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RESEARCH ARTICLE

REVISED Impact of variable electricity price on heat pump operated buildings

[version 2; peer review: 3 approved]

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Abstract

Background

Residential buildings with heat pumps show promising possibilities for demand-side management. The operation optimization of such heating systems can lead to cost reduction and, at the same time, change electricity consumption patterns, which is especially prevalent in the case of a variable price signal. In this work, we deal with the following question: How does the volatility of a variable retail electricity price change the energy consumption of buildings with a smart energy management system?

Methods

In this context, we take Austria as an example and aggregate the findings of individual households to the national stock of single-family houses. This is done by simulating and optimzing heating operation in single representative buildings. The aggregation is done based on national building information statistics.

Results

This part of the Austrian building stock could shift 19.7 GWh of electricity per year through thermal inertia using a real-time electricity price from 2021. We show the future potential under the assumption of three electricity price trends for 2030, representing different decarbonisation ambition levels. The trends show that higher decarbonisation levels which lead to higher electricity prices increase the incentive to shift electric loads.

Open Peer Review

Approval Status ✓ ✓ ✓

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Conclusions

Real time pricing turns out to be an effective incentive for buildings to shift electric loads by pre-heating the building mass. However, cost savings for individuals are relatively low which is why additional monetary incentives are needed to tap into that potential. Increased daily peak-to-peak demand from these buildings has to put into perspective to the overall grid load.

Keywords
demand-side management, heat pump, load shifting, optimization, building stock



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REVISED **Amendments from Version 1**

In the updated manuscript explanations and limitations of the modeling approach were added. Additionally, we added a paragraph discussing the limited cost savings for single households and the "benchmark" scenario was renamed to "reference" scenario. The "Methodology" Section was divided into subchapters (Model overview, 5R1C model, Heat pump, Thermal storages, Model objective, Austrian building stock and Electricity price scenarios) for clarity and the term "flexibility" was defined. A Nomenclature was added, additionally we checked the consistency when citing names, corrected some spelling errors, Figure 1 was changed making the heating system type more clear, we checked that all variables in equations are explained in the text, used "heated area" instead of "effective area" and "effective heated area" and explained "NUTS3" and the "heat transfer coefficient" in footnotes. Also, all the subscripts and superscripts were aligned throughout the text, and clarified that savings in the result section are annual and quantified how cheap a home energy management system would have to be, to be economically viable for households without any thermal storage. Finally, the tenses were changed, past tense was used to describe our own work and present tense to describe work done by others.

Any further responses from the reviewers can be found at the end of the article

Character	unit	description
HP	-	heat pump
DR	-	demand response
RTP	-	real time price
SFH	-	single family house
SEMS	-	smart energy management system
COP	-	coefficient of performance
DHW	-	domestic hot water
T	K	temperature
m	k	mass
c	J/kgK	specific heat capacity
Q	Wh	thermal energy
p	€	price
P	W	electric power
E	Wh	electric energy
U	W/m^2K	heat transfer coefficient
Ψ	W/mK	heat transfer coefficient for thermal brigdes
l	m	length
χ	W/K	heat transfer coefficient through punctual thermal bridge
b_{tr}	-	heat transfer adjustment factor
b_{ve}	-	temperature adjustment factor for air flow
q_{ve}	m^3/s	air volume flow
k	J/m^2K	specific thermal capacity of building element
η	-	efficiency factor
θ_{air}	°C	indoor air temperature
θ_{sup}	°C	ventilation supply temperature
θ_{s}	°C	node temperature
θ_{m}	°C	thermal mass temperature
$\theta_{m\,avg}$	°C	average thermal mass temperature
C_m	J/K	thermal capacity of a building
A	m^2	area
A_{tot}	m^2	total surface area of building
A_f	m^2	heated floor area
A_m	m^2	effective mass related area
Λ_{at}	-	ratio between surface area inside the building and heated area
$H_{tr,em}$	W/K	transmission heat transfer coefficient between outside and the thermal mass node
$H_{tr,op}$	W/K	transmission heat transfer coefficient through opaque building elements
$H_{tr,w}$	W/K	transmission heat transfer coefficient through windows
$H_{tr,is}$	W/K	transmission heat transfer coefficient between the surface area node and indoor air temperature
$H_{tr,ve}$	W/K	transmission heat transfer coefficient of the ventilation
$H_{tr,1}$	W/K	transmission heat transfer coefficient
$H_{tr,2}$	W/K	transmission heat transfer coefficient
$H_{tr,3}$	W/K	transmission heat transfer coefficient
$H_{tr,ms}$	W/K	transmission heat transfer coefficient between the thermal mass node and the surface area node
h_{ms}	W/K	transmission heat transfer coefficient between the outside air and the surface area node
H_D	W/K	transmission heat transfer coefficients for direct heat transmission
H_g	W/K	transmission heat transfer coefficients to the ground
H_U	W/K	transmission heat transfer coefficients to unconditioned rooms
H_A	W/K	transmission heat transfer coefficients to adjacent buildings

1. Introduction

With increasing renewable power generation integrated into the power system, the fluctuations from the supply-side need to be balanced. Demand response (DR) can bring a valuable contribution to the power system by using time of use dependent pricing schemes[1]. Residential buildings provide promising options for DR, especially the buildings with heat pumps (HP) and thermal storage that can be incentivized to shift loads by a price signal[2].

The operation of the HP can be optimized either by an in-house smart energy management system (SEMS) or a remote aggregator meaning that the heating system will be operated not by the homeowner. We will focus on an in-house operation implying that homeowners provide flexibility for their own benefit. In this paper we investigate one of many different incentives that can be used to influence the local control. One straightforward way is to introduce a variable real-time electricity price (RTP). If the prices in the following hours are known, the HP operation can be adapted to the price settings and economically optimize HP operation. Naturally, lower prices will occur when the production of renewable electricity is high, and prices will be higher when there are fewer renewables in the electricity mix[3].

Existing studies have evaluated the economic impacts of different pricing schemes on the HP-operated buildings[4–6]. In most studies, the flexibility is provided by the battery or thermal storage in the building. Flexibility in these studies is defined as the amount of energy (electrical or thermal) that is used at a different time than originally anticipated. In this sense flexibility could be interchangeably used with the term load shifting. As shown in another strand of literature, the load shifting potential of the building's thermal mass is also significant[7,8].

In this study, we combine these two strands of literature and investigate how much the electricity consumption profile can be influenced if we combine variable electricity prices with the SEMS. We consider the flexibility of building mass alone and compare it to the flexibility with implemented thermal storage systems. Two research questions are formulated: How can RTP signals influence cost-minimizing control strategies of residential single family houses (SFH)? Second, what are the implications of variable real-time electricity pricing and in-house SEMS at the national level?

To answer these two questions, our study includes three parts:

- First, we developed an hourly technology operation model for individual households by taking a single SFH with a HP installed as an example. Assuming the electricity price, outside temperature, and radiation as input, the model determines the operation of the HP. The model can run in two modes. In the reference mode, the operation of technologies is simulated keeping indoor temperature above a certain level, with the energy consumption and cost calculated accordingly. In the optimization mode, technologies' operation is optimized to minimize the energy cost.

- Second, we developed multiple scenarios for variable electricity prices following the RTP mechanism based on the Balmorel model[9,10]. The modeled prices reflect different scenarios with increasing marginal costs for power plants that provide flexibility. This way, we investigate how price volatility influences the incentive for load shifting.

- Third, by linking to the INVERT/EE-LAB[11] building stock model, we aggregate the results of individual households to the building stock level and explore the impact of RTP and in-house SEMS on the load shifting potential and the peak demand of the Austrian SFH building stock.

This paper contributes to existing literature by investigating load shifting potential on an hourly level over the whole year taking also future electricity price scenarios into account. Specifically the impact of increased price volatility is investigated. Additionally we show how load shifting measurements could influence the total peak demand on an aggregated level. The remainder of this paper is structured as follows. Section 2 overviews existing studies on HP-operated residential buildings' flexibility potential and different variable electricity price mechanisms. Section 3 introduces our model in detail and provides the input data and scenario definitions. Then, in Section 4, we present the results by analyzing the impact of various electricity prices on the load shifting behavior and the fiscal incentive. At last, we conclude in Section 5, discuss the limitations of this approach, and point out the need for further research.

2. Literature review

In literature, HP-operated buildings' economic advantages with a variable price scheme are often discussed in combination with storage applications. Bechtel *et al.*[12] analyze how different buffer heat storage sizes and the HP power impact the cost savings of a HP-operated building with a variable price signal. They find that HP start-ups can be reduced significantly with higher storage capacity. Operation costs can be reduced by up to 20% with a 1500 l buffer storage in an SFH. However, when considering the additional investment costs for the larger storage, a 200 l buffer storage is preferred. The electricity prices used in this particular study are historical prices for the German-Luxemburg market (EPEX Spot). They do not consider different price schemes in this study. In a case study, Fitzpatrick *et al.*[4] compare three different electricity tariffs for a residential building with a combined HP and gas boiler. The house had a 2000 l buffer storage and a 400 l domestic hot water tank. It turned out that the building provided the highest flexibility with the RTP scheme. The other pricing schemes are a two-level day/night tariff and a critical peak pricing with three different price levels depending on the hour of the day. Patteeuw *et al.*[6] on the other hand, showed that dynamic time of use pricing performs inferior in comparison to the direct load control in regards to CO2 savings and cost savings with a high level of residential HP penetration. They assessed the value of load shifting in high-energy-efficient HP buildings. Two load shifting controls are adapted: 1) a direct load control where the HP load is

controlled by a third party and 2) real time pricing. They analyzed how load shifting with residential HPs can reduce CO2 emissions and what incentive is best for home owners to participate in load shifting.

Ostergaard and Andersen[5] investigated the impact of electricity taxes on the incentive to increase HP power and thermal energy storage. Additionally, they examine the incentive of the alignment of HP operation with the dynamic electricity system needs in a district heating system. Variable taxes (hourly) incentivizes increasing thermal energy storage by 20%. The HP capacity however, is not affected. They do not consider different electricity pricing schemes.

Other studies denote that load shifting through variable electricity tariffs will lead to a higher electricity demand overall[13,14]. Miara *et al.*[13] states that HP systems in combination with buffer storage provide promising DR possibilities. However, because of heat losses and the increased HP operating temperatures when charging the buffer storage, the electricity consumption increases by 20% when DR is fully exploited. Kelly *et al.*[14] tries to shift all heating loads from peak periods to off-peak periods in a typical detached dwelling in the UK. A 1000 l hot water storage is sufficient, but the overall electricity demand increases by 60%. Additionally, the tank's charging demand is 50% higher than the average house would have had in the peak period.

Many studies investigating the impact of variable electricity prices focus primarily on load shifting with thermal or electrical storage. However, as widely discussed in existing studies, the thermal inertia of buildings also provides significant potential for load shifting.

For example, Golmohamadi[15] creates a stochastic model predictive controller for HP buildings focusing on thermal inertia and heat storage in the building. They find that ambient temperature and electricity price uncertainty has a more significant impact on the economic analysis than the domestic hot water consumption uncertainties. Sperber *et al.*[7] find that the maximum shiftable load in German SFH is 57 GW *el* by increasing the indoor temperature by 2°C. Weiß *et al.*[8] focuses on the peak shaving potential in the Austrian building stock through thermal inertia. They concluded that 50% of the heating peak loads could be shifted to off-peak hours for buildings built after 1980 by turning off the heating system until indoor temperature is reduced from 22°C to 19°C in a typical winter week. Masy *et al.*[16] find that 3–14% of the heating load can be shifted by using thermal inertia in a single, well-insulated building. While the heat transfer rate between the interior and the thermal mass is low, the amount of energy stored is still impressive. In this regard, Wolisz[17] suggests that by pre-heating a building for two hours, the heating demand for the following four hours can be reduced by 20% although the simulated building is made out of bricks and has no insulation. Floor heating and direct thermal activation are more effective in shifting loads with thermal inertia, however HP peak loads can still be significantly reduced with a radiator heating system and the proper control strategy[18].

In this work, we dive deeper into the effect of a variable electricity price for buildings operated with a HP. Among different variable electricity price mechanisms (*e.g.* critical peak pricing, day/night tariffs, or real-time pricing), we focus on the RTP for two reasons: (1) some real-time pricing schemes for residential consumers are already established in Austria; (2) it is a straightforward way to incentivize residents to shift their demand and has been proven to be more effective than other pricing schemes[4].

3. Methodology

Model overview

We developed an hourly technology operation model for individual households to model the response of households' energy consumption to variable electricity prices. The model calculates the operation of technologies throughout a whole year (8760 hours) in two modes: 1) reference mode, in which the energy demand of the building is met to keep a certain comfort level, and 2) optimization mode, in which a SEMS minimizes the operation cost of the household while keeping the same comfort level. Both modelling modes are shown in Figure 1 which also presents the model's general set up. Further details can be found in 19[1].

Figure 1 presents the model's general set up - input and output. Further details can be found in 19[1].

The relevant parts of the model for this paper are introduced as follows.

The necessary heating demand was calculated with a simplified five resistance one capacity (5R1C shown in Figure 2) approach following the DIN ISO 13790. This norm is outdated and has been replaced by the DIN ISO 52016. But the computational effort to implement the DIN ISO 52016 into the optimization framework is much higher. Both modeling approaches have been compared in 20. And the 5R1C approach has been tested against results from Energy Plus, Invert/EELab and the VDI 6007[21–23]. They show that the heating demand calculated by the 5R1C model is reasonably accurate, whereas cooling demand is strongly overestimated. Bruno *et al.*[24] investigated the thermal dynamics of the 5R1C approach compared to TRYNSIS. Similarly to that study we compared the dynamic behavior of our model to a simulation in IDA ICE[2]. Our approach with only one capacity underestimates the thermal inertia in general, specifically when there is floor heating, which is quite often the case in SFHs with

[1] The Code is openly accessible under https://github.com/H2020-newTRENDs/FLEX[25].

[2] https://www.equa.se/de/ida-ice

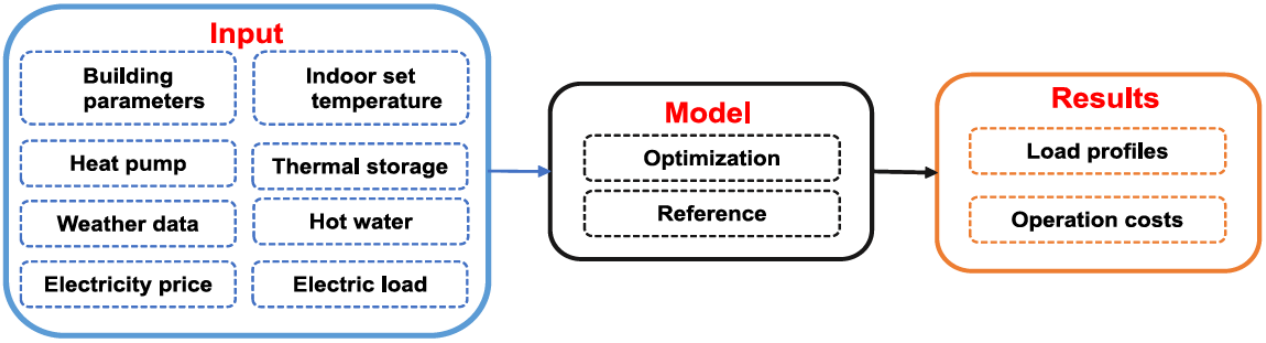

Figure 1. **Overall structure of the model.**

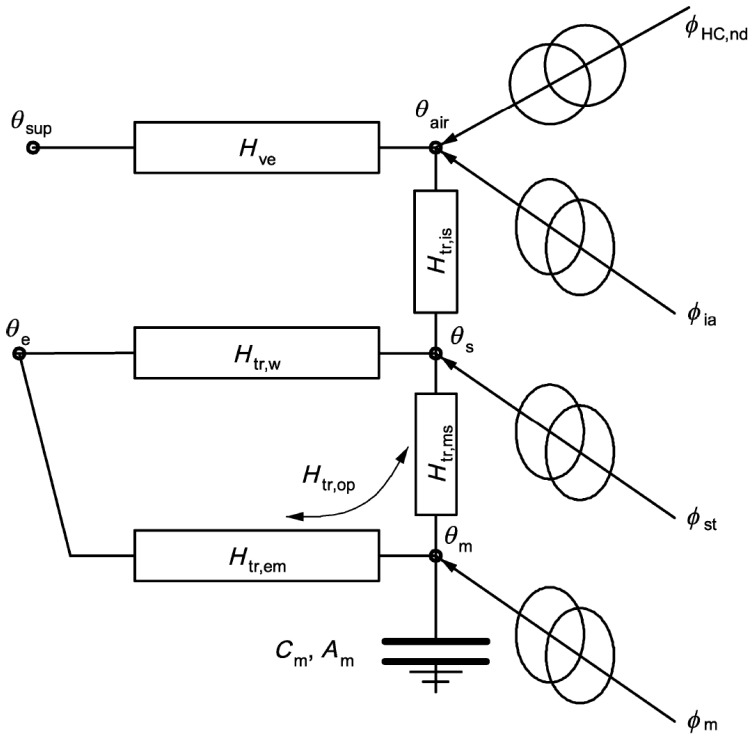

Figure 2. **5R1C circuit representation.**

heat pumps. Therefore, the results obtained by this approach can be seen as a lower benchmark to the actual flexibility potential.

5R1C model

Figure 2 shows the circuit representation of the 5R1C model described in the DIN ISO 13790. The relation between outside temperature ($\theta_{outside}$), indoor temperature (θ_{air}) and heating demand (ϕ_{HC}) is provided by the following equations. A detailed description of the calculation methodology can be found in the DIN ISO 13790. In the following equations, ϕ represents any kind of heat flow in W and θ is used to describe temperatures in $°C$. Equation 1 describes the relation between the indoor temperature (θ^t_{air}) and the provided heating energy (ϕ^t_{HC}). ϕ_{ia} describes the heat flow from internal gains:

$$\theta^t_{air} = \frac{H_{is} \times \theta^t_s + H_{ve} \times \theta^t_{sup} + \phi_{ia} + \phi^t_{HC}}{H_{is} + H_{ve}} \quad (1)$$

θ_{sup} describes the air temperature from the ventilation system. If no ventilation system with heat exchangers is adopted θ_{sup} is set to $\theta_{outside}$. In this study ventilation systems are neglected.

$$\phi_{ia} = 0.5 \times \phi_{int} \quad (2)$$

ϕ_{int} describe the internal heat gains in W/m^2. For simplification the internal gains (ϕ_{int}) are kept constant with $3.4W/m^2$, although in reality they can change every hour.

The node temperature θ_s is calculated through following equation:

$$\theta_s^t = \frac{H_{ms} \times \theta_{m_{avg}}^t + \phi_{st}^t + H_w \times \theta_{outside}^t + H_{tr1} \times (\theta_{sup}^t + \frac{\phi_{ia} + \phi_{HC}^t}{H_{ve}})}{H_{ms} + H_w + H_{tr1}} \quad (3)$$

The average temperature of the thermal mass ($\theta_{m_{avg}}^t$) in each timestep is calculated as follows:

$$\theta_{m_{avg}}^t = \frac{\theta_m^t + \theta_m^{t-1}}{2} \quad (4)$$

θ_m^t and θ_m^{t-1} represent the temperature of the thermal mass in the current and in the previous timestep and have to be calculated for each timestep individually:

$$\theta_m^t = \frac{\theta_m^{t-1} \times (\frac{C_m}{3600} - 0.5 \times (H_{tr3} + H_{em})) + \phi_{m_{tot}}^t}{\frac{C_m}{3600} + 0.5 \times (H_{tr3} + H_{em})} \quad (5)$$

with the heat flow to the thermal mass node $\phi_{m\ tot}$:

$$\phi_{m_{tot}}^t = \phi_m^t + H_{em} \times \theta_{outside}^t + H_{tr3} \times (\phi_{st}^t + H_w \times \theta_{outside}^t + \frac{H_{tr1}}{H_{tr2}} \times (\frac{\phi_{ia} + \phi_{HC}^t}{H_{ve}} + \theta_{sup}^t)) \quad (6)$$

The heat flow to the indoor surface node s, ϕ_{st} is calculated with

$$\phi_{st}^t = (1 - \frac{A_m}{A_t} - \frac{H_w}{9.1 \times A_t}) \times (0.5 \times \phi_{int} + \phi_{sol}^t) \quad (7)$$

with ϕ_{sol} describing the solar gains.

$$\phi_m^t = \frac{A_m}{A_{tot}} \times (0.5 \times \phi_{int} + \phi_{sol}^t) \quad (8)$$

Every parameter described with an H represents a transmission heat transfer coefficient and is given in W/K. All building specific parameters are described in the following equations:

$$H_{tr1} = \frac{1}{1/H_{ve} + 1/H_{is}} \quad (9)$$

with H_{ve} being the ventilation transfer coefficient.

$$H_{tr2} = H_{tr1} + H_w \quad (10)$$

$$H_{tr3} = \frac{1}{1/H_{tr2} + 1/H_{ms}} \quad (11)$$

$$H_{is} = h_{is} \times A_{tot} \quad (12)$$

with h_{is} being the heat transfer coefficient between the air node θ_{air} and the surface node θ_s which equals to $3.45W/m^2K$[1]. A_{tot} denotes the total surface area of the building in m^2.

$$A_{tot} = \Lambda_{at} \times A_f \quad (13)$$

where A_f is the heated floor area in m^2 and Λ_{at} represents the dimensionless ratio between the surface area of all surfaces that face into the space and the heated floor area. Λ_{at} is set to 4.5[3].

$$H_{em} = 1/(\frac{1}{H_{op}} - \frac{1}{H_{ms}}) \quad (14)$$

H_{op} is presenting the heat transfer coefficient through opaque building elements. H_{ms} *is* calculated with the following equation:

$$H_{ms} = h_{ms} + A_m \quad (15)$$

h_{ms} denotes the heat transfer coefficient between the nodes m and *s* and is fixed with $9.1W/m^2K^1$.

A_m is the effective mass-related area in m^2 and is calculated with following formula:

$$A_m = \frac{C_m^2}{\sum (A_j \times k_j^2)} \quad (16)$$

A_j represents the surface area of the building element j in m^2 and k_j represents the specific thermal capacity of a building element j in J/m^2K. C_m is provided in J/K and denotes the total thermal capacity of the building mass:

$$C_m = \sum (k_j \times A_j) \quad (17)$$

$$H_{op} = H_D + H_g + H_U + H_A \quad (18)$$

H_D, H_g, H_U and H_A represent the transmission heat transfer coefficients for direct heat transmission to the external environment (H_D), for the steady-state heat transmission to the ground (H_g), through unconditioned rooms (H_U) and to adjacent buildings (H_A). The calculation of these four parameters is described in the DIN ISO 13789. In the following equation H_X stands for either H_D,H_g,H_U,H_A:

$$H_X = b_{tr,x} \times (\sum_i A_i \times U_i + \sum_k l_k \times \psi_k + \sum_j \chi_j) \quad (19)$$

with U_i being the heat transfer coefficient in W/m^2K for the respective building element *i*.

ψ... linear heat transfer coefficient for a thermal bridge

l... length of a thermal bridge

χ... heat transfer coefficient for a punctual thermal bridge

$b_{tr,x}$... adjustment factor if the temperature on the other side of the component is not equal to the temperature of the external environment

[3] Value taken from DIN ISO 13790

The total ventilation heat transfer coefficient (H_{ve}) is calculated as follows:

$$H_{ve} = \rho_a \times c_a \times (\sum_k b_{ve,k} \times q_{ve,k}) \quad (20)$$

$\rho_a \times c_a$... volume-related heat storage capacity of the air in J/m^3K

q_{ve}... the time-averaged air volume flow

b_{ve}... the temperature adjustment factor for airflow element k. If the supply air temperature is not equal to the temperature of the external environment, $b_{ve} \neq 1$.

Heat pump

Space heating and hot water demand are met by an HP where the coefficient of performance (COP) is dependent on the supply and the source temperature (in K):

$$COP^t = \eta * \frac{T^t_{supply}}{T^t_{supply} - T^t_{source}} \quad (21)$$

η represents a constant efficiency factor and is set to 0.35 for air source HP and 0.4 for ground source HP[4]. For space heating, an average supply temperature (T^{supply}) of 35°C was assumed, and for domestic hot water, the supply temperature was 55 °C. If the HP charges a thermal storage, the supply temperature rose by 10 °C. Indoor temperature was set to be within 20°C and 23°C. For the air source HP the source temperature (T^{source}) was the outside temperature and assumed to be a constant 10°C for the ground source. The maximal electric capacity of the HP was determined by calculating the necessary thermal power of the building and COP at design conditions. In Austria, design outside temperature is around -12°C[26].

Austria's outside temperature and radiation profile is generated by weighting the profiles for every NUTS3[5] region in Austria by their respective residential floor area and taking the average. The data is downloaded from PV GIS[27] for 2019.

Thermal storages

To determine the influence of thermal storage devices on a building to shift electric loads, we simulated a SFH once without any thermal storage device and once with a buffer storage for heating and a tank for domestic hot water (DHW). The size of the DHW storage was chosen to be 400 l, and the buffer storage for heating had a volume of 750 l. Following assumptions were made regarding the hot water storage to keep the model linear:

- The temperature inside the tank is homogenous.
- The temperature surrounding ($T_{tank}surrounding$) the tank is constant at 20°C.
- Thermodynamic properties of the water (volume, heat capacity (c_{water} in $\mathrm{J/kgK}$) and pressure) are constant.

The following equations represent the physical limitations of the hot water tanks:

$$Q^t_{tank} = m_{water} * c_{water} * (T^t_{tank} - T^{min}_{tank}) \quad (22)$$

$$T^0_{tank} = T^{min}_{tank} \quad (23)$$

$$28° \leq T^t_{tank} \leq 45°, 65° \quad (24)$$

$$Q_{loss\,tank} = \Lambda * A_{tank} * (T^t_{tank} - T_{surrounding\,tank}) \quad (25)$$

Q^t_{tank} denotes the energy stored in a tank (J) at a particular hour with m_{water} (kg) being the mass of the water and T^{tank}_t the current temperature inside the tank. T^{tank}_{min} is the minimum temperature inside the tank and was chosen to be 28°C. T^{tank}_0 is the temperature inside the tank at the start of the simulation. The maximum temperature of the buffer heating storage is 45°C and 65°C for the DHW storage. To prevent legionella the DHW tank is regularly heated above 60°C. Both storages have the same insulation with a heat transfer coefficient (U_{tank}) of 0.2 W/m2. The buffer storage and the DHW tank have a surface area (A_{tank}) of 4.6 m^2 and 3 m^2, respectively. Q^{tank}_{loss} describes the thermal losses of the storage.

In the further course, we simulated multiple representative buildings from the Austrian SFH building stock and aggregated the results to the national level.

Model objective

An optimization was developed in Pyomo[28] and solved by Gurobi[6] to minimize the household energy cost. The objective function of the model is to minimize the operation costs over one year on an hourly basis:

$$min\ Cost = \sum_{t=1}^{8760} P^t * E^t \quad (26)$$

With P^t being the electricity price and E^t the amount of electricity bought from the grid at a certain hour. The electricity consumption is composed of fixed and variable components. Fixed components of the electricity consumption are internal loads from appliances and lighting as well as the electricity demand of the HP for hot water generation in case there is no DHW storage. The electricity consumption profile is a synthetic load profile for a single household[7]. The hot water demand consumption rate is assumed to be 90 l per day[29] with an initial temperature of 10°C and a supply temperature of 55°C. The hourly demand profile is taken from the Hotmaps project[30].

[4] η was chosen to make the COP of the HP consistent with data from manufacturers: Bosh, Viessmann, Helios

[5] Nomenclature of territorial units for statistics: NUTS 3: small regions for specific diagnoses. from: https://ec.europa.eu/eurostat/web/nuts/overview

[6] Mathematical programming solver, https://www.gurobi.com/

[7] available under: https://www.apcs.at/de/clearing/technisches-clearing/lastprofile, last visited: 17.11.2022

The variable electric load consists of the electricity demand from the HP. The SEMS can increase the heating demand in a specific timeframe by pre-heating the building and reduce it in the following hours. Additionally, if the building is equipped with thermal storages, they can be charged and discharged at any time. Thus, the SEMS can shift electricity demand for heating even more effectively.

Similar to 4 shifted energy ($E_{shifted}$) in this study was defined as the difference between the electric power consumption profiles with and without DR:

$$E_{shifted} = \int P^t_{Reference} - P^t_{SEMS}\, dt \quad if \quad P^t_{Reference} > P^t_{SEMS} \tag{27}$$

$P^t_{Reference}$ denotes the electric load from the grid in the reference case and P^t_{SEMS} the load with a SEMS installed. If P^t_{SEMS} is higher than $P^t_{Reference}$ the building is being pre-heated or storages are charged. Likewise the energy is shifted whenever $P^t_{Reference}$ is higher than P^t_{SEMS}. Naturally the shifted energy is is lower than the energy used to charge storages and building mass due to thermal losses.

The reference model cannot shift any loads. Heating demand is calculated based on the same 5R1C approach with the assumption that the air temperature inside the building should not drop below 20°C. The HP then provides the needed heating power to keep the temperature at 20°C with the corresponding COP. As there is no non-smart logic on when to fill and discharge a thermal storage based on the variable price, the reference model does not adapt thermal storages.

Austrian building stock

To capture the possible impact of price incentivized load shifting of the Austrian SFH building stock, we coupled our model to the INVERT/EELab building stock model[11]. In this database, the SFH building stock in Austria is represented by 36 building categories. Each category represents a typical SFH built in a certain time period and its overall thermal insulation properties. The different representative buildings and the installed number of HP in each category are presented in Figure 3. More information about the buildings is provided in Table 1. The appendix "mon" indicates that the buildings are under protection. Gen2, gen3, and gen4 indicate that these buildings have undergone a certain renovation, with higher numbers representing more recent renovations. We can see that most HPs have been installed in modern buildings. Overall Austria has around 1.55 million SFHs out of which 180 000 have a HP installed[8]. In 2023, the Austrian federal government implemented strong incentives for exchanging oil and gas boilers with HPs by subsidising installation costs up to 75%.

[8] Statistik Austria: https://www.statistik.at/

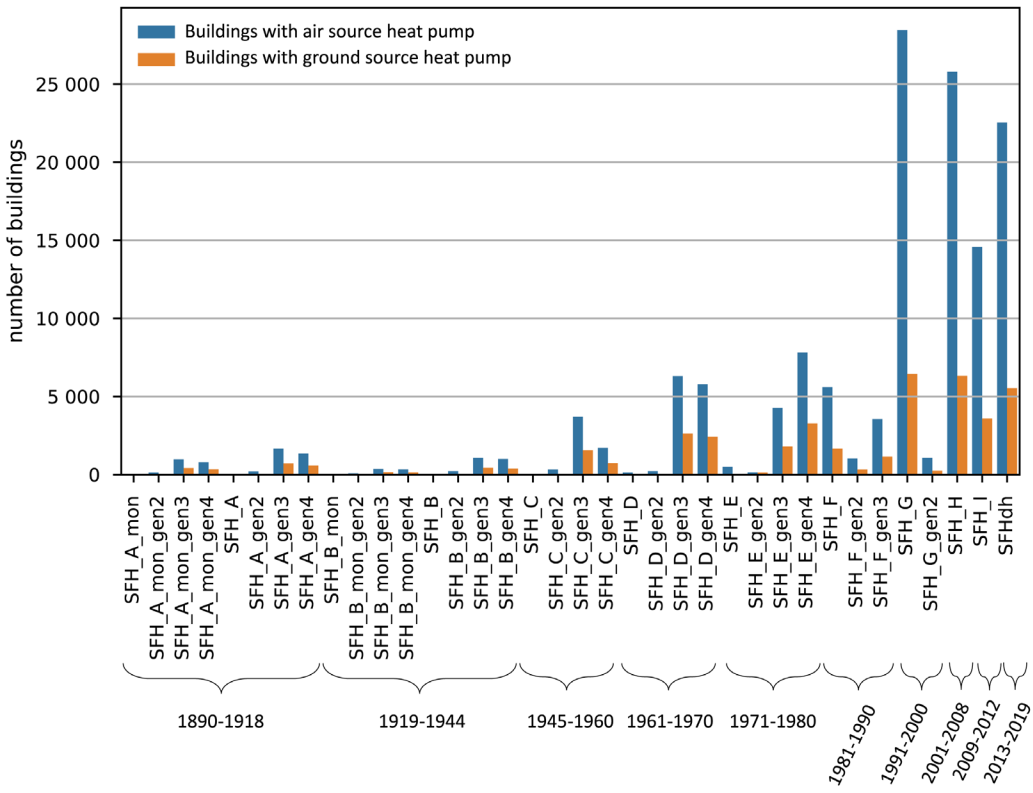

Figure 3. Number of buildings with HPs ins the Austrian SFH building stock[11].

Table 1. Building IDs with 5R1C parameters[11].

ID	Name	Generation of renovation	Age class	A_f (m²)	H_{ve}	H_{op}	$H_{tr,w}$	C_m (mio. J/K)
1	SFH A mon	-	1890–1918	129	36	229	101	53
2		1				242	87	
3		2				250	78	
4		3				198	76	
5	SFH A	-	1890–1918	129	36	227	101	53
6		1				241	87	
7		2				250	78	
8		3				164	67	
9	SFH B mon	-	1919–1944	136	38	290	116	46
10		1				306	100	
11		2				316	89	
12		3				206	78	
13	SFH B	-	1919–1944	136	38	288	117	46
14		1				305	100	
15		2				316	89	
16		3				189	74	
17	SFH C	-	1945–1960	144	41	278	116	31
18		1				295	99	
19		2				304	89	
20		3				183	70	
21	SFH D	-	1961–1970	154	44	193	95	33
22		1				206	82	
23		2				212	77	
24		3				150	68	
25	SFH E	-	1971–1980	163	46	204	101	35
26		1				214	90	
27		2				226	79	
28		3				159	71	
29	SFH F	-	1981–1990	166	46	141	79	35
30		1				149	71	
31		2				142	69	
32	SFH G	-	1991–2000	170	48	120	71	31
33		1				122	68	
34	SFH H	-	2001–2008	170	48	90	59	19
35	SFH I	-	2009–2012	170	48	87	62	19
36	SFH dh	-	2012–2019	170	48	59	47	19

Thus it is expected that the share of SFHs with a HP will increase significantly within the next years[9]. Thus, it is expected that the share of SFHs with a HP will increase significantly within the next years. However, in the following analysis we did not change the total amount of heat pump operated buildings nor the characteristics of the building stock itself. Otherwise the resulting shifted electricity would heavily dependent on the chosen building stock scenario and not on the electricity price itself. From Figure 3 we can see that most buildings with heat pumps installed are modern buildings. The chosen 35°C for the supply temperature for all buildings is too low for the old buildings. This simplification however, does not change the results. A higher or lower efficiency of the heat pump reflects itself in the annual heating costs of a building and can therefore also be interpreted as a change in mean electricity price. For the optimization however, only the relative change from one hour to another in price is relevant.

Complete data on the buildings including window areas are provided in 31 in the "Variable_Price_Paper.sqlite" file under the table name "OperationScenario_Component_Building".

Electricity price scenarios

The electricity price is the driving factor of the energy cost minimization problem. In future decarbonized electricity systems, a higher price variance on electricity spot markets is expected for systems with very high shares of renewable generation[3]. This is because of more hours with spot prices close to zero due to very high shares of renewable generation with low variable generation costs. In times of low renewable generation and high load on the other side, flexibility options at higher costs like dispatchable generation units, storage discharge, or import set the marginal price, which results in relatively high spot prices. The Austrian electricity system for 2030 was modeled with the bottom-up energy system model Balmorel[9,10] to reflect such a decarbonized power system with higher price variance. In Balmorel we modeled the Austrian electricity and district heat system as well as the neighboring countries Czech Republic, Germany, Hungary, Italy, and Slovenia to capture export and import dynamics. Installed generation capacities, national electricity demand, and net transfer capacities were based on the Ten-Year Network Development Plan (TYNDP) 2020 National Trends scenario.[10] For Austria, the assumptions were based on the national energy and climate plan WAM scenario[11] and were refined to reflect the 100% renewable target (nationwide in annual balance terms) until 2030. That means that Austria meets its goals defined in the renewable expansion act[32] and becomes a net exporter of electricity. The installed capacities in Austria for these simulations are depicted in Table 3 in the Annex. All electricity generated by natural gas is exported (on annual balance). The model with input parameters has been tested and validated in 33,34. Within these system boundaries, electricity demand and supply are matched within a market model, considering supply costs following the merit order principle under the assumption of a perfectly competitive market. It is not determined specifically in which type of market the transactions take place economically. The marginal cost of supplying power demand are derived which can be interpreted as the geographically specific market price of power in the model output.

The aim is to reflect various electricity market settings where different price patterns occur. We modeled three price scenarios to analyze sensitivities differing in the assumed CO_2 price. The CO_2 price influences the high-price hours when gas-fired units in this system define marginal costs. However, this could be any other flexibility option (eg. hydro pump storage) at a high price level in a different market setting. It should be noted that the flexibility provided by the HPs in the building stock were not considered in the Balmorel calculation. An investigation of the impact of HP flexibility on the electricity price was done in 3.

In total four different electricity profiles were investigated in this study to establish a relation between the volatility of the electricity price and the shifted load by the building. The first profile is Austria's actual day-ahead electricity spot price 2021 from ENTSO-E[12]. The other three prices were modeled with Balmorel. To every price profile a hypothetical fixed grid fee plus taxes of 20 cents/kWh were also added in order to derive the retail electricity price.

The resulting mean plus standard deviation for all price profiles are provided in Table 2. With an increasing CO_2 price, the price profile's mean value and volatility increase. All prices are depicted in Figure 4. The sharp increase in Price scenario 1 is due to the gas shortage at the end of 2021.

In Figure 5 the daily peak-to-peak amplitude difference of all four prices is visualized. The peak-to-peak difference[13] in the day ahead price from 2021 increases drastically throughout

Table 2. Mean and standard deviation of the price scenarios and CO_2 price as well as the number of local maxima in the profile.

Price scenarios	mean (cent/kWh)	CO2-price (€/tCO_2)	Number of local maxima
Price 1	30.69 ± 7.76	-	1225
Price 2	26.05 ± 2.27	53	621
Price 3	28.87 ± 3.52	106	646
Price 4	34.11 ± 6.35	212	618

[9] https://www.oesterreich.gv.at/themen/umwelt_und_klima/energie_und_ressourcen_sparen/1/raus_aus_oel.html

[10] available under https://tyndp.entsoe.eu/, last vistited: 29.06.2022

[11] Umweltbundesamt, last visited: 17.11.2022

[12] available under: https://www.entsoe.eu/, last visited: 29.06.2022

[13] The maximum peak-to-peak difference is defined as the difference between the lowest and the highest value within a day.

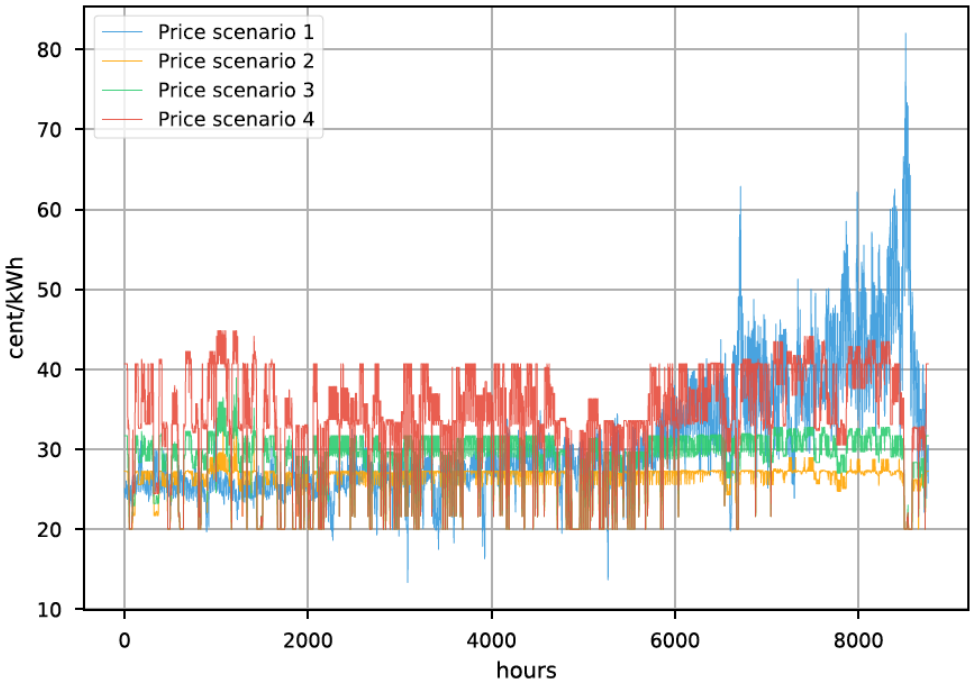

Figure 4. Electricity prices.

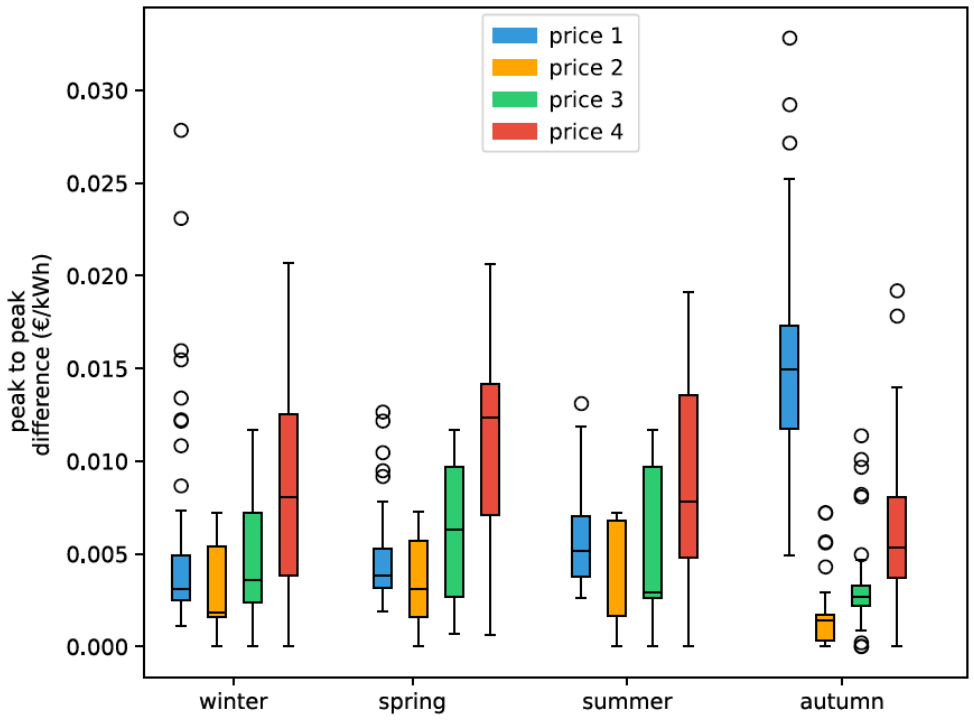

Figure 5. Box plots of seasonal effect in electricity price based on daily peak-to-peak amplitude difference. Box plots show the median (horizontal line) and the interquartile range (IQR) (box outline). The whiskers extend from the hinge to the highest and lowest values within 1.5 × IQR of the hinge, and the points represent the outliers.

the year. In the modelled prices for 2030 incisive events, like energy shortages, are not considered, thus the prices were not fluctuating that much throughout the year.

Another significant difference between the 2021 real time price and the simulated prices is the frequency of change. It is visible in Figure 4 that price 1 is changing more frequently than the others. Table 2 shows the number of local maxima in the respective price profiles. The price from 2021 has about twice as many peaks as the prices from 2030 (price 2, 3 and 4). In this work, we focus on volatility in terms of price spread. Structural price volatility in the form of higher frequency can also significantly impact the potential of load shifting. Studies showed that HPs could participate in the intra-day and even the frequency regulation market[35,36]. But in order to participate in the regulation market they need to be pooled in order to reach the necessary capacity[37]. In this study we do not consider participation of residential HPs other than the day ahead market. Thus price frequencies are limited to hourly changes. Although the thermal inertia of a building is slow, high frequency of price change generally results in higher cost savings for HPs if they react to the price signal.

Another factor that drives the optimization is the outside air temperature in case of an air source heat pump. However, the change in COP due to the change in source temperature is negligible in comparison to the electricity price when it comes to load shifting incentive.

In the following chapter we will first present the results on single building level before moving to the aggregated results on national level. The single building chosen to investigate the single load profiles is a typical modern SFH in the Austrian building stock, built after 2010. The building has a floor area of 170 m^2 and a useful energy demand for space heating of 45 W/m^2. The thermal capacity of this building is low and the insulation level high compared to older buildings in the building stock. Then the same building is simulated with a 400l DHW storage and a 750l space heating buffer storage to show the difference in load shifting potential by implementing thermal storages.

4. Results and discussion

The data for all results describe in the following chapters is available at 31.

Results of individual households

In this section, the effects of different RTP schemes on an individual household optimization are analyzed.

In Figure 6 the grid electricity demand for a household in the 12th week is visualized. The three load profiles represent the load if no load shifting is happening (reference), load

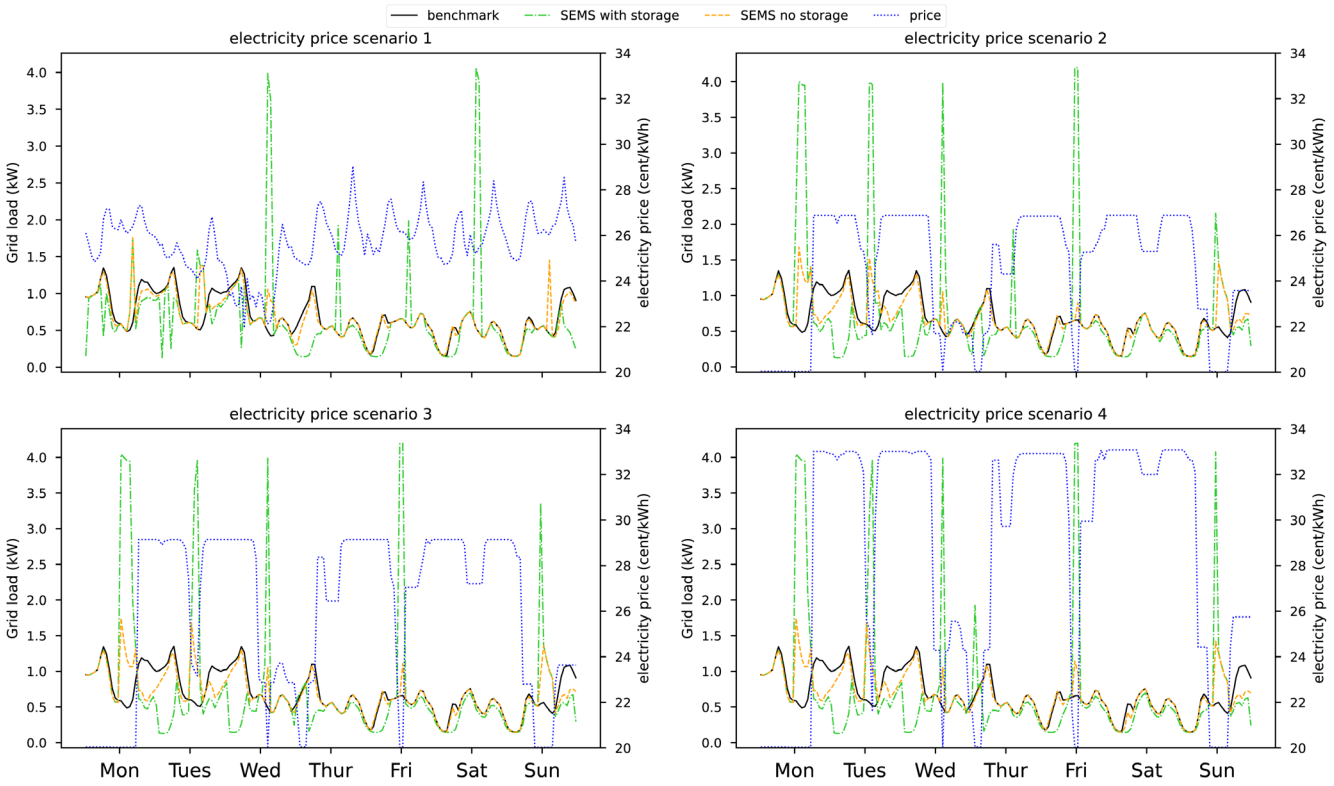

Figure 6. Electricity bought from the grid with and without SEMS in the 12th week of the year. The electricity price is visualized on the right-hand axis.

shifting without any thermal storage (SEMS no storage) and load shifting with a DHW and heating buffer storage (SEMS with storage). On the right-hand y-axis, we see the electricity price profile. We chose the 12th week because during this period price 1 is similar to prices in the years prior to 2021.

Looking at the price scenarios 2, 3, and 4 we see that the higher price difference only increases the incentive to shift loads marginally when thermal storages are available. A change of 6 cent/kWh is enough to charge the thermal storages with the HP. Without thermal storage the peak loads during low energy price times, are limited by the maximum indoor set temperature. With higher price volatility the building is pre-heated to a greater extend if possible.

Figure 7 shows the amount of electricity bought at a specific price. In the reference case electricity is bought independently from the price. But when the household was optimized, electricity was bought at lower prices and demand was reduced at higher prices. In price scenarios 2,3, and 4 the amount of electricity purchased from the grid when the price is at its lowest almost doubles when the household has the thermal storages implemented. Even without thermal storage, the increase in electricity consumption at lower prices and the decrease at higher prices are visible.

The maximum average indoor set temperature was varied between 23, 25, and 27°C during winter to investigate the sensitivity of the allowed indoor set temperature bandwidth for pre-heating. Figure 8 shows that higher electricity price volatility increases the incentive to shift energy by pre-heating the building. Comparing the price scenarios 1 to 2,3 and 4, we see that price 1 creates a greater incentive to shift load than price 2 and 3 without the thermal storage. This is due to the nature of the price profiles. Price 1 is changing much more frequently than the other 3 prices. But with the implementation of thermal storages shifted demand is much higher in the price scenarios 3 and 4 and even in price 2 the shifted energy is almost as high as in price 1. The thermal storages compensate for the lower frequency of price changes by storing much more energy in a short period of time. The correlation between the allowed indoor temperature bandwidth and the energy shifted by the optimization is not linear because of the increase in thermal losses with higher indoor temperatures.

If the building has installed thermal storages, the shifted energy rises to around 450 kWh/year in the first price scenario. This result is in line with 4 where a building with 310 m² floor area, 2000 l buffer storage, and 400 l DHW storage shifts a maximum of 1370 kWh of electric energy. The allowed indoor temperature is still impacting the total amount of shifted load even though the load shifting is done predominantly by the storages. The amount of energy that is shifted with the implementation of thermal storages is by a multitude higher in this case. The absolute amount of

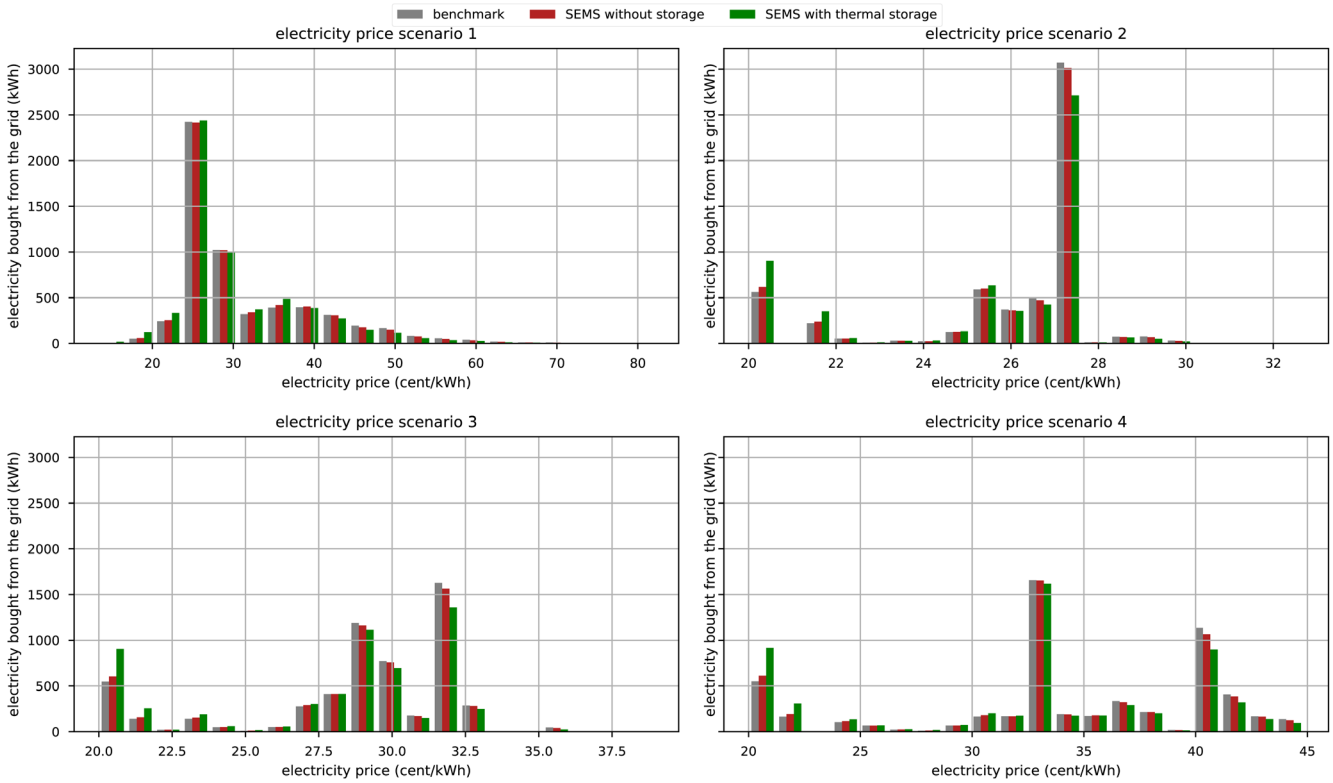

Figure 7. Electricity demand at certain prices in the reference case and with the implementation of SEMS. "With thermal storage" indicates that the house has a 750 l buffer storage and a 400 l DHW storage.

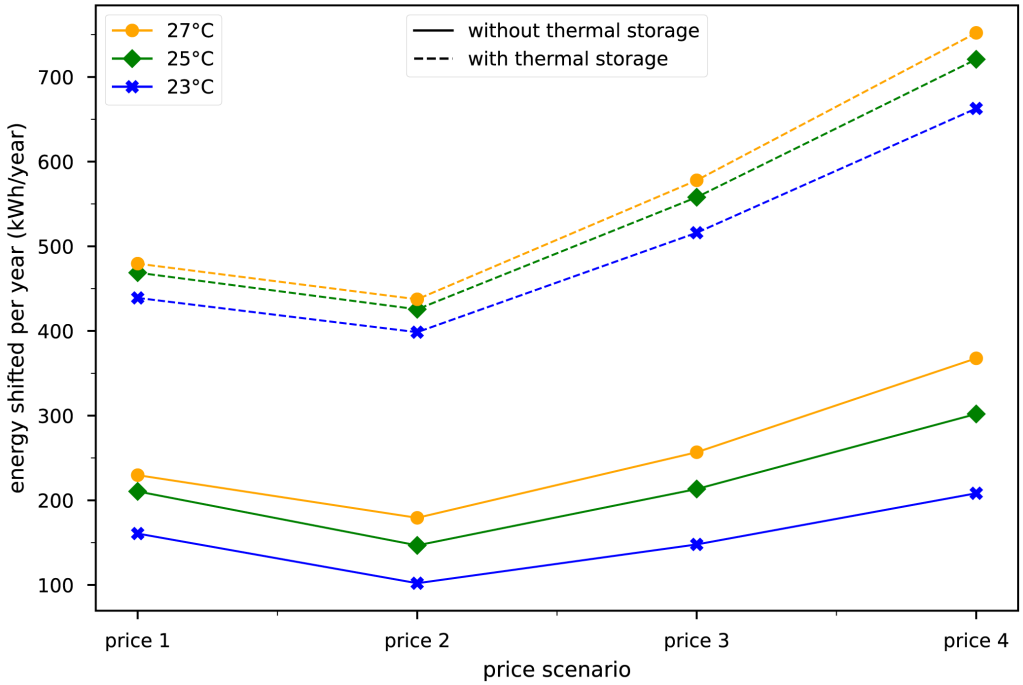

Figure 8. Energy shifted over one year in the building with no thermal storage and the building with DHW storage and buffer storage. The temperatures represent the maximum allowed indoor temperatures during winter.

shifted energy through thermal storages is almost independent of the building type. Buildings with higher thermal mass and higher energy need, can shift more electricity through the thermal mass. However thermal storages are always prioritized for load shifting because the losses are smaller. Thus any price change which would incentivise a house to pre-heat will give an even higher incentive to shift load *via* the thermal storage. Although thermal storages efficiently shift energy with minimal losses, using a building's existing thermal mass provides a low-cost way in terms of investment costs if storages are not already installed.

In Figure 9, the annual operation cost savings for each building type are visualized without any thermal storage. With a higher volatility in price change, the economic optimization of HP becomes more lucrative. The optimization is less lucrative for modern buildings. These buildings are characterized by lower thermal mass and a higher degree of insulation. Thus, they have a much lower heat- and electricity demand. The same reason accounts for the difference between air source and ground source HP since the ground source HP is more efficient. Because of the high volatility in the 2021 price profile at the end of the year, the implementation of a SEMS is more lucrative in the buildings compared to the second price profile. A sensitivity analysis showed, that with prices prior to 2021, economic gains through the SEMS were always lower than in the second price scenario. The annual operation cost reductions are generally between EUR 2 and EUR 23 depending on the price profile and the energy demand of the house. If these buildings adapt a 750l heating buffer and a 400l DHW storage, the cost reductions would rise between EUR 5 and EUR 95 without taking any investment costs into account. Therefore, implementing a SEMS into buildings that would use only the thermal mass storage for demand shifting must be very cheap (between 10€ and 100€, depending on the building type) to yield return of investments after, for example five years. Without additional monetary incentives, homeowners are unlikely to tap into the potential of load shifting through the thermal mass alone. This finding is in accordance with other studies that suggest that the additional investments by individual buildings will not be compensated by participating in DR[38].

Upscaling to the building stock

In this section, the potential load shift for the whole SFH building stock in Austria is presented in dependence on the four electricity price signals. The used methodology however can be applied to any other European country.

The total amount of electricity shifted over one year in each price scenario is visualized in Figure 10 on the left side. In this case only the thermal mass of the buildings is used for load shifting. The potential of the building stock to shift load *via* HPs is around 20 GWh when considering the price from 2021. This corresponds to approximately 1.5% of the electricity consumed by these households within the same time period. The increasing volatility in price scenarios 2, 3 and 4 leads to a significant increase in electricity being

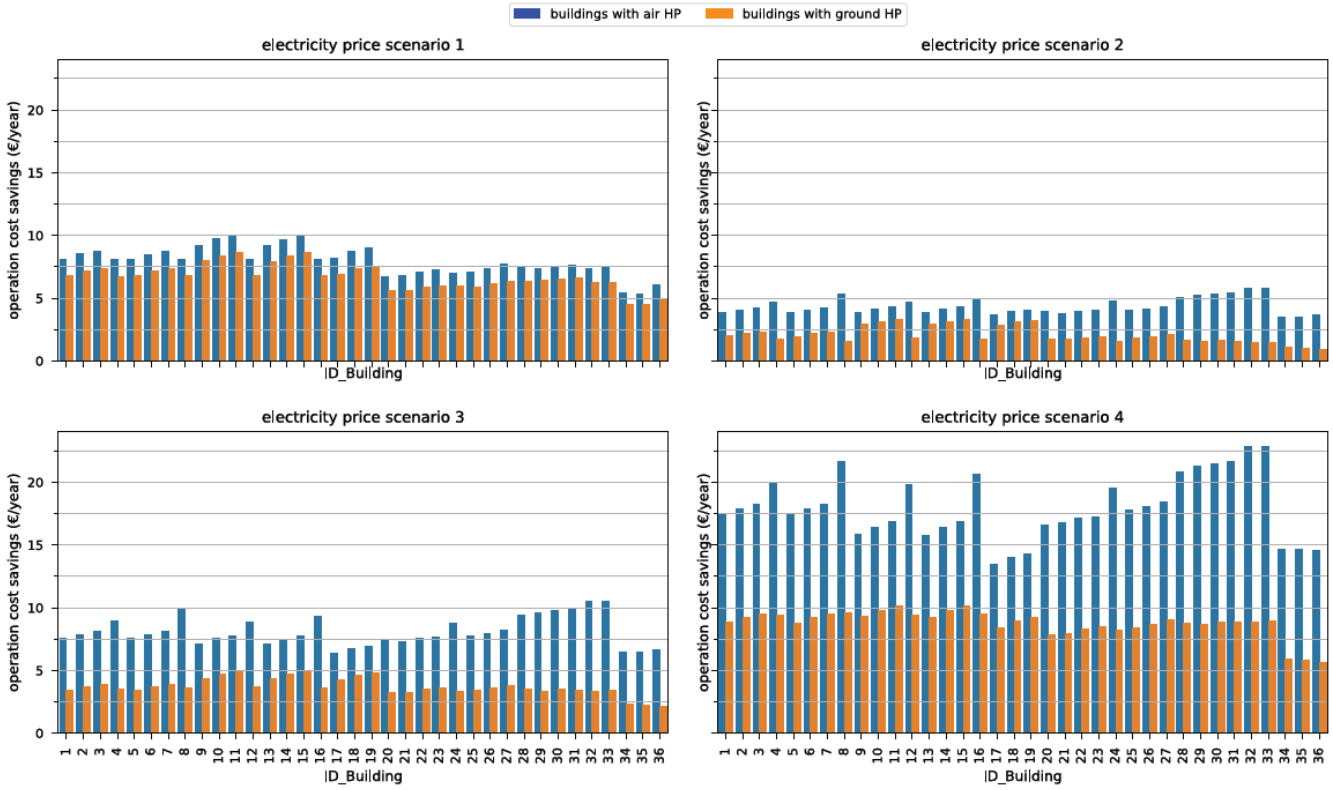

Figure 9. Operation cost savings per building type and HP type in all four electricity price scenarios.

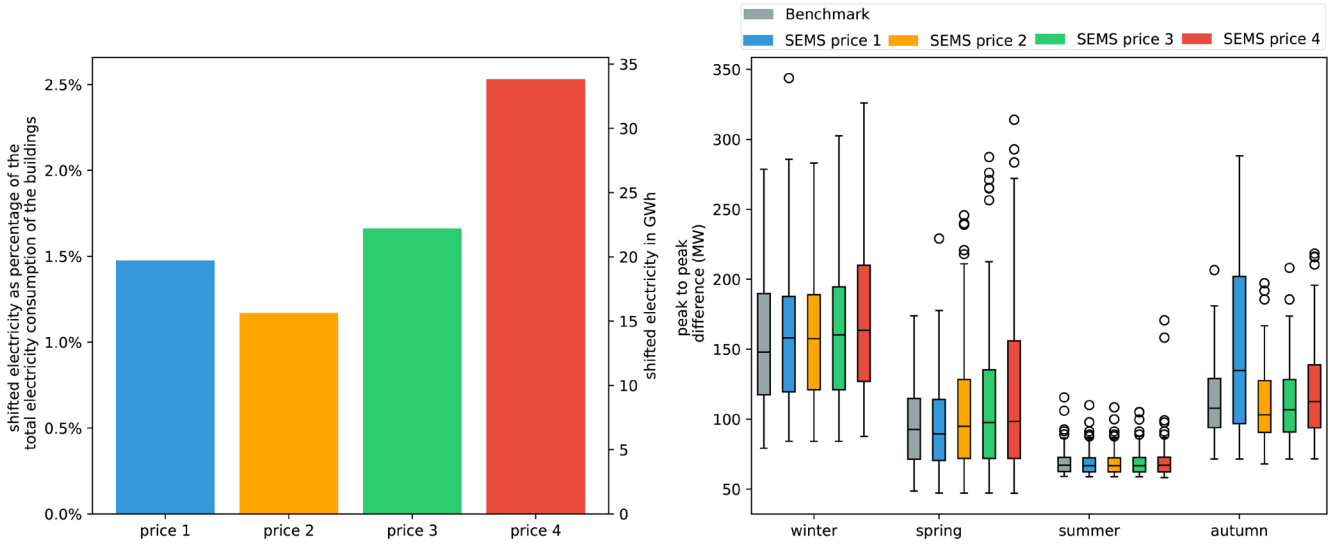

Figure 10. Left: Amount of electricity shifted throughout the year based on the different price scenarios. Right: Box plots of seasonal effect in grid demand, based on daily peak-to-peak amplitude difference. Box plots show the median (horizontal line) and the interquartile range (IQR) (box outline). The whiskers extend from the hinge to the highest and lowest values within 1.5 × IQR of the hinge, and the points represent the outliers.

shifted showing that variable price profiles can give an increasing incentive to shift loads. On the right hand side of Figure 10 the maximum daily peak-to-peak difference of the aggregated load profiles of SFH with HP in the Austrian building stock is visualized. The reference case represents the peak-to-peak demand for the case of no DR. In literature,

it is often mentioned that load shifting will result in an even higher peak demand[14] [14]. In the resulting aggregated load profiles, this effect is only marginally visible except in autumn. The electricity price in 2021 was becoming so volatile and high that daily peak-to-peak loads were significantly higher than the reference and all the other scenarios. The peak-to-peak difference of all HP heated SFH buildings in Austria reached a maximum of 350 MW. The peak demand in the Austrian grid was in the magnitude of 80 GW. Therefore potential of the shifting electricity through the thermal mass of SFH was small but not neglect-able.

As shown before, buildings with implemented storage capacities can shift a lot more electricity. To see how strongly storage capacities can influence the peak-to-peak difference on a daily basis and the overall shifted demand we generated a scenario where every single building with a HP has a 750l heating buffer storage and a 400l DHW storage. The real market penetration of hot water storages in HP operated buildings in Austria is unknown. The following results serve as a reference. In Figure 11 we can see that the peak-to-peak difference is more than two-folding compared to the reference, reaching 700 MW. Also peak demand is reached throughout the year independent of the price scenario. However the occurrence of high peak-to-peak demands increases with increasing price volatility. The total amount of electricity shifted rises to 74 GWh in price scenario 1 which is almost four times higher than without thermal storage capacity.

The results show that HPs can effectively shift electricity through the thermal mass. Peak loads increase only marginally for buildings without any storage capacity. Thermal losses that occur when pre-heating a building significantly limit the maximum peak power from an economic perspective when optimizing such buildings' heating demand. However, with available storages the peak-to-peak demand can more than double. This is especially relevant when HP penetration in a certain region is very high, and HPs are operated with the same strategy. This problem can be avoided by providing different price incentives for users. It is therefore crucial that the price signal reflects electricity scarcity in such a system. Overall the results show that there is significant potential for DR in the residential building stock. This potential can increase even further in the future depending on decarbonisation ambitions and energy scarcity. Furthermore, the potential for the thermal mass is bigger if temporarily cooling down buildings to a certain temperature (*e.g.* 18°C) is considered as well.

5. Conclusion

The findings in this paper indicate that through the use of RTP in HP operated SFH, large amounts of the electricity can be shifted by the use of thermal mass. An increase in the volatility of such RTP naturally increases the incentive to shift demand. In the year 2021, SFHs in Austria with HPs would shift 19.7 GWh of electricity to lower operating costs if an SEMS was installed without considering any kind of thermal or electrical storages. If thermal storages are considered this amount could be more than doubled. Increasing the volatility of price changes increases the amount of shifted electricity. However, the fiscal incentive to shift demand is unlikely to trigger investments for additional equipment to participate in DR. The installation costs of such an SEMS would strongly impact the decision to implement it. For a single building yearly savings are between EUR 2 and EUR 23 (without thermal storage) and EUR 5 and EUR 95 (with thermal storage) depending on the RTP and the building

[14] The peak demand is the maximum demand in a given time interval.

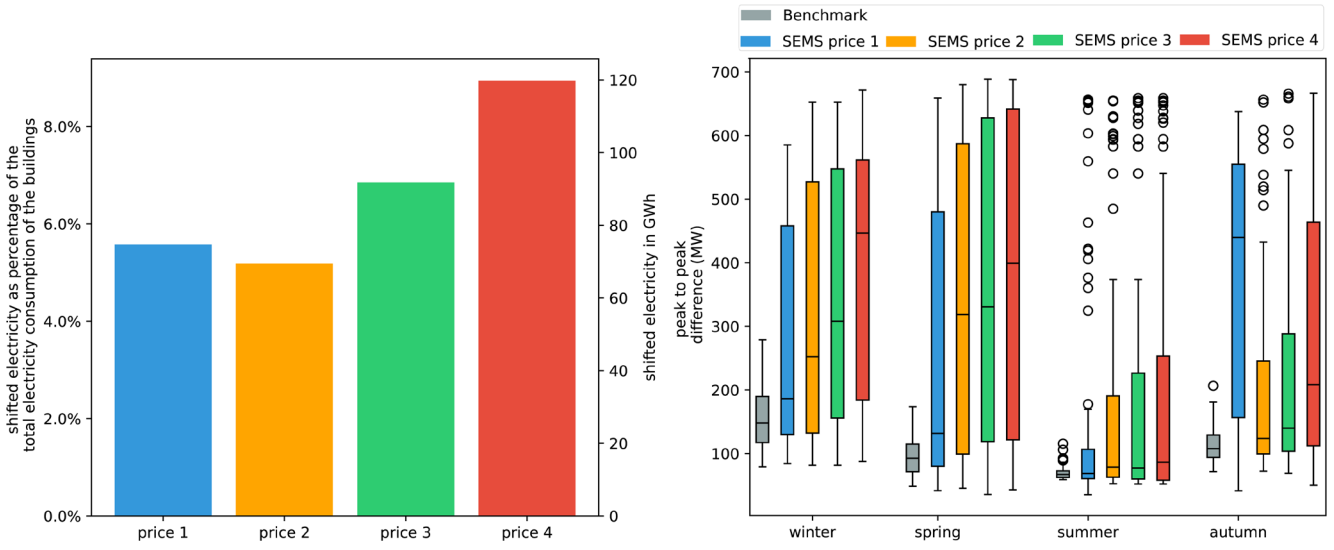

Figure 11. Left: Amount of electricity shifted throughout the year based on the different price scenarios with buildings having thermal storages. Right: Box plots of seasonal effect in grid demand, based on daily peak-to-peak amplitude difference. Box plots show the median (horizontal line) and the interquartile range (IQR) (box outline). The whiskers extend from the hinge to the highest and lowest values within 1.5 × IQR of the hinge, and the points represent the outliers.

parameters. Further, we showed that the economic optimization of current buildings in the building stock is slightly more lucrative for buildings with higher energy demand. Comparing the peak-to-peak difference of the resulting profiles in the Austrian SFH building stock with HPs, higher peak loads can be expected when optimizing the HP based on a price profile. However, the effect is limited for buildings without storage devices. Further, the resulting peak loads of individual buildings will have to be compared to the overall electricity demand in the region.

One limitation of this paper is the neglect of changing prices due to load shifting by the buildings. A large penetration of HP-operated buildings that shift loads could lead to a self-cannibalism effect. Further, the possibility of extending the thermal comfort within the buildings down to 18°C for a short period of time would generate additional load shifting potential. The real amount of heating buffer and DHW storages has not been considered for the whole building stock due to the lack of data. Therefore, our results can only serve as a reference to evaluate the impact of SEMS on load shifting. Another aspect that will be considered in further studies are multi family buildings and photovoltaic installations combined with HP. A photovoltaic system would decrease the electricity consumption from the grid and, at the same time, increase the profitability of a SEMS because the SEMS will increase the self-consumption rate of the photovoltaic system.

6. Ethics and consent

Ethical approval and consent were not required.

7. Data availability

Underlying data

Zenodo: Results from the FLEX Model for the paper "Impact of variable electricity price on heat pump operated buildings" https://doi.org/10.5281/zenodo.7299360[31].

This project contains the following underlying data:

- Variable_Price_Paper.sqlite (Contains the input data and results for the scenario without any storage capacities.)

- Variable_Price_Paper_SFH_23.sqlite (Contains the input data and results for the single building with a maximum indoor set temperature of 23°C during winter.)

- Variable_Price_Paper_SFH_25.sqlite (Contains the input data and results for the single building with a maximum indoor set temperature of 25°C during winter.)

- Variable_Price_Paper_SFH_27.sqlite (Contains the input data and results for the single building with a maximum indoor set temperature of 27°C during winter.)

- Variable_Price_Paper_TS.sqlite (Contains the data for model input and results for the scenario with the 750l heating buffer storage and the 400l DHW tank.)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

8. Software availability

Source code available from: https://github.com/H2020-newTRENDs/FLEX

Archived source code at time of publication: https://doi.org/10.5281/zenodo.7330631[25]

License: MIT

9. Author contributions

Conceptualisation – Philipp Mascherbauer, Lukas Kranzl, Songmin Yu, and Franziska Schöniger; Methodology, formal analysis, writing – Philipp Mascherbauer, Songmin Yu, and Franziska Schöniger; Supervision and review – Lukas Kranzl, Songmin Yu; Methodology review and editing – Songmin Yu and Lukas Kranzl. All authors have read and agreed to the published version of the manuscript.

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Version 2

Reviewer Report 10 January 2025

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✔ **Patrik Schönfeldt**
DLR Institute for Networked Energy Systems, Oldenburg, Germany

Summary
The paper analyses the effect of (hypothetical) economically optimal operation of heat pumps considering the thermal inertia of the building. The authors find that a significant share of the electricity demand of buildings can be shifted that way. However, the individual savings only due to dynamic pricing following the day-ahead electricity market are marginal and will probably not justify the installation of energy management systems.

Overall impression
Structure, sound and story line of the paper are concise and easy to follow. There are very limited inconsistencies in the formatting but they are not so severe that they distract from the content.

Aspects that might profit from further comments

1. Page 5: You mention an hourly model. While this is aligned with the day ahead electricity market, it might remain unclear to the reader if the resolution is sufficient to model the thermal system.
2. Page 5: Commenting on cooling demand of the equivalent circuit models of the building might be distracting, as cooling is not part of the current study. As, however, heat pumps can be used for cooling, arising difficulties for future studies (e.g. in warmer climate) might be pointed more explicitly.
3. Page7: A constant energy demand sounds overly optimistic, as gains below average are to be expected for the night (less use of appliances, less activity of the inhabitants).
4. Page 8: The Approximation of the COP using a constant Lorentz efficiency (Eq. 21) tends to largely deviate from more accurate models. In particular, the COP is underestimated for high temperature deltas and overestimated for low temperature deltas [cf. Ref-1]. Additionally, combined with the time resolution, part-load efficiency might have a significant effect. (Please estimate the order of magnitude.)
5. Page 8: Regularly heating above 60 °C is only one method to prevent Legionella, especially for single family houses using heat pumps it is probably less prevalent when compared to apartment blocks. [I have no citable statistics, however.]

6. Page 8: A demand of 90 Liters at 55 °C sounds rather high. That would convert to 180 Liters with a (still warm) tap temperature above 30 °C. (Unluckily, I do not have access to the cited norm.)
7. Page 9/ 10: To estimate the potential with higher adoption of heat pumps, the total number of buildings in the classes (including also those with other heating systems), would be an interesting addition (e.g. to Table 1).
8. Page 11 ("Otherwise the resulting shifted electricity would heavily depend ..."): The resulting shifted electricity also heavily depends on the scenario if you choose the status quo as your scenario. In particular, assuming an unchanged building stock for 2030 is probably worse than a badly assumed renovation rate.
9. Page 11: The statement about the chosen supply temperature of 35 °C to be "too low for the old buildings" is too general. The needed temperature also depends on the area of the radiators (or floor heating). In particular, if the building hull is improved, even existing radiators can be large enough to reduce the supply temperature to the given level. Even if this is not the case, using a heating curve with a flow temperature depending on the demand is state of the art, so 35 °C is even realistic for a major time of the year for partly reconstructed buildings e.g. Ref-(2).
10. Page 11, Table 2: The lower number of local maxima might be caused by the fact that there are flat plateaus in the synthetic merit order.
11. Page 15: While thermal storage has lower losses, charging it should require higher temperatures compared to space heating. Please comment on the effect of the reduced COP. There should be a point in time at the end of the time-widow for demand-shifting, when increased losses (time-dependent) are preferable over the reduced COP (one-time effect).
12. Page 15: Consideration of PV (for future work) might also be mentioned already here and not just in the summary.
13. Page 17: Existing storage tanks (esp. for solar thermal use in existing building stock) might be mentioned before the summary already.

Suggestions for formatting

1. Page 6ff: Use of italic writing in the symbols is not consistent between Figure 2 and Equations. In the figure, upright letters are used for parameters and italic ones for variables. This formatting that could be adapted for the Equations.
2. Page7: In the line above Eq. 14, footnote 3 might be confused with an exponent.
3. Page 8: Starting from Eq. 20, the asterisk (*) is used for multiplications. Before, the times-symbol (×) was used.
4. Page 8: Index typesetting of Q_{loss,tank} is inconsistent with later text (Q_{loss}^{tank}).
5. Page8: Before Eq. 26, you change from active verbs to passive ones. (Before, "was developed" indicated it was not your work. But I assume that you implemented the model.)
6. Page 9: A cleaner formulation of Eq. 27 might include "P_ref - min(P_ref, P_SEMS)" instead of the "if".
7. Page11 (""In total four different electricity profiles were investigated): This is passive again, although you performed the study.
8. Page 11ff: It might be a good idea to give more speaking names than scenario 1, 2, 3, and 4. Names like "2021", "2030 low", "2030 medium", "2030 high" wuld make it easier to follow.
9. Page 15: Spaces are missing in "750 l" and "400 l". (Units were correctly typeset before.)

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Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: energy system optimisation, energy system modelling, thermal energy systems, sector integration

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 17 January 2023

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Wiebke Meesenburg

Section of Thermal Energy, Department of Civil and Mechanical Engineering, Technical University of Denmark, Lyngby, Denmark

The presented paper investigates the load shift potential of single-family houses equipped with heat pumps in Austria by demand side management. The analysis is based on the Austrian single family building stock, Austrian temperature profiles and historic electricity prices as well as electricity price forecasts for the year 2030. The authors conclude that the load shift of the overall building stock without thermal storages in the buildings is small compared to the overall electricity demand in Austria but not negligible. When equipped with thermal storage for domestic hot water and space heating the buildings can shift up to twice the load compared to the case without storage. The authors discuss that widely employed demand side management based on real time pricing may lead to local congestions in the electricity grid. Which may have to be taken into account for the design of future tariff structures.

Overall, the paper is well written. The problem formulation is clear and motivated. The research question addressed is highly topical and interesting to different stakeholders not only in Austria, but also in other countries. The method applied is appropriate. The description of the method should however be improved, by a) dividing into more subchapters and b) revision of the part Technology operation model of individual households. I suggest to revise the explanations of all variables (see detailed comments below) and to also add a nomenclature. The presented results are explained clearly and support the conclusions.

Please, also address the following minor comments and suggestions:

Introduction:

1. In the readers guide at the end of the introduction all sections are called “section b”, please revise.

Literature review:

1. The following terms are used without being defined. I suggest to introduce them and clarify how they relate to the terms used in the current paper:
    1. *Flexibility* (page 3, regarding reference [4] Fitzpatrick *et al.*)
    2. *Dynamic time of use pricing* (Is this different to “*real time pricing*” introduced by you?, How?, page 3).
    3. *Direct load control (page 3).*

2. Regarding reference [7] Sperber *et al.*: You write that the maximum shiftable load in German SFH is 57 GW_{el}. Please, specify which number of SFH was considered and for which period of time this load may be shifted.

3. Be consistent with the use of names when referencing literature (sometimes you used only the last names, other times you used both first name and last name (e.g. Gabrielle Masy and Henryk Wolisz).

Method:

1. Figure 1. The model/figure needs to be explained in more detail. "Heat pump" and "thermal storage", "Hot water" are not input parameters. Please, clarify, which input parameters are used for these appliances. In the "model" box: Do "Optimization” and "Reference” refer to

case 1) and 2) described in the text? Please, clarify.

2. Page 5 and 6: It seems to me that the following variables are not explained. Please check:
    1. $\theta_{outside,}$ $\theta_{s,}$ θ_{e}
    2. Φ_{ia}, Φ_{st}
    3. H_{tr1}, H_{tr2}, H_{tr3}, H_{op}
3. Page 6: Is *effective area* and *effectively used floor area* the same?
4. Page 6: Please, add a reference for the assume heat transfer coefficient or specify how they were determined.
5. Page 8: Add a reference for NUTS3 or add an explanation.
6. Page 8. Equation (22). Shouldn't it be T_t^{tank} instead od T_1^{tank}?
7. On page 6 you used t to indicate the time step as a superscript, while on page 8 you use it as a subscript. Please, align to be consistent.
8. Page 8: Add an explanation for why 28 °C was chosen as the minimum temperature in the tank. I would assume this to be higher in practice for domestic hot water tanks (due to risk of legionella growth).
9. Page 8: Specify which Area is meant by A_{tank} and use superscript for writhing m^{2}.
10. Page 8: You write*: Heating demand is calculated based on the same 5R1C approach with the assumption that the air temperature inside the building should not drop below 20°C. The HP then provides the needed heating power with the corresponding COP.*

It does not become entirely clear, whether the heat pump is always providing the load to keep the temperature constant at 20 °C OR does the heat pump turn on when the temperature drops to 20 °C and then heats up the room to an upper threshold temperature? Please, clarify.

1. Page 9: You mention that the electricity price is the driving factor of the energy cost minimization problem. Please, add a description of how the varying COP of the heat pump due to changes in the outdoor temperature influences the optimization.
2. Page 9: What is meant by the following sentence? Please explain in more detail: However, this could be any other flexibility option at a high price level in a different market setting.
3. Page 9: Add a spacing between value and unit (20_cents/kWh).

Results:

1. First paragraph on page 11: I think this paragraph should be moved to the method section.
2. Page 11: Please, argue why you looked into room temperatures of up to 27 °C (this seems very high) and not into lower room temperatures of possibly down to 18 °C.
3. Page 13: Economic results for SFH with and without storage. Please, expand on these

results. Are these annual savings? Were the investment costs for the storages taken into account? What does "relatively cheap" mean?

4. Page 15: Correct the word "*neglect-able*" at the end of the first paragraph.

5. Page 15: Second paragraph. You use the terms *peak demand* and *peak-to-peak demand*. Please introduce both in the context of your results and possibly explain the difference.

6. Page 15: You write: capacity. Thermal losses that occur when pre-heating a building significantly limit the maximum power peak when optimizing such buildings' heating demand. It is not entirely clear to me what you refer to. Please, explain in more detail.

Format:

1. Past tense should be used when writing about your own present work. Present tense should be used when referring to previously published work (Gastel and Day, 2017[1]).

References

1. Gastel B, Day RA: How to Write and Publish a Scientific Paper. *Cambridge University Press*. 2017.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Thermal energy systems, heat pumps, flexible operation of heat pumps, dynamic system modelling, integration of heat pumps with district heating

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 15 Apr 2024

Philipp Mascherbauer

Thank you a lot for the comments! In the following we will answer each comment individually.

1. *Overall, the paper is well written. The problem formulation is clear and motivated. The research question addressed is highly topical and interesting to different stakeholders not only in Austria, but also in other countries. The method applied is appropriate. The description of the method should however be improved, by a) dividing into more subchapters and b) revision of the part Technology operation model of individual households. I suggest to revise the explanations of all variables (see detailed comments below) and to also add a nomenclature. The presented results are explained clearly and support the conclusions.*
    - Thank you for your comments. We addressed them and changed the structure of the chapters, explained the variables and added a nomenclature. The Methodology chapter now has the following subchapters: “Model overview, 5R1C model, Heat pump, Thermal storages, Model objective, Austrian building stock and Electricity price scenario”. We also moved some parts to the respective sub chapters to hopefully make the whole methodology more clear
2. *In the readers guide at the end of the introduction all sections are called “section b”, please revise.*
    - Thank you, this was corrected.
3. *The following terms are used without being defined. I suggest to introduce them and clarify how they relate to the terms used in the current paper:*
    - *Flexibility (page 3, regarding reference [4] Fitzpatrick et al.)*
        - We added the following sentences to explain the term flexibility: “Flexibility in these studies is defined as the amount of energy (electrical or thermal) that is used at a different time than originally anticipated. In this sense flexibility could be interchangeably used with the term load shifting.”
    - *Dynamic time of use pricing (Is this different to “real time pricing” introduced by you?, How?, page 3).*
        - No, it is not different from real time pricing. Thanks for pointing it out, we adapted the wording accordingly.
    - *Direct load control (page 3).*
        - Direct load control refers to a control where the loads of the households are controlled by a third party (eg. The electricity distribution company) to directly manage demand response. We added a short explanation in the text.
4. *Regarding reference [7] Sperber et al.: You write that the maximum shiftable load in German SFH is 57 GWel. Please, specify which number of SFH was considered and for which period of time this load may be shifted.*
    - The study includes the German building stock from (Loga, Tobias, et al. "Deutsche Wohngebäudetypologie." Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden 2 (2015).). From around 18 mio. Buildings 66% are single family houses of which around 2.5% are heated by heat pumps. The period of time is different for each

building type defined, however the 57GWel were achieved by lifting the indoor temperature in the entire SFH building stock by 2°C (20°C-22°C) and letting it cool down again. We added this explanation in the script.

5. *Be consistent with the use of names when referencing literature (sometimes you used only the last names, other times you used both first name and last name (e.g. Gabrielle Masy and Henryk Wolisz).*
    - Thank you! We fixed it and are only citing by last name now.
6. *Figure 1. The model/figure needs to be explained in more detail. "Heat pump" and "thermal storage", "Hot water" are not input parameters. Please, clarify, which input parameters are used for these appliances. In the "model" box: Do "Optimization" and "Reference" refer to case 1) and 2) described in the text? Please, clarify.*
    - We changed Figure 1. Input parameters are now more specific (Heating system type, hot water demand and thermal storage size). Yes "Optimization" and "Reference" refer to the case 1) and 2). We added the description in the text accordingly.
7. *Page 5 and 6: It seems to me that the following variables are not explained. Please check*:
    - *θoutside, θs, θe*
    - *Φia, Φst*
    - *Htr1, Htr2, Htr3, Hop*
        - We checked the variables and included a description in the text of the ones where a description was missing. Also, we added a description of every variable in the nomenclature.
8. *Page 6: Is effective area and effectively used floor area the same?*
    - Yes, thank you for pointing out that this is not clear. The effective area can be interpreted as the conditioned floor area or heated area. We re-phrased the terms to make it clear.
9. *Page 6: Please, add a reference for the assume heat transfer coefficient or specify how they were determined.*
    - The heat transfer coefficient was taken from the norm. We added a reference.
10. *Page 8: Add a reference for NUTS3 or add an explanation.*
    - We added a footnote explaining NUTS3.
11. *Page 8. Equation (22). Shouldn't it be Tttank instead od T1tank?*
    - Yes, thanks. We corrected it.
12. *On page 6 you used t to indicate the time step as a superscript, while on page 8 you use it as a subscript. Please, align to be consistent.*
    - Thank you for pointing that out. We aligned the super- and subscripts.
13. *Page 8: Add an explanation for why 28 °C was chosen as the minimum temperature in the tank. I would assume this to be higher in practice for domestic hot water tanks (due to risk of legionella growth).*
    - Thank you, we added the following sentence: "To prevent legionella the DHW tank is regularly heated above 60°C."
14. *Page 8: Specify which Area is meant by Atank and use superscript for writhing m2.*
    - A is the surface area of the tank. We added a short explanation and use m2 with a superscript.
15. *Page 8: You write: Heating demand is calculated based on the same 5R1C approach with*

the assumption that the air temperature inside the building should not drop below 20°C. The HP then provides the needed heating power with the corresponding COP. It does not become entirely clear, whether the heat pump is always providing the load to keep the temperature constant at 20 °C OR does the heat pump turn on when the temperature drops to 20 °C and then heats up the room to an upper threshold temperature? Please, clarify:

- The heat pump does always keep the temperature constant at 20°C. The room is not pre-heated. We added “The HP then provides the needed heating power to keep the temperature at 20°C…”. Hopefully this makes it clearer for the reader.

16. *Page 9: You mention that the electricity price is the driving factor of the energy cost minimization problem. Please, add a description of how the varying COP of the heat pump due to changes in the outdoor temperature influences the optimization.*
    - Thank you for pointing that out. Indeed in case of an air source heat pump the varying COP is influencing the optimization. But the effect is negligible in comparison with the incentive the electricity price provides since the change in COP is not that pronounced throughout the day. We added a short paragraph explaining this at the end of the electricity price chapter.
17. *Page 9: What is meant by the following sentence? Please explain in more detail: However, this could be any other flexibility option at a high price level in a different market setting.*
    - We mean any other technology that could provide flexibility to the electricity grid like a hydro pump storage. The marginal costs of these flexible power plants would likely also be high. We added the example of the hydro pump storage in the text, to give an example.
18. *Page 9: Add a spacing between value and unit (20_cents/kWh).*
    - Thank you, done.
19. F*irst paragraph on page 21: I think this paragraph should be moved to the method section.*
    - Thank you, we moved it to the “Method” section.
20. *Page 11: Please, argue why you looked into room temperatures of up to 27 °C (this seems very high) and not into lower room temperatures of possibly down to 18 °C.*
    - Yes 27°C is unusually high. We want to show how a bigger temperature bandwidth (3°C, 5°C, 7°C) for pre-heating the building increases the shifted load. To keep this approach simple we always stayed with the fixed 20°C as minimum temperature. A temperature increase from 18°C to 25°C would yield similar results as the 20°C-27°C option with an even slightly higher shifted demand due to lower thermal losses. We added to the text, that we are focusing on the temperature bandwidth: "...to investigate the sensitivity of the allowed indoor set temperature bandwidth for pre-heating."
21. *Page 13: Economic results for SFH with and without storage. Please, expand on these results. Are these annual savings? Were the investment costs for the storages taken into account? What does "relatively cheap" mean?*
    - Yes, they are annual operation cost savings without factoring in any investment costs. We added more details in the text, making the clearer. We also exchanged the term “relatively cheap” with “very cheap (between 10€ and 100€ depending on the building type) to yield return of investments after, for

example five years.

22. *Page 15: Correct the word "neglect-able" at the end of the first paragraph*.
    - Corrected
23. *Page 15: Second paragraph. You use the terms peak demand and peak-to-peak demand. Please introduce both in the context of your results and possibly explain the difference.*
    - Thank you. We added: "The maximum peak-to-peak difference is defined as the difference between the lowest and the highest demand value within a day." and "The peak demand is the maximum demand in a given time interval." as explanations.
24. *Page 15: You write: capacity. Thermal losses that occur when pre-heating a building significantly limit the maximum power peak when optimizing such buildings' heating demand. It is not entirely clear to me what you refer to. Please, explain in more detail.*
    - With higher indoor temperatures the thermal losses rise significantly and the economic incentive to pre-heat the building further and shift more electricity is reduced. This effect caps the peak power consumption from the heat pump. We added to the text that the losses cap the peak power from an economic perspective in the optimization. We hope this is clear now.
25. *Past tense should be used when writing about your own present work. Present tense should be used when referring to previously published work (Gastel and Day, 20171)*.
    - Thanks, we switched to using present tense for the literature we are referring to and past tense for the results of this paper.

Competing Interests: No competing interests were disclosed.

Reviewer Report 12 December 2022

https://doi.org/10.21956/openreseurope.16510.r30465

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Evelyn Sperber
Department of Energy Systems Analysis, Institute of Networked Energy Systems, German Aerospace Center (DLR), Stuttgart, Germany

Summary of report:
This paper analyzes the effects of a cost-minimized heat pump operation considering different thermal storage options and different real time price scenarios, taking the example of Austria. The authors find that large amounts of electricity can be shifted with real time pricing, especially if thermal storages are used and if the volatility of prices is high. However, cost savings for households are limited and thus unlikely to provide enough monetary incentives for participating in Demand Response.

Overall impression:

Introduction:

- Your introduction has a very clear storyline and is very well-structured. The objective of your research is very clear and you did a good job explaining the context as well as the state of research.

- Your case study is limited to Austria. That is okay, but for a better interpretation of results it would be nice if you could inform the reader about the (projected) relevance of heat pumps for Austrian buildings.

Methodology:

- Generally, your methodology description is well-written: it is widely clear, thorough and also clearly states the assumptions made.

- You write: *"And the 5R1C approach has been tested against results from Energy Plus, Invert/EELab and the VDI 6007. They show that the heating demand calculated by the 5R1C model is reasonably accurate, whereas cooling demand is strongly overestimated*." Have you also tested the 5R1C model against Energy Plus etc. regarding the replication of thermal inertia? I think that this point is even more important than the good accuracy regarding the heating demand estimation, as it determines the load shifting potential. Literature gives some hints that 1 C might be not enough to adequately reflect the thermal inertia (see e.g. Bruno *et al.*, 2016[1]).

- I recommend to reconsider the representation of heat pumps in your model. The average supply temperature of 35°C seems very optimistic (very low) for old buildings that are not well insulated, as far as I understand from Figure 1. Is it possible that you vary the supply temperature according to the building type?

- I'm not sure if the COP formula (Equation 21) is correct. Is it possible that the reciprocal value of η should be used? Otherwise COP values below 1 are obtained (for instance if using 35°C supply temperature and 10°C source temperature).

- I found it a bit difficult to follow your objectives and partly methods considering the electricity price scenarios you investigate.
  - Could you please explain how electricity prices are derived from BALMOREL? Does the model incorporate a day-ahead market representation?
  - Is the "benchmark" heat pump operation considered in the load for BALMOREL (to ensure that price patterns somehow reflect the electricity demand of heat pumps?)
  - I find it a bit arbitrary to use 2030 electricity price scenarios without changing the heat pump market penetration compared to 2021. Why do you do so? Is there no large uptake of heat pumps foreseen in Austria for the next years (like in Germany, for example)?
  - I think it would help the reader when you state already at this point that you do not consider changing prices due to load shifting. I think this is an important limitation that should already be addressed in the methodology.
  - Maybe a small explanation regarding the price increase in scenario 1 in the course of the year would be helpful (e.g. refer to gas crisis).

Results:

- Your explanation of the results is generally very clear, and the figures you use are very illustrative. You provide interesting sensitivity analyses, e.g. regarding the maximum average indoor set temperature. It is great that you provide the data of your results!

- You write: *"However thermal storages are always prioritized for load shifting because the losses are smaller."* Also, when having a look at Figure 8, it seems that there is no need to make use of the thermal mass of buildings as the most relevant effect stems from thermal storage. Maybe you should put this a bit into perspective, considering that households have to invest in thermal storages, while thermal mass is available for free.

- As cost savings are quite limited for households, have you considered to further increase price volatility (especially downwards) by providing time-dependent grid fees plus taxes (instead of fixing them at 20 ct/kWh). For instance, if taxes are somehow linked to electricity wholesale prices, the minimum of your prices could fall below 20 ct/kWh, and consequently the use of thermal storage could be increased. I think the load shifting effects in your study are quite small, because real time prices are generally high, and thus storage is not used so much (because use of storage triggers thermal losses that have to be paid). I would at least suggest that you discuss this a little.

Conclusion:

- Your conclusion captures the storyline of the paper, and gives a good overview of what you've done. It is also very good that you address important limitations.

- I only miss some conclusions regarding the load shifting potential when a thermal storage is used. Maybe you can add a sentence?

Additional smaller remarks:

Introduction:

- "*In the benchmark mode, the operation of technologies is simulated based on specific assumptions, […]*" -> Unclear. Do you mean "inflexible", heat demand oriented operation?

- I actually find the wording "benchmark" quite misleading. The terminus implies that this is the best case (in whatever regard). In terms of cost, however, it is "worse" than the SEMS. Maybe you reconsider the wording and instead use something like "baseline" or "reference"?

- "*The remainder of this paper is structured as follows […]*" The following references seem incorrect – they all refer to "section b" which is the literature review.

Results and Discussion:

- *"The benchmark case is directly correlated to the occurrence of the electricity price."* -> I do not understand this sentence. What do you mean by "occurrence of the electricity price"?

Footnotes:

- Footnote 2: little spelling error regarding Bo**s**ch.

References
1. Bruno R, Pizzuti G, Arcuri N: The Prediction of Thermal Loads in Building by Means of the EN ISO 13790 Dynamic Model: A Comparison with TRNSYS. *Energy Procedia*. 2016; **101**: 192-199 Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Energy systems analysis; demand response with residential heat pumps; reduced-order building modeling; optimization

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 12 Apr 2024

Philipp Mascherbauer

Thank you very much for your comments! In the following we will answer below your original comments:

1. *Your case study is limited to Austria. That is okay, but for a better interpretation of results it would be nice if you could inform the reader about the (projected) relevance of heat pumps for Austrian buildings.*
    - Thank you, we added an additional paragraph explaining the projected relevance of heat pumps for the future Austrian building stock. “In 2023, the Austrian federal government implemented strong incentives for exchanging oil and gas boilers with HPs by subsidising installation costs up to 75%. Thus it is expected that the share of SFHs with a HP will increase significantly within the

next years."

2. *You write: "And the 5R1C approach has been tested against results from Energy Plus, Invert/EELab and the VDI 6007. They show that the heating demand calculated by the 5R1C model is reasonably accurate, whereas cooling demand is strongly overestimated." Have you also tested the 5R1C model against Energy Plus etc. regarding the replication of thermal inertia? I think that this point is even more important than the good accuracy regarding the heating demand estimation, as it determines the load shifting potential. Literature gives some hints that 1 C might be not enough to adequately reflect the thermal inertia (see e.g. Bruno et al., 2016).*
    - Thank you for your comment. Meanwhile we have tested the dynamic behaviour of the thermal inertia against Energy Plus calculations. We saw that our approach with only one capacity underestimates the thermal inertia in general but specifically when there is floor heating used which is quite often the case in single family buildings with heat pumps. Therefore, our approach can be seen as a lower benchmark to the actual flexibility potential. We added the following statement in the script: "Bruno et al. investigated the thermal dynamics of the 5R1C approach compared to TRYNSIS. Similarly to that study we compared the dynamic behavior of our model to a simulation in IDA ICE. Our approach with only one capacity underestimates the thermal inertia in general, specifically when there is floor heating, which is quite often the case in SFHs with heat pumps. Therefore, the results obtained by this approach can be seen as a lower benchmark to the actual flexibility potential.".
3. *I recommend to reconsider the representation of heat pumps in your model. The average supply temperature of 35°C seems very optimistic (very low) for old buildings that are not well insulated, as far as I understand from Figure 1. Is it possible that you vary the supply temperature according to the building type?*
    - Yes, we agree, a uniform supply temperature does not accurately represent the efficiency of the systems, especially in old buildings. However, this assumption does not impact the results significantly for 2 reasons: 1) The building stock with heat pumps mainly consists of modern buildings. 2) Our results are always relative meaning they are measured against the same building with the same efficiency but no smart energy system. A lower efficiency would change the total amount of shifted electricity slightly but the relative amount will stay the same. We added the following statement to the text: "The chosen 35°C for the supply temperature for all buildings is too low for the old buildings. This simplification however, does not change the results. A higher or lower efficiency of the heat pump reflects itself in the annual heating costs of a building and can therefore also be interpreted as a change in mean electricity price. For the optimization however, only the relative change from one hour to another in price is relevant."
4. *I'm not sure if the COP formula (Equation 21) is correct. Is it possible that the reciprocal value of η should be used? Otherwise COP values below 1 are obtained (for instance if using 35°C supply temperature and 10°C source temperature).*
    - The formula is correct however it needs to be calculated in K. We added a short note to avoid confusion. In your example with an η of 0.35 the COP would be ~4.3.
5. *I found it a bit difficult to follow your objectives and partly methods considering the*

electricity price scenarios you investigate.
    - Thank you for your comment. We re-structured the section of the Electricity price scenarios to hopefully make it clearer.
6. *Could you please explain how electricity prices are derived from BALMOREL? Does the model incorporate a day-ahead market representation?*
    - BALMOREL is a partial equilibrium model for simultaneous optimisation of electricity and district heat generation, transmission, and demand. The electricity prices are derived as the marginal costs under the assumption of a perfectly competitive market following the merit order principle. We added the following text to hopefully make it clear: "Within these system boundaries, electricity demand and supply are matched within a market model, considering supply costs following the merit order principle under the assumption of a perfectly competitive market. It is not determined specifically in which type of market the transactions take place economically. The marginal cost of supplying power demand are derived which can be interpreted as the geographically specific market price of power in the model output."
7. *Is the "benchmark" heat pump operation considered in the load for BALMOREL (to ensure that price patterns somehow reflect the electricity demand of heat pumps?)*
    - Yes, in Balmorel the electricity demand of the current heat pumps in Austria are included. However, the prices are not impacted by the flexibility provided by the heat pumps. This is a limitation of this approach which is explained in the limitation section. Additionally we added the following text in the Method section: "It should be noted that the flexibility provided by the HPs in the building stock were not considered in the Balmorel calculation. An investigation of the impact of HP flexibility on the electricity price was done in [35]."
8. *I find it a bit arbitrary to use 2030 electricity price scenarios without changing the heat pump market penetration compared to 2021. Why do you do so? Is there no large uptake of heat pumps foreseen in Austria for the next years (like in Germany, for example)?*
    - Thank you for your comment. Indeed there is a large uptake of heat pumps foreseen in Austria for the next years. With a greater number of heat pumps also the potential flexibility rises significantly. We wanted to investigate the isolated impact of the price variability on the flexibility potential. Therefore, we did not change the heat pump penetration or building stock characteristics for this analysis. "However, in the following analysis we did not change the total amount of heat pump operated buildings nor the characteristics of the building stock itself. Otherwise the resulting shifted electricity would heavily dependent on the chosen building stock scenario and not on the electricity price itself."
9. *I think it would help the reader when you state already at this point that you do not consider changing prices due to load shifting. I think this is an important limitation that should already be addressed in the methodology.*
    - Thank you, we added this statement. "It should be noted that the flexibility provided by the HPs to the electricity system is not considered in this analysis. An investigation of the impact of HP flexibility on the electricity price was done in [35]"
10. *Maybe a small explanation regarding the price increase in scenario 1 in the course of the*

year would be helpful (e.g. refer to gas crisis).
    - We included one sentence explaining the price increase in this scenario, thanks! "The sharp increase in Price scenario 1 is due to the gas shortage at the end of 2021"

11. *You write: "However thermal storages are always prioritized for load shifting because the losses are smaller." Also, when having a look at Figure 8, it seems that there is no need to make use of the thermal mass of buildings as the most relevant effect stems from thermal storage. Maybe you should put this a bit into perspective, considering that households have to invest in thermal storages, while thermal mass is available for free.*
    - Thank you for pointing that out. We added a sentence stating that the thermal mass provides a low-cost in terms of investment costs. "Although thermal storages efficiently shift energy with minimal losses, using a building's existing thermal mass provides a low-cost way in terms of investment costs if storages are not already installed."
12. *As cost savings are quite limited for households, have you considered to further increase price volatility (especially downwards) by providing time-dependent grid fees plus taxes (instead of fixing them at 20 ct/kWh). For instance, if taxes are somehow linked to electricity wholesale prices, the minimum of your prices could fall below 20 ct/kWh, and consequently the use of thermal storage could be increased. I think the load shifting effects in your study are quite small, because real time prices are generally high, and thus storage is not used so much (because use of storage triggers thermal losses that have to be paid). I would at least suggest that you discuss this a little.*
    - Thank you for your comment. We added a paragraph discussing this. You are right, individual cost saving could be a lot higher with additional time-dependent grid fees. Absolute cost savings can even be increased by increasing the overall fixed fees which is likely to happen in the future. Correct, the storage losses through the thermal mass limit the shifted demand, however this is only dependent on the price spread from one hour to another. For example, we see the increase in demand shift with high volatility in electricity prices in 2021 in the last quarter. The absolute price however does not have an impact. Another reason for the relative small shifted amounts lies in the nature of our modelling approach. We added a statement in the method section that our results can be seen as a lower benchmark for the potential of load shifting through the thermal mass.
13. *I only miss some conclusions regarding the load shifting potential when a thermal storage is used. Maybe you can add a sentence?*
    - Thank you, we added a sentence stating that the shifted amount of electricity can more than double if thermal storages are considered. "If thermal storages are considered this amount could be more than doubled."
14. *"In the benchmark mode, the operation of technologies is simulated based on specific assumptions, [...]" -> Unclear. Do you mean "inflexible", heat demand oriented operation?*
    - Yes, we mean inflexible heat demand oriented operation. The indoor temperature will be kept above a certain level and the necessary heat demand is calculated. We changed the sentence slightly: "In the benchmark mode, the operation of technologies is simulated keeping indoor temperature above a certain level..." We hope this is clear now, thank you!
15. *I actually find the wording "benchmark" quite misleading. The terminus implies that this is*

the best case (in whatever regard). In terms of cost, however, it is "worse" than the SEMS. Maybe you reconsider the wording and instead use something like "baseline" or "reference"?
    - Thanks for your comment, we switched to the word "reference" to describe the simulation.

16. *The remainder of this paper is structured as follows [...]" The following references seem incorrect – they all refer to "section b" which is the literature review.*
    - Thank you, the references are fixed now.
17. "*The benchmark case is directly correlated to the occurrence of the electricity price." -> I do not understand this sentence. What do you mean by "occurrence of the electricity price"?*
    - Thank you for pointing that out. We meant that the electricity is bought independently from the price, thus electricity bought at a certain price is directly correlated to how often this price occurs. We replaced the sentence with: "In the reference case electricity is bought independently from the price."
18. *Footnote 2: little spelling error regarding Bosch.*
    - Thank you, error is corrected.

1.

Competing Interests: No competing interests were disclosed.