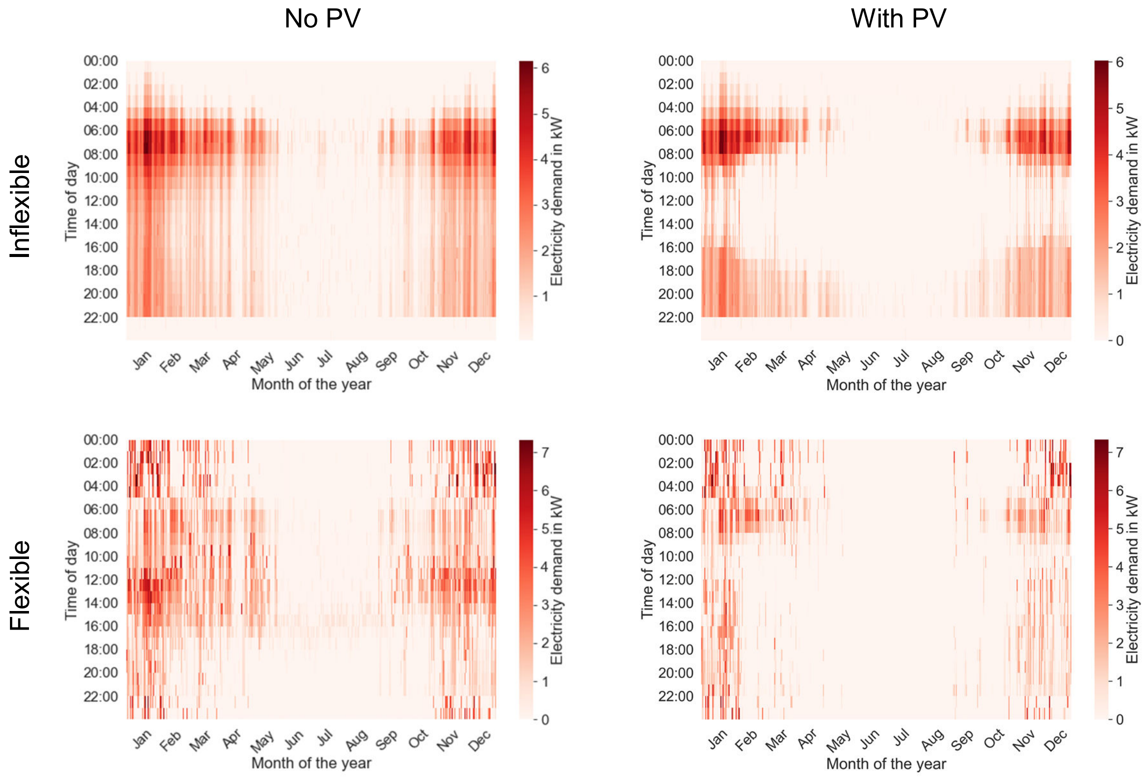


Figure 2: Temporal pattern of electricity consumption from grid of an air/water heat pump in the 1969_MR building type for both inflexible and flexible operation, as well as impact of PV self-consumption

In the *flexible* mode, however, this pattern disappears as heat pump operation shifts to midday. Several factors drive this shift. First, real-time prices tend to be lower at midday, not only due to a high share of low-cost PV supply on the wholesale market, but also because the large number of heat pumps in the scenario influences wholesale prices. Under inflexible operation, heat pumps contribute to morning price peaks, which in turn serves as a signal for flexible heat pumps to avoid high-price periods. Additionally, midday ambient temperatures are generally higher, resulting in a better coefficient of performance and reduced heat losses through the building envelope, ultimately enhancing efficiency and making midday operation more favorable.

The *use of local PV* significantly reduces the amount of electricity drawn from the grid during the day, even in the inflexible case. Flexible operation reduces grid consumption further, as more locally produced electricity can drive heat pumps and store the heat in the buildings, thus increasing the share of PV self-consumption for heating (see section 3.1.3).

In summary, heat pump operation is significantly altered in the flexible scenarios, driven not only by RTP but also by improved operational efficiency. This is particularly evident when local PV is used, as higher indoor temperatures allowed during midday further enhance efficiency.

3.1.2 Electricity consumption for heating

To illustrate the annual impact of these operational changes, Figure 3 presents the total annual electricity consumption for an air/water heat pump across different building types and flexibility scenarios. Error bars indicate the range of results (mean ± standard deviation) based on three weather years.

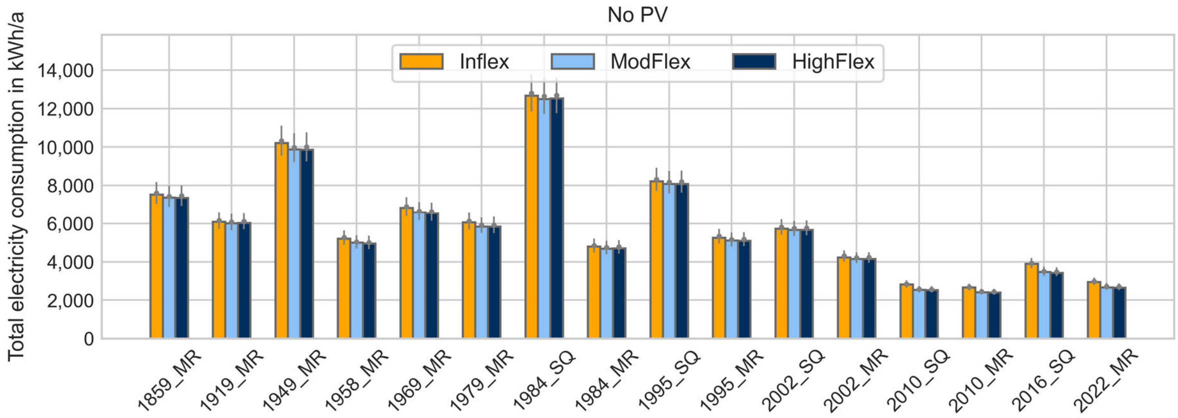


Figure 3: Annual electricity consumption from grid for heating per building type and flexibility mode for an air/water heat pump (no PV)

The variations across building types are remarkable. Electricity demand is notably higher for older, non-refurbished buildings, reaching up to 13,000 kWh/a, while newer (and smaller) buildings see demand as low as 2,400 kWh/a.

In all of the operational scenario variants, however, annual demand variations remain minor, as the average setpoint temperature is consistent across all cases. Yet, well-insulated buildings with high thermal inertia and underfloor heating (labels 2010-2022) show up to a 12% reduction in demand when heat pumps are operated flexibly. This is due to better utilization of free heat sources, such as solar gains, enabled by permitted temperature fluctuations throughout the day.

3.1.3 Heating-related self-sufficiency rates with PV

The electricity consumption figures for heat pumps previously presented in Figure 3 assume no local PV self-consumption. However, as indicated by the operational characteristics in Figure 2, PV can significantly influence the electricity consumption of flexible heat pumps. To highlight this effect on an annual basis, Figure 4 illustrates the percentage of local PV that covers electricity demand for heating using an air/water heat pump.

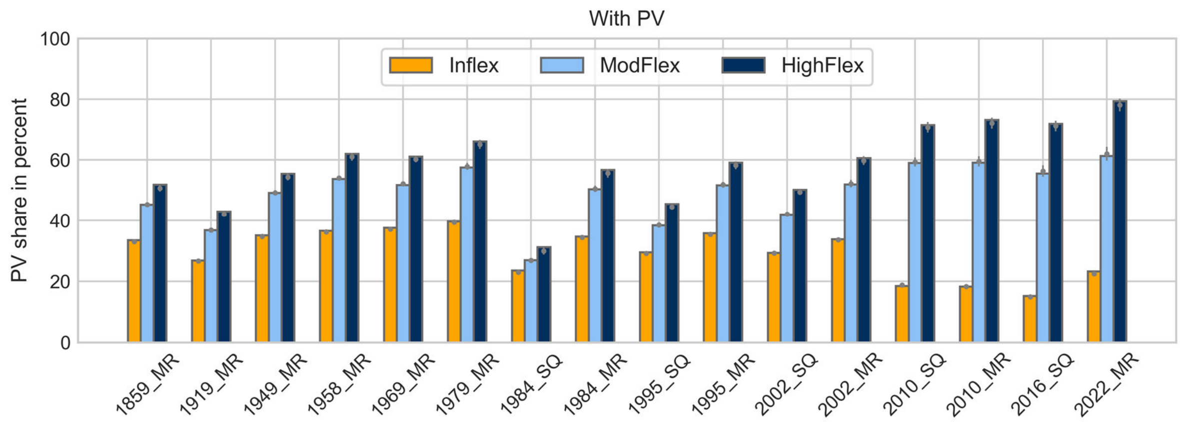


Figure 4: Heating-related self-sufficiency rate per building type and flexibility mode for an air/water heat pump

In the *inflexible* scenario (orange bars), PV shares range from 15% to 40% across building types. Newer buildings with assumed underfloor heating (labels 2010-2022) show the lowest shares, as these buildings require a lot of electricity in the early morning hours after the night set-back, when PV generation is still low. Conversely, moderate flexibility (*ModFlex*) heat pump operation increases PV utilization by allowing indoor temperatures to more gradually match PV generation. Self-sufficiency rates then rise significantly to up to 60%, particularly in those newer buildings with high thermal inertia, where the PV share triples. This increase is driven by a greater demand response potential of these building types (Sperber et al. 2020), allowing buildings to remain within temperature limits overnight while shifting most electricity consumption to daylight hours.

Higher user tolerance (*HighFlex*) further enhances this effect, enabling more demand to be moved from night to day, thereby maximizing PV self-consumption. For older buildings, greater user tolerance increases the PV share by an average of 5 percentage points, whereas for newer buildings, the increase can reach 18 percentage points, compared to *ModFlex*.

Note that these effects are not necessarily driven by RTP – under the assumed scenario, self-consumption is always more cost-effective than grid consumption[6]. However, user flexibility in allowing indoor temperature variations primarily enables higher self-consumption rates.

3.1.4 Electricity cost for heating

To clarify the financial impact of RTP on heat pump users, Figure 5 presents the specific electricity costs for space heating and DHW generation using an air/water heat pump across building types and flexibility scenarios. The upper plot shows the results for case *no PV*, while the lower plot shows the results including PV self-consumption. To isolate the impact of flexibility from building size and base consumption, costs are expressed in ct/kWh of electricity consumed.

[6] In the scenario outlined, the charges, taxes, and levies applied to electricity prices result in a real-time price that consistently exceeds the opportunity cost of PV self-consumption.

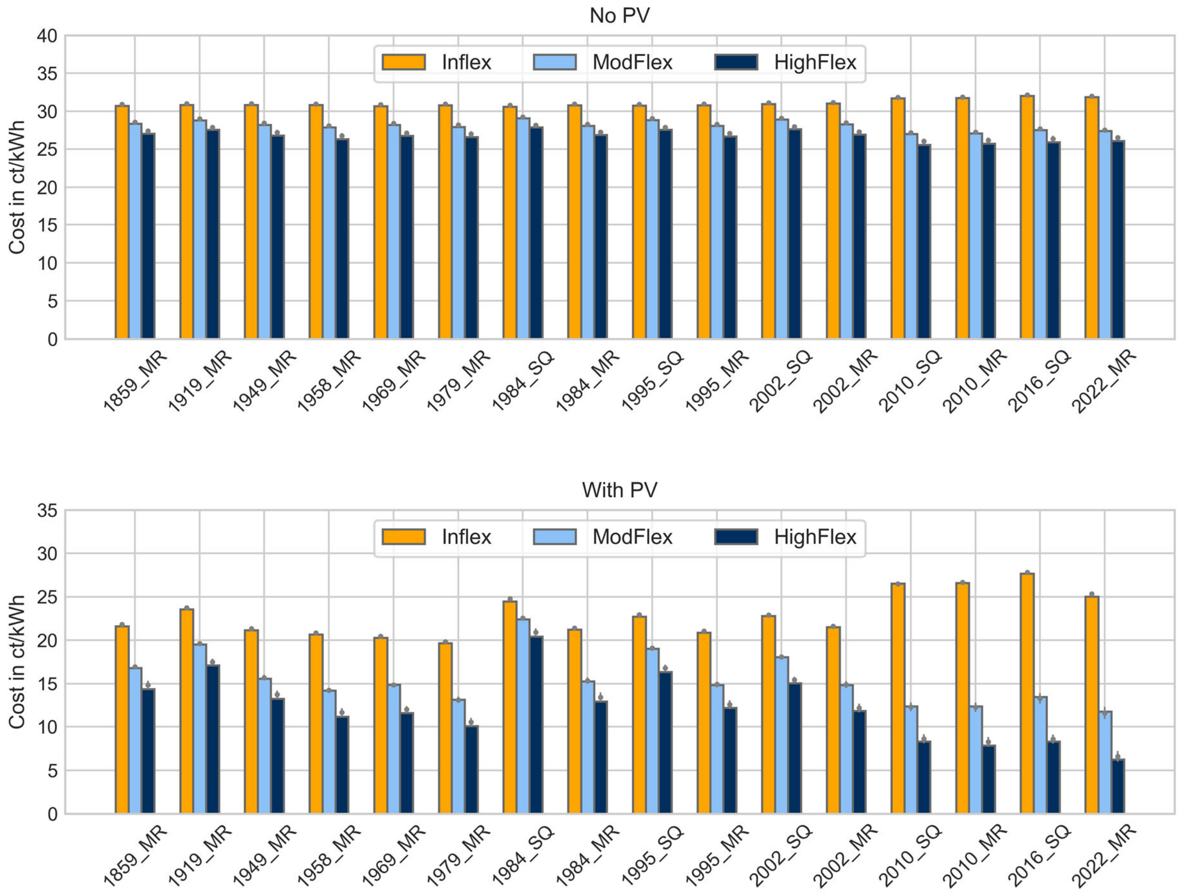


Figure 5: Specific electricity cost for heating per building type and flexibility scenario for an air/water heat pump, no PV (top plot) and with PV (bottom plot)

In the *no PV* variant, costs average 31 ct/kWh in the *Inflex* case, with only minor variations across building types. While electricity demand remains largely unchanged across flexibility scenarios (see section 3.1.1), costs do vary. Flexible heat pump operation lowers costs, with higher user tolerance levels (*HighFlex*) leading to greater electricity cost savings**.** This is because heat pump operators are more responsive to price peaks when user flexibility is higher. Heat pump operators with more flexibility can better respond to price peaks, reducing costs by up to 6 ct/kWh, particularly in newer, well-insulated buildings. In older and energetically less efficient buildings, however, the saving potential is lower. Due to high heat losses and limited thermal storage capacity, these homes require near-continuous heating, making it difficult to shift demand in response to price signals.

With PV self-consumption, cost differences between building types and flexibility scenarios become more pronounced. Increased reliance on low-cost, self-generated electricity reduces costs by 14 ct/kWh (*ModFlex*) and up to 19 ct/kWh (*HighFlex*)**.** Again, the greatest savings potential is observed in newer buildings with high thermal inertia. Notably, this analysis accounts for reduced support payments due to lower PV electricity feed-in.

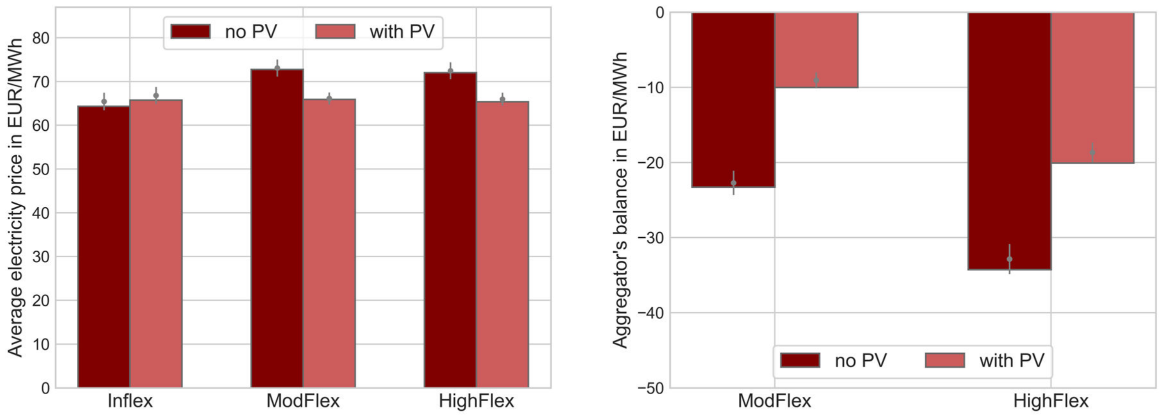
In summary, heat pump users can achieve significant electricity cost savings under flexible operation with RTP, especially when combined with local PV. Note that expenses for flexible heat pump operation are not yet accounted for in these figures.

3.2 Aggregator's perspective: The financial imbalance

While this study primarily focuses on user effects, it is also important to consider the role of aggregators[7] in the RTP framework and their impact on user cost savings. In the assumed model, the aggregator sells electricity to flexible heat pump users at a real-time price based on forecasted day-ahead prices but purchases it at the actual market clearing price.

Simulations indicate that flexible heat pump operation under RTP can lead to higher day-ahead electricity prices compared to inflexible operation (Figure 6a). This occurs because flexible heat pump users shift their demand to periods with lower forecasted prices, causing a collective overshoot effect in the market, often described as the "avalanche effect" (Ensslen et al. 2018).

As a result, the aggregator's expenditure on purchasing electricity at the day-ahead price exceeds its revenue from selling it to users at RTP, leading to a negative balance of about 10-35 €/MWh, especially when user flexibility is high (Figure 6b). To compensate for this cost imbalance, an aggregator fee is applied, which is ultimately passed on to heat pump users and paid ex post.



a) Average day-ahead electricity price *b) Aggregator's financial balance*

Figure 6: Average day-ahead electricity price and aggregator's financial balance

The average financial imbalance – and thus the aggregator fee – is lower in scenarios *with PV*. Self-consumption is always cheaper than consumption from grid due to the static price components on real-time electricity prices. Due to the alignment of low market prices with local PV generation, less grid electricity is sold to heat pump users with PV when real-time prices are low. This reduces the avalanche effect. In contrast, during periods of low local PV generation, reliance on grid electricity increases. The correlation between local and system-level PV generation leads to a general increase in real-time prices during periods of PV scarcity.

[7] Although we employ the term "aggregator" in this study, it is not necessarily indicative of a new market role. Instead, the coordination and procurement of decentralized flexible heat pumps could also be undertaken by existing retailers.

3.3 The combined perspective: Users' effective cost savings

To assess the overall financial attractiveness of heat pump operation with RTP for users, it is necessary to consider the aggregator fee (section 3.2) and the further infrastructure costs of flexible heat pump operation, i.e. smart meter gateways and the home energy management system, alongside the "gross" electricity cost reductions (section 3.1.4). Consequently, the effective net cost savings – electricity cost reductions minus these expenses – are only modest (Figure 7).

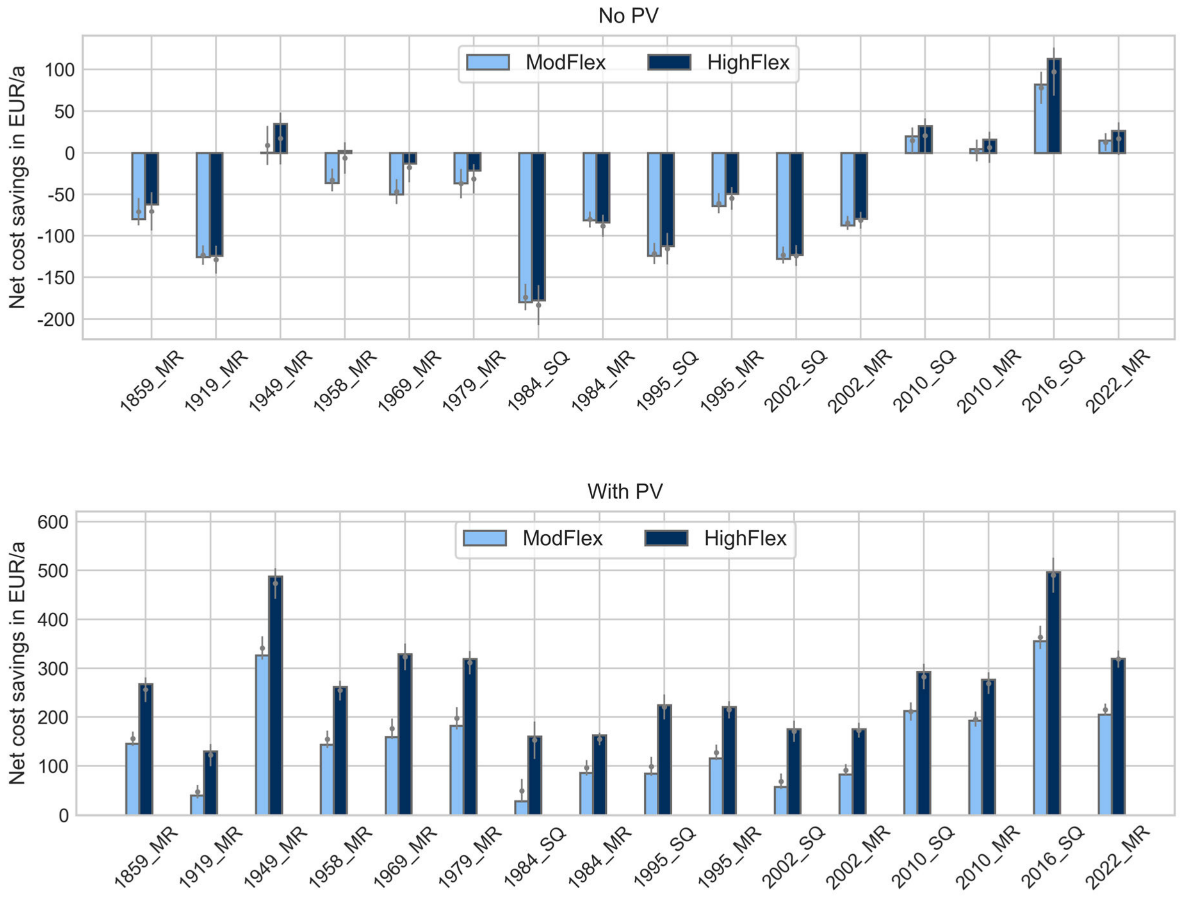


Figure 7: Annual effective cost savings per building type and flexibility scenario for an air/water heat pump, no PV (top plot) and with PV (bottom plot)

The findings reveal significant disparities in the financial viability of RTP-based heat pump operation across different building types. *Without local PV*, most households face challenges under RTP, particularly very old and/or poorly insulated buildings with limited demand response potential. Only moderately refurbished building types with a certain baseline consumption benefit financially from RTP. These buildings can shift heating loads to low-price periods without compromising comfort, and their higher baseline consumption makes them less vulnerable to fixed costs, such as those associated with smart meter gateways and home energy management systems. As a result, electricity cost savings can reach up to €100 per year for the best-performing building types (label 2016_SQ) without PV.

However, when combined *with local PV* generation, the situation improves considerably. All building types benefit from flexible heat pump operation, with households achieving net cost savings of up to €500 per year, cutting annual heating costs by approximately 50%. Greater flexibility is associated with higher savings. Two key factors contribute to the improved cost balance for households with PV: First, reduced grid consumption, lowering exposure to retail electricity prices and aggregator fees, and second, lower fees on remaining grid consumption compared to *no-PV* scenarios (see Figure 6b).

4 Conclusion

The adoption of RTP for heat pump operation presents both opportunities and challenges for users, with key factors being building energy efficiency and local PV availability. Users in well-insulated houses and those with local PV generation benefit the most, achieving significant effective heating cost reductions of up to 50%. These benefits are enhanced by a higher comfort tolerance regarding indoor temperature variations. In contrast, users in older, poorly insulated buildings may face financial disadvantages, particularly in the absence of PV. Critical to effective financial attractiveness is the cost of enabling flexible heat pump operation, including the aggregator fee and costs for smart meter gateways and home energy management systems. These can offset the savings in electricity costs for heating, which are achieved through cost-optimized heat pump operation.

For RTP to effectively incentivize demand-side flexibility, providers of RTP (such as aggregators or retailers) should address building efficiency disparities and prioritize buildings capable of shifting demand without compromising thermal comfort. This is particularly relevant for well-insulated buildings and those with high thermal inertia, such as those with underfloor heating. Policy measures should support energy efficiency retrofits of buildings equipped with heat pumps, as improved insulation enhances the ability to benefit from RTP. However, given the limited financial profits even for suitable buildings, policymakers should consider alternative incentive mechanisms to promote the flexibility that is urgently needed to balance supply and demand in future energy systems.

Importantly, this study highlights that many user benefits stem not from RTP itself, but from user flexibility. Allowing higher indoor temperatures during the daytime enhances PV self-consumption, optimizes the use of free heat sources, and improves heat pump efficiency by increasing the coefficient of performance while reducing thermal losses through the building envelope. This makes demand-side flexibility a crucial complement to overall energy efficiency – particularly as it incurs no additional costs beyond modest adjustments in thermal comfort.

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6 Literature

BMWK - Federal Ministry for Economic Affairs and Climate Action (2022): Eckpunktepapier zur Diskussion der Beschleunigung des Wärmepumpenhochlaufs. Vorhaben und Maßnahmen zum 2. Wärmepumpen-Gipfel. Online verfügbar unter https://www.bmwk.de/Redaktion/DE/Downloads/Energie/2-waermepumpen-gipfel-eckpunktepapier.html, zuletzt geprüft am 02.05.2024.

Ensslen, Axel; Ringler, Philipp; Dörr, Lasse; Jochem, Patrick; Zimmermann, Florian; Fichtner, Wolf (2018): Incentivizing smart charging: Modeling charging tariffs for electric vehicles in German and French electricity markets. In: *Energy Research & Social Science* 42, S. 112–126. DOI: 10.1016/j.erss.2018.02.013.

Gottwalt, Sebastian; Ketter, Wolfgang; Block, Carsten; Collins, John; Weinhardt, Christof (2011): Demand side management—A simulation of household behavior under variable prices. In: *Energy Policy* 39 (12), S. 8163–8174. DOI: 10.1016/j.enpol.2011.10.016.

Huckebrink, David; Finke, Jonas; Bertsch, Valentin (2023): How user behaviour affects emissions and costs in residential energy systems—The impacts of clothing and thermal comfort. In: *Environ. Res. Commun.* 5 (11), S. 115009. DOI: 10.1088/2515-7620/ad0990.

Kopsakangas Savolainen, Maria; Svento, Rauli (2012): Real-Time Pricing in the Nordic Power markets. In: *{E}nergy {E}conomics* 34 (4), S. 1131–1142. DOI: 10.1016/j.eneco.2011.10.006.

Loga, Tobias; Stein, Britta; Diefenbach, Nikolaus; Born, Rolf (2015): Deutsche Wohngebäudetypologie. Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden. Institut Wohnen und Umwelt.

Roth, Alexander; Gaete-Morales, Carlos; Kirchem, Dana; Schill, Wolf-Peter (2024): Power sector benefits of flexible heat pumps in 2030 scenarios. In: *Commun Earth Environ* 5 (1), S. 1–12. DOI: 10.1038/s43247-024-01861-2.

Schimeczek, Christoph; Nienhaus, Kristina; Frey, Ulrich; Sperber, Evelyn; Sarfarazi, Seyedfarzad; Nitsch, Felix et al. (2023): AMIRIS: Agent-based Market model for the Investigation of Renewable and Integrated energy Systems. In: *JOSS* 8 (84), S. 5041. DOI: 10.21105/joss.05041.

Sperber, Evelyn; Frey, Ulrich; Bertsch, Valentin (2020): Reduced-order models for assessing demand response with heat pumps – Insights from the German energy system. In: *Energy and Buildings* 223, S. 110144. DOI: 10.1016/j.enbuild.2020.110144.

Sperber, Evelyn; Schimeczek, Christoph; Frey, Ulrich; Cao, Karl Kiên; Bertsch, Valentin (2025): Aligning heat pump operation with market signals: A win-win scenario for the electricity market and its actors? In: *Energy Reports* 13, S. 491–513. DOI: 10.1016/j.egyr.2024.12.028.

Stute, Judith; Pelka, Sabine; Kühnbach, Matthias; Klobasa, Marian (2024): Assessing the conditions for economic viability of dynamic electricity retail tariffs for households. In: *Advances in Applied Energy* 14, S. 100174. DOI: 10.1016/j.adapen.2024.100174.