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Incentivising demand-side flexibility with heat pumps – what are the benefits to residential consumers?

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Abstract

The transition from fossil fuels to renewable energy is driving a paradigm shift in the energy system. Instead of generation ramping up and down to meet demand, the system now needs a flexible demand-side which can respond to peaks and troughs in generation and alleviate grid congestion. Heat pumps are part of the solution and are technically capable of providing demand-side flexibility. However, regulatory and market challenges mean that the full value of flexibility from heat pumps is not being captured – especially in the residential market. This study presents a quantitative assessment of the (financial) value to residential consumers of flexible operation of heat pumps in selected European markets. It assesses the energy cost savings achievable from implicit flexibility (heat pump optimisation in response to variable tariffs) under different conditions, how sensitive the results are to changes in the market and regulatory environment, and how savings could be maximised. Results show that heat pump optimisation can provide significant running cost savings today, and savings could grow even more in future in line with the increasing volatility of electricity prices. However, this potential can only be fulfilled if market and regulatory barriers are removed: consumer price signals do not always incentivise flexible operation; tariffs to enable flexibility do not exist in many markets; and energy price structures such has high fixed fees limit the savings gained from HP optimisation. Ensuring this value is accessible to consumers not only benefits the energy system, but can also accelerate the decarbonisation of heat by strengthening the economic case for switching from fossil boilers to heat pumps. In markets where the case for switching to heat pumps remains marginal, the additional running cost savings through flexibility can make or break the HP proposition.

Keywords: implicit flexibility; variable tariffs; spot markets; electricity price volatility; heat pump optimisation; running cost savings

1. Introduction

1.1. Why is the need for demand side flexibility growing?

The transition from a fossil fuel-based energy system to one based on renewable energy and electrification, is driving a paradigm shift in the energy system, which is positioning demand-side flexibility (DSF) as a critical tool to enable decarbonisation. The need for DSF is particularly urgent in Europe:

On the generation side: Inflexible renewable generation overtook more flexible fossil fuel generation as the dominant electricity generator in Europe in 2023 [2] and will continue to grow. In the old fossil-dominated energy system, electricity generation was flexible - it ramped up and down to meet demand through e.g. switching on a gas-fired 'peaking plant' on a cold winter day. But in today's renewable-based energy system, wind and solar generation are inflexible, so it is the demand-side – through demand-side flexibility - which must ramp up and down in response to fluctuations in wind and sun.

On the demand side: The electrification of heat and transport is gaining traction - heat pumps' share of the European annual heating market has increased from 9%-24% since 2018 [3,4], and electric vehicles' share has grown even faster to reach a similar share of annual car sales [5,6]. This shift decarbonises demand but also contributes to congestion on electricity grids (distribution grid congestion is already a challenge in some markets such as the Netherlands). Therefore, the ability for demand-side assets like HP to shift operating times away from peak periods in response to the needs of the grid is critical.

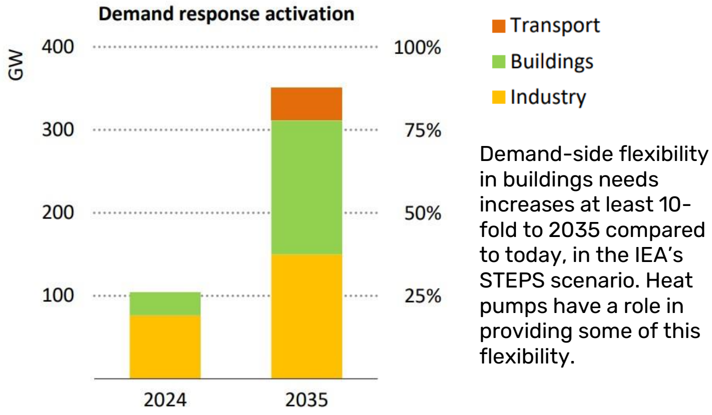


Figure 1. Expected growth in demand-side flexibility ('demand response') capacity required in the global energy system, 2024-2030 [7]

The IEA [7] forecasts a dramatic increase in the amount of demand-side flexibility required in future, defining DSF as a critical tool, alongside storage and energy efficiency, for managing the new generation/demand environment. While technical solutions exist for DSF, the uptake of DSF in the market has been slow [1], particularly in the residential sector, where it is not always incentivised. There are several reason for this e.g: (i) regulatory and market barriers making DSF value inaccessible; (ii) existing electricity pricing structures limiting the potential customer benefits; or (iii) a lack of evidence to quantify the real value of DSF, upon which business models and customer propositions can be designed.

1.2. Aims and research questions

This paper aims to better quantify the value to residential end-users of using heat pumps (HP) for DSF, how this value varies, and why. 'Value' is defined here as financial benefits to consumers through energy bill savings. Only "*implicit"* DSF is considered, where HP operating times are adjusted in response to variable electricity tariffs, enabling running cost savings for the customer. We refer to this as 'HP optimisation to variable tariffs'. [Note that we do not address *explicit* flexibility in this paper, which involves capturing value through trading flexibility from aggregated demand-side assets on the energy markets].

Implicit DSF with heat pumps is well-established in the Nordic markets. In Sweden, residential consumers have had access to variable electricity tariffs based on the Nordpool day-ahead spot market since 2017. This has led to offers from most HP providers, which can automate heat pump operation in response to these variable prices, and deliver running cost savings to end-users. Experience to date indicates that these savings could potentially be even greater in other markets, but that equivalent spot price-based variable tariff offerings are extremely limited or non-existent in these markets.

The main research question is: 'What running cost savings can be achieved through HP optimisation to variable tariffs in Sweden, and how would the savings compare in other European markets (UK, Germany and Netherlands), if equivalent tariffs were available?'

In addition, we investigate the sensitivity of the results under different scenarios, to assess how the savings could be maximised further, for example through:

1. Changing electricity pricing structures (i.e. changing the shares of the different cost components, in particular the 'cost of energy', in the total electricity bill)
2. Increased volatility of wholesale electricity prices
3. Shifting to more granular price signals (i.e. 15-minute rather than 30 or 60 minute settlement periods)
4. Building houses to 'nordic standards' in other markets

We address these questions by modelling HP optimisation in response to variable-rate electricity prices in different scenarios. We calculate the running cost savings achieved in comparison to 'normal' HP operation, which operates in response to outdoor temperature and indoor climate requirements and does not have variable electricity prices.

2. Heat pump optimisation to variable-rate tariffs

2.1. What is a variable-rate tariff?

There are many different types of electricity tariffs for residential customers available in Europe, but they can be broadly categorised as 'fixed-rate' and 'variable-rate'. The main difference between them is in the way the 'cost of energy' is translated into an end-user price/kWh:

- **In fixed-rate tariffs**: The price/kWh is set at a fixed, flat rate for a year ahead, regardless of the cost of energy on the spot market. The total bill relating to the cost of energy varies only with the *volume* of electricity consumption. Fixed rate tariffs do not enable implicit flexibility from assets such as heat pumps (though other business models can enable different types of flexibility which we will not go into in this paper).
- **In variable-rate tariffs**: The price/kWh varies with the *timing* of electricity consumption, changing at set time intervals (typically 30-60 minutes), reflecting the changing cost of energy on the spot market. Variable-rate tariffs are necessary to enable implicit flexibility from demand-side assets like heat pumps.

The 'cost of energy' is only one component of the final electricity bill, typically making up between 35-60% of the total electricity bill across Europe (see Table 1, [16]). The precise make-up of the electricity bill varies depending on the contract type and the country. We base our analysis on a variable-rate tariff which changes hourly in each country, for a residential customer with a heat demand of around 12.000 kWh.

Table 1: Main components of electricity bills. *The percentages in the third column relate to the range of shares across different European countries, based on source [16].

Component	How it is charged in a variable-rate tariff?	Approx. share of total electricity bill – range across Europe* [16]
1. **Cost of energy:** Wholesale cost of buying the energy on the wholesale (spot) market	Per kWh rates vary during the day, typically increasing at times with high demand but scarce supply (e.g. no wind). This disincentivises consumption and reduces the supply/demand imbalance.	35-60%
2. **Taxes & levies:** including policy costs and other taxes	Flat rate per kWh of consumption, which can vary by consumption band. For the purpose of this research, we assume all residential customers are in the same band.	0-10%
3. **Network and distribution charges**	Often consists of a fixed daily fee, plus a flat rate per kWh, which can vary depending on e.g. total consumption, or peak consumption.	10-15%
4. **Value Added Tax**	Added as a percentage on all components of the electricity bill	5-25%

2.2. How does heat pump optimisation to variable-rate tariffs work?

The usual operating patterns of a heat pump can be optimised in response to external signals such as spot prices (a component of variable-rate tariffs). The heat pump's control strategy is to shift its operation times as far as possible towards the times where the prices are lowest, and away from the most expensive times. By nudging the heat pumps' electricity consumption towards times with lower spot prices, total running costs can be reduced compared with a control strategy which only takes into account outside temperature and heat demand profiles.

Figure 2 shows operating patterns of a NIBE heat pump in Sweden, as it responds to hourly price signals from the Nordpool spot market. Spot prices are set 24-hours ahead based on forecasted supply and demand patterns. The heat pump adjusts the timing and power of its output to minimise operation during high price times, and capitalise on the cheapest periods. Comfort boundaries are set by the end-user – for example, that the house may not drop below 20°C. The extent to which operating patterns can be adjusted depends on various factors such as:

- How quickly the house leaks heat (defined by building characteristics e.g. thermal inertia, size/surface area, U-value)
- Volume of storage (e.g. size of hot water tank)
- Comfort requirements (how cold are end-users willing to let the house become?)
- The outside temperature (influences the efficiency of the heat pump)

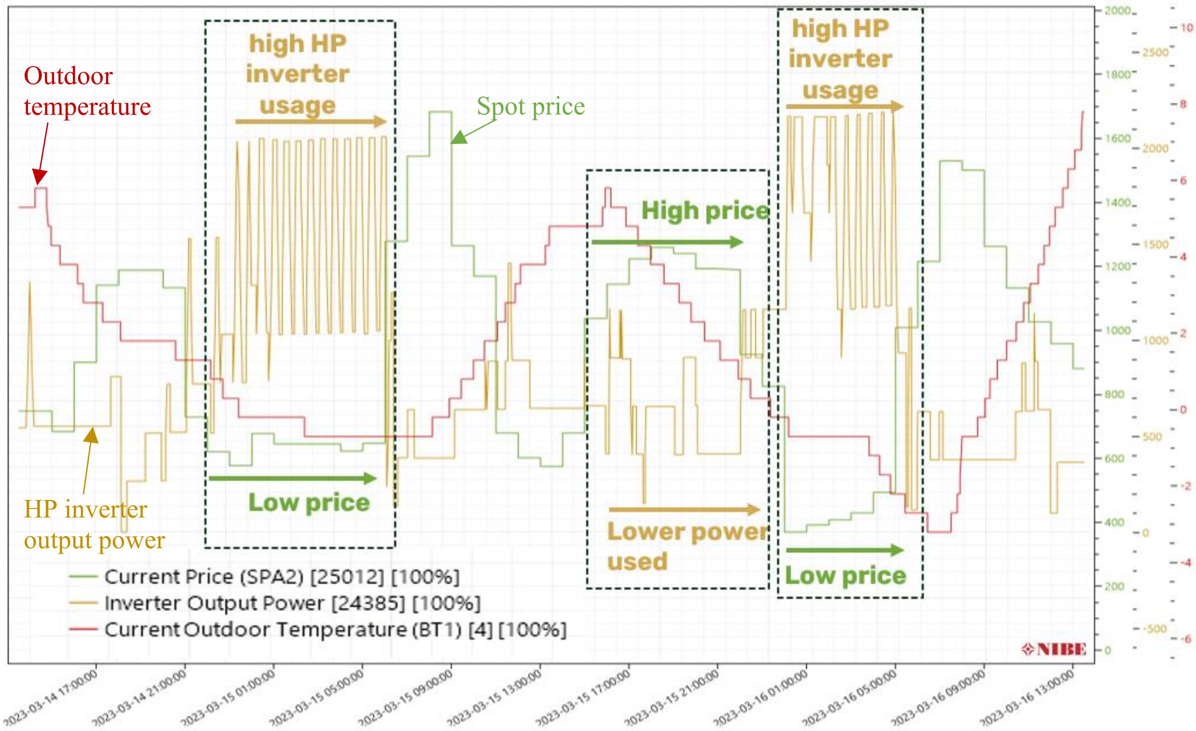


Figure 2. Extracted operating data from a NIBE heat pump as it regulates HP power (yellow) in response to outdoor temperature (red) and variable electricity price (green). [8]

3. Approach: Assessing running cost savings from HP optimisation in different countries and scenarios

Evidence from Sweden suggests that savings through optimisation to variable-rate tariffs can amount to around 15-20% on the 'cost of energy' part of the electricity bill, compared to running the HP with no optimisation [8]. It is important to note that since the 'cost of energy' is only one part of the full electricity bill (see Table 1), the savings on total running cost are lower. Modelling has been carried out to test the savings potential in Sweden, to investigate whether such savings could be achieved or exceeded in other markets, and to investigate which factors could increase the value of these savings.

3.1. Heat pump optimisation model

A General Algebraic Modelling System (GAMS) was developed [9] to simulate HP optimisation in response to hourly spot prices. The model was designed to control the output level and timing of the HP's operation over a year under varying price and outdoor temperature conditions. It incentivises the HP to produce more heat during periods of low price and high HP coefficient of performance (COP) – thus minimising total running costs (within comfort boundaries – indoor temperature must remain between 20-25◦C).

The model's objective function is defined as Min Z = $\sum \lambda(t) \cdot E(t)$ [9] where Min Z refers to minimising running costs during the set time period, and E is a function of the thermal output and the HP coefficient of performance (COP). The COP is a function of the heat generated and the electricity consumed by the HP. Performance data from field measurements from a NIBE A/W HP in Sweden was used to generate a linear regression to calculate how the COP varies with outdoor temperature. This was then adapted to predict HP electricity consumption in different countries and scenarios. Input data includes:

- full year data for hourly electricity spot prices in Sweden, UK, Germany & Netherlands [10]
- full year outdoor temperature data for all four countries [11]

- full year hourly heat pump performance measurements from a NIBE S2125 air/water HP installed in Sweden [12]
- Building characteristics (size, U-values, thermal inertia indicators) for typical single-family house built in the 1980s-1990s in all four countries, based on standardised building typologies developed by the Episcope project [13]
- Comfort boundaries - maximum and minimum required indoor temperatures
- Electricity price structure (break-down of electricity price components) for all four countries [16]

Annual running costs are calculated for a typical house in each country, using the country-specific input data highlighted above. Comfort boundaries are kept constant in all countries. We calculate running costs under two core scenarios:

- <u>'Optimised' HP operation</u>: HP responds to hourly variable electricity prices and tries to minimise running hours at expensive times and vice versa (while maintaining set comfort requirements)
- <u>'Normal' HP operation</u>: HP operates 'normally' with no influence from hourly variable prices

We differentiate between:

- <u>Savings on the 'cost of energy'</u>: Running cost savings on the energy component of the bill (Component 1 in Table 1) achieved by optimising HP operation to hourly spot prices, as compared with normal operation.
- <u>Savings on total running cost</u>: Running cost savings on the entire electricity bill (Components 1-4 in Table 1 combined) under optimised and normal scenarios.

3.2. Market factors influencing running cost savings potential from optimised HP operation

Table 2 outlines some of the key factors influencing the potential running cost savings from optimised HP operation. Table 3 presents a qualitative assessment of how the four markets investigated compare on each of these factors. The assessment indicates that although Sweden scores highest on having the 'requirements' in place for capturing running cost savings from HP optimisation (factors 1 and 2), there could be untapped potential for even greater savings to be made in other markets – particularly where 'influencing factors' relating to the energy price structures (factors 4-6) may increase the amount of savings to be made. The outcomes of this qualitative analysis are further tested and potential savings across countries and scenarios quantified in the modelling work, presented in section 4.

Table 2. Market-related factors influencing the potential running cost savings from optimised HP operation compared to 'normal' operation

Factor	Importance	
1. Is smart meter infrastructure in place?		Requirement: Without smart meters, no variable tariffs are accessible
2. Availability of variable-rate electricity tariffs for residential customers?		Requirement: Variable tariff signals are necessary for HP optimisation.
3. Building thermal characteristics e.g. thermal inertia, surface area, U-value (it loses heat slowly)		Influencer: Increases the potential savings, as the better the building retains its heat, the longer the HP can be ramped down (e.g. at cheap times) without affecting the indoor temperature
4. High share of final electricity price which is linked to 'spot price' (i.e. cost of energy – see Table 1)		Influencer: Increases the potential savings by exposing the end-user more to the variable part of the price
5. High average wholesale electricity price level		Influencer? May increases the potential savings because there is more to save in real term
6. High variability in the wholesale price		Influencer? May increases the potential savings because the HP can run at even cheaper times (as long as it can minimise operation in the more expensive times)

Table 3: Qualitative analysis of market-related factors influencing the potential running cost savings from optimised HP operation compared to 'normal' operation: How do selected countries compare? [13,15,16,17,18]. *Note that U-value is used as one indicator of building thermal characteristics for the purpose of this Table, as it is the building characteristic which varies the most between countries.

		SE	UK	DE	NL	Factor
requirements	Smart meter roll out	100%	62%	1%	90%	1
requirements	% of residential electricity tariffs on the market which are variable	75%	40%	30%	50%	2
influencers	U-value of typical detached house built in 1980-1995*	0.28	0.67	0.55	0.83	3
influencers	Spot price (energy component) share of total electricity price (see Table 1)	42%	57%	39%	43%	4
influencers	Mean spot price, 2023 (EUR cents / kWh)	8.50	20.49	16.20	16.45	5
influencers	Spot price variabiliy, 2023 (standard deviation from mean)	4.73	5.64	4.64	5.10	6

Enables greater potential savings (green) | Reduces potential savings (red)

4. Results: What running cost savings can optimised HP operation achieve compared to normal operation?

4.1. Running cost savings from HP optimisation could be higher in markets other than Sweden

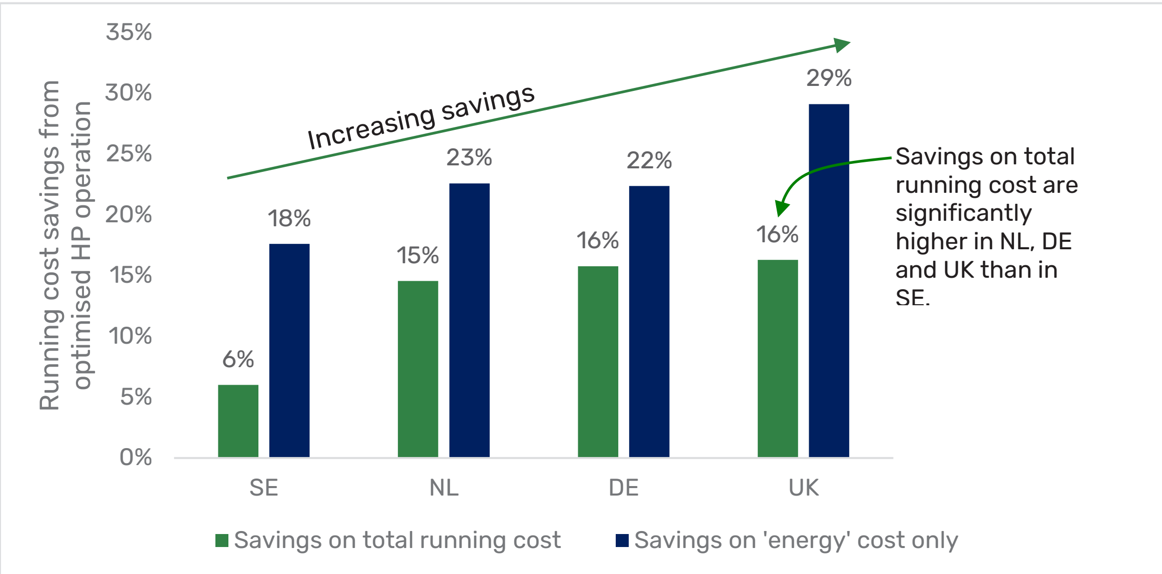


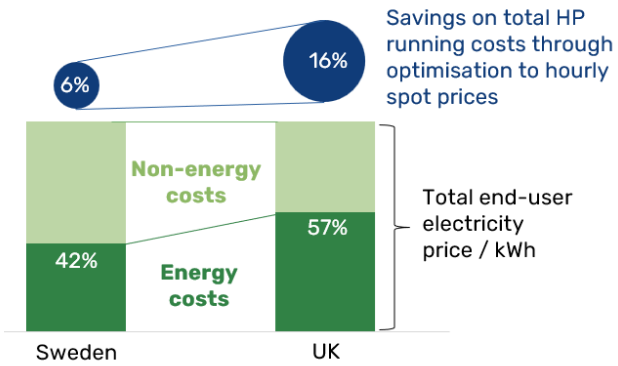
Figure 3: Running cost savings from optimised HP operation in comparison to normal operation – comparing savings on 'cost of energy' versus savings on total running cost (including all components of the electricity bill)

Sweden is one of the countries with the most extensive experience of heat pump optimisation to variable-rate tariffs, where 10s of 1000s of customers are already engaged in it [15]. However, the modelling presented here indicates that the potential savings in the Netherlands, Germany and UK could potentially exceed savings seen in Sweden. The modelling results presented in Figure 3 indicate savings of from 18% (in Sweden) to 29% (in the UK) are possible on the 'energy' component of the energy price – this is part of the price which is linked to the spot price. Savings on the total running costs are lower, ranging from 6% (Sweden) to 16% (UK). The savings modelled for Sweden are close to the experience on the ground in Sweden [17], which suggests savings of around 15% on the 'cost of energy'.

Three factors explain why Sweden might see lower running cost savings than other markets from optimised HP operation.

1. The influence of the spot price (reflecting the 'cost of energy') on the total end-user running costs (Figure 4): The high share of fixed fees on Swedish electricity bills means that the spot price accounts for less than half (42%) of the electricity price, whereas in the UK it is 57% [16]. This means that variations in the spot price have a bigger influence on the total bill in the UK than in Sweden. HP optimisation according to the spot price can therefore save more money in the UK than in Sweden (all other factors being equal).
2. The influence of spot price volatility on the potential savings on 'cost of energy' (Figure 5 & 7). The volatility in the spot price throughout the year is a measure of the spread of prices from low to high. The higher the volatility, the bigger the swings between high and low prices. Spot price volatility is influenced by several factors, of which the electricity generation mix is one of the most important: a higher share of inflexible and unpredictable generation like wind and solar increases price volatility; and a higher share of flexible and predictable generation like gas plants, nuclear, biomass and hydro power decrease price volatility. The spot price is much more volatile in e.g. UK (where wind & solar accounts for almost 40% of generation) than in Sweden(where wind & solar accounts for 25% of generation). Figure 6 illustrates the greater spot price volatility in the UK compared to Sweden. The modelling broadly supports the hypothesis that the greater the spot price volatility, the greater the potential savings from HP optimisation to variable tariffs). Figure 5 also shows that the greatest savings are achieved where both the volatility and the mean spot price are higher

Figure 4: the 'cost of energy' has a smaller influence on the total end-user electricity price in Sweden than in UK



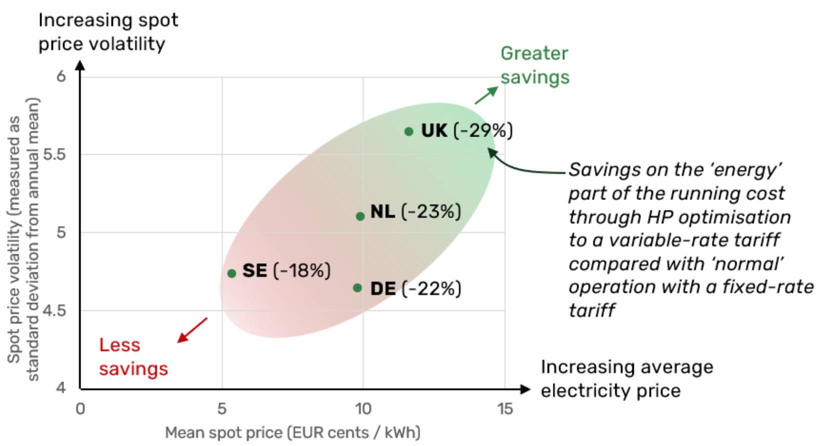


Figure 5: Differences in spot price volatility and mean spot price per market – 'energy' component of the electricity price only. (Spot price data from [10], % savings data from the modelling in this study)

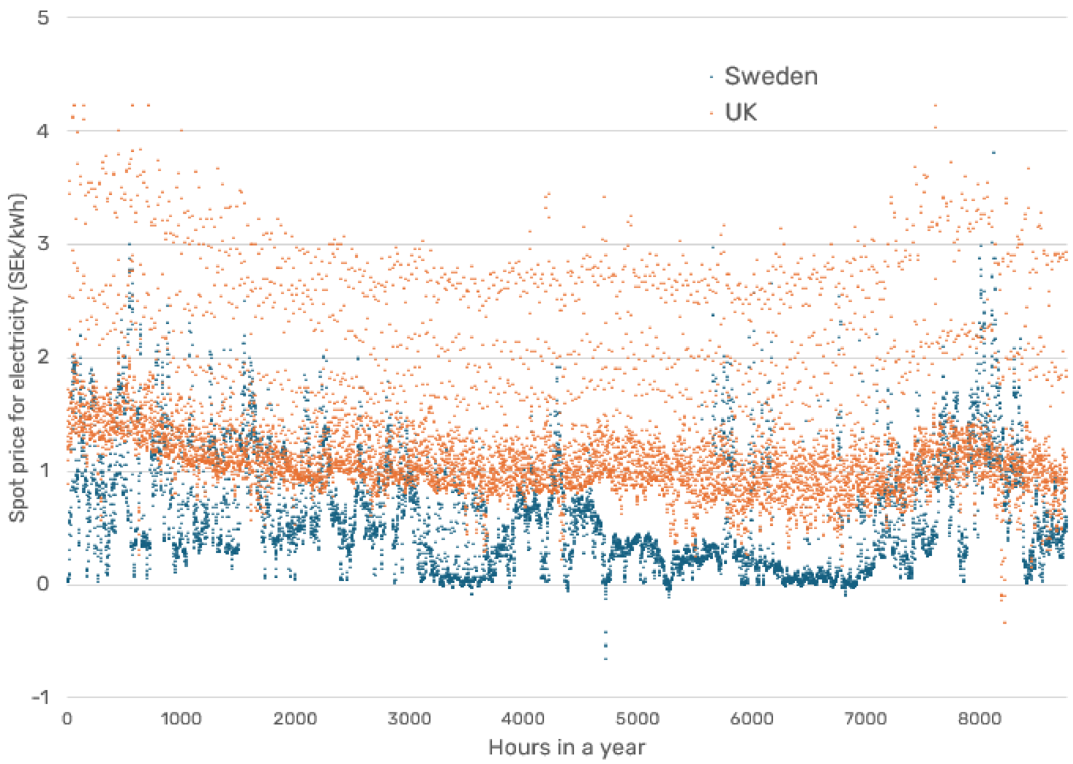


Figure 6: Sweden has lower spot price volatility than the UK [10]

4.2. Improving the thermal characteristics of the building increases the potential savings from optimisation

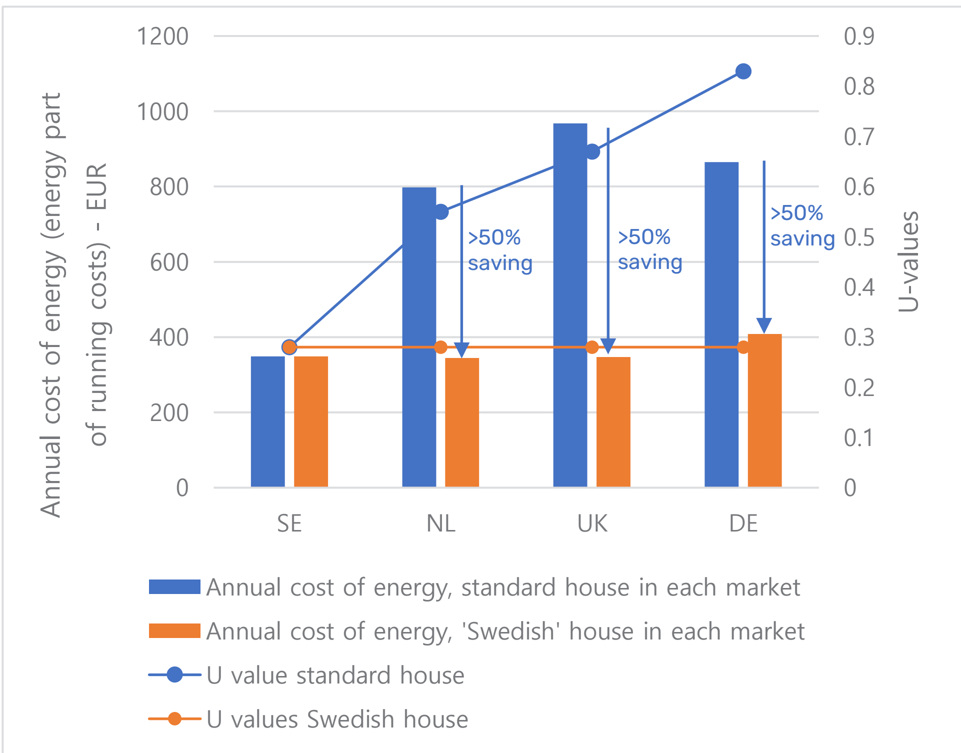


Figure 7: Comparing annual cost of energy with a standard house in each market compared with a Swedish house in all markets. Considers ‘cost of energy’ only (Component 1 in Table 1) – not tot total running costs.

The running cost savings which can be achieved from HP optimisation depend on the extent to which operating patterns can be adjusted from 'normal' e.g. how much the HP is ramped down in output, and for how long, when the spot price is high. The thermal characteristics of the building are one key influencer on this. Building thermal characteristics (size, thermal inertia and U-value) for typical detached homes from the 1980s and 1990s [13] are compared across the four countries when calculating the heat demand, showing that typical Swedish house loses heat most slowly compared to houses in the other markets (see Table 2).

To investigate the impact of this difference in building characteristics, the typical Swedish house – with a notably lower U-value - was modelled in the UK, NL and DE (all other model inputs were held constant). As shown in Figure 7, the annual 'cost of energy' is more than halved in all markets, when the house has 'Swedish' building characteristics instead of the typical building characteristics for that market. This illustrates the importance of the building thermal mass in determining how far heat pump operating patterns can be adjusted in response to variable prices.

4.3. Potential savings increase by lowering comfort requirements

The comfort requirements in the house are another critical factor influencing the extent to which HP operating patterns can be adjusted from 'normal' in response to the fluctuating spot price. In short, if lower temperatures are acceptable, the HP can run for fewer hours or with less power. To quantify this, sensitivity tests compared the base-case ('normal' operation) with 2 'optimised operation' comfort scenarios: 'normal comfort' with a minimum temperature in the building of 20◦C, and 'low comfort' with a minimum temperature of 17.5◦C. All other model inputs were held constant. As shown in Figure 8, the lower comfort level increases savings on the 'cost of energy' from 18% to 30% in the case of Sweden. Given the other results, the extent of additional savings in other countries could be even greater.

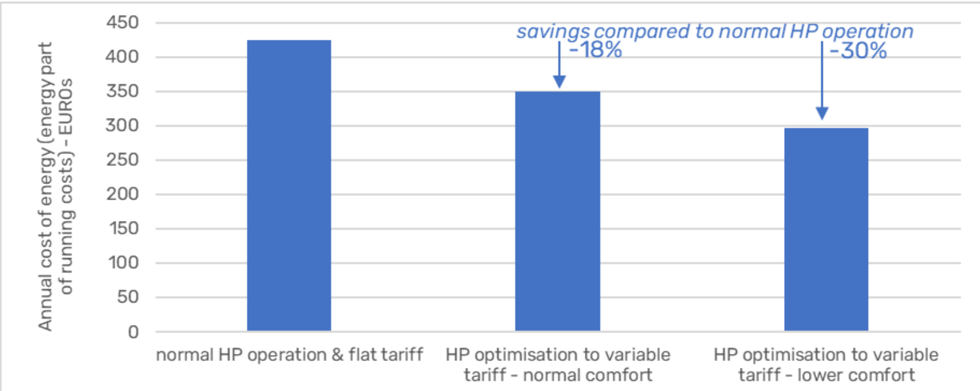


Figure 8: Impact of lowering comfort levels on potential savings – based on Sweden base-case. Considers 'cost of energy' only (Component 1 in Table 1) – not tot total running costs.

4.4. Moving to more granular spot price time-periods may increase the potential savings

Most variable tariffs to date have been based on hourly spot prices, but the European electricity market is transitioning towards more granular settlement periods in the day-ahead market (from 60-minute to 15-minute). This is driven at an EU level by Regulation which came into force on the 1st October 2025 [18]. A similar shift is also being consulted on in the UK [19]. The aim of the move to more granular settlement periods is to more accurately reflect and manage the real-time fluctuations in supply and demand. This could potentially increase the savings from HP optimisation as HP operation can be controlled even more accurately.

To test this, HP optimisation was modelled in response to 15-minute spot price intervals in Germany and compared with the results from optimisation to 60-minute spot price intervals. Results shown in Figure 9 indicate that savings from HP optimisation on the cost of energy compared to 'normal' operation could be doubled from 22% to 37%, through switching to more granular spot prices.

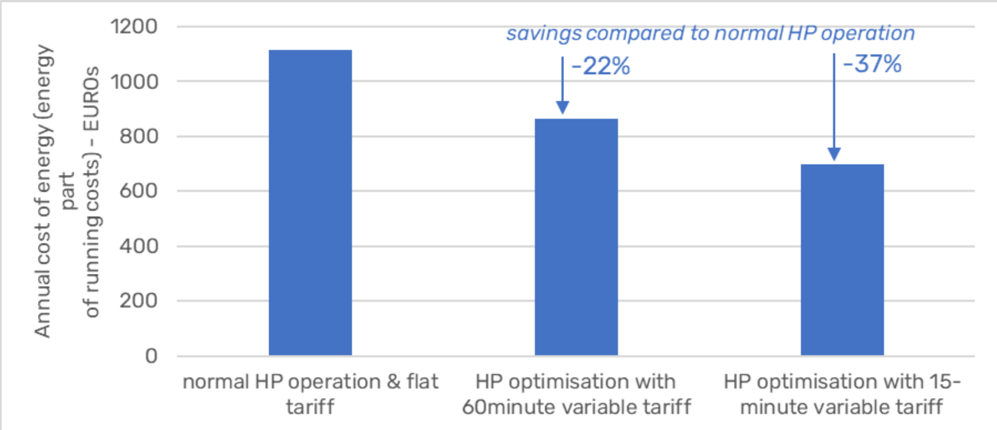
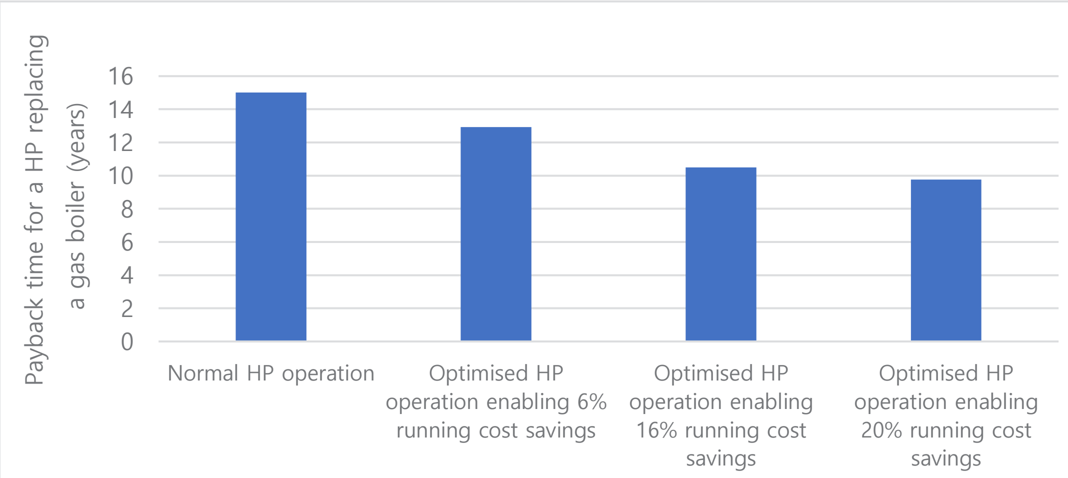


Figure 9: Impact of shifting to more granular spot price settlement periods – Germany base-case

4.5. Heat pump optimisation savings can reduce payback times for heat pumps replacing gas boilers

Running cost savings associated with heat pump optimisation to variable tariffs can play a role in strengthening the economic proposition for heat pumps replacing fossil boilers. Simple marginal payback was calculated based on an upfront cost for an air/water heat pump and a gas condensing boiler which is modelled on the UK and typical for several European countries. The energy price ratio (EPR) is set at 2.84, at which marginal savings can be made by switching from a gas boiler to a heat pump. It is equivalent to the EPR in the UK or Germany with standard HP tariffs. Figure 10 illustrates how the payback time can be reduced from >14 years to <10 years where running cost savings are achieved through optimisation.



Energy Price Ratio (EPR), in fixed-rate HP tariff): 2.84
In variable-rate tariff, the EPR varies

Fully installed costs:
Heat pump incl. subsidy: EUR 9.000;
Gas condensing boiler: EUR 4.300

Heat demand:
12.000 kWh

Seasonal efficiencies:
HP: 350%*; Boiler: 90%

Simple marginal payback for a HP replacing a gas boiler is calculated as a function of (1) HP running costs under 'normal' operation and various 'optimised' operation scenarios, (2) boiler running costs - constant in all scenarios, (3) HP and boiler fully installed costs (constant for all scenarios).

Figure 10: Comparing marginal payback time for heat pumps replacing gas boilers under different optimisation scenarios. *For the purpose of this analysis, we assume a comparable seasonal efficiency for the optimised and normal operation.

5. Conclusions

The research highlights that total running cost savings in the range 6% to 16% can potentially be captured for residential customers through HP optimisation to variable-rate tariffs, under the right conditions. These savings can be increased even further in buildings with:

- Greater influence of the spot price on the total electricity price
- Increased volatility in the spot price
- Construction standards which minimises heat loss from buildings
- Lowering comfort requirements
- Moving to more granular spot price time-periods

Savings achievable in the UK, Netherlands and Germany could be significantly higher than those already established in Sweden, showing that there is untapped potential. We can identify several building blocks which can support and maximise the value from HP optimisation to variable-rate tariffs:

- Ensure complete smart meter roll out (Germany in particular is far behind)
- Ensure wider access to and uptake of variable-rate tariffs is essential (access is high in the Nordic markets but lags behind almost everywhere else).
- Electricity price structures which include a high share of non-energy costs (e.g. in Sweden) must be addressed where they reduce the value of flexibility to consumers.
- Quantify and promote the benefits of HP optimisation in strengthening the economic case for heat pumps compared to gas – especially where the current economic case is marginal (for example in the UK). Field testing to prove the concept will strengthen the argument.
- Adapt business models depending on the 'risk' which consumers want to take. Not all customers want to take the full risk of variable prices, so business models which can combine a fixed tariff with e.g. bonuses and rewards for flexibility could have a lot of potential.

The future is positive, as the potential savings from optimisation to variable-rate tariffs is likely to increase:

- We are likely to see even more volatile electricity prices as the energy transition accelerates, which increases potential savings
- The trend is towards more granular spot prices, which again can potentially increase savings
- Additional flexibility value streams will become more accessible to heat pumps as energy markets become more open, allowing independent aggregators access to the flexibility markets, and ultimately enabling small residential assets such as heat pumps to be traded as part of aggregated loads.

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