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The potential of decentral heat pumps as flexibility option for decarbonised energy systems

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Abstract Decarbonising the energy system requires high shares of variable renewable generation and sector coupling like power to heat. In addition to heat supply, heat pumps can be used in future energy systems to provide flexibility to the electricity system by using the thermal storage potential of the building stock and buffer tanks to shift electricity demand to hours of high renewable electricity production. Bridging the gap between two methodological approaches, we coupled a detailed building technology operation model and the open-source energy system model Balmorel to evaluate the flexibility potential that decentral heat pumps can provide to the electricity system. Austria in the year 2030 serves as an example of a 100% renewable-based electricity system (at an annual national balance).

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Center for Energy, Integrated Energy Systems, AIT Austrian Institute of Technology, Vienna, Austria e-mail: Gustav.Resch@ait.ac.at Results show that system benefits from heat pump flexibility are relatively limited in extent and concentrated on short-term flexibility. Flexible heat pumps reduce system cost, CO₂ emissions, and photovoltaics and wind curtailment in all scenarios. The amount of electricity shifted in the assessed standard flexibility scenario is 194 GWh_{el} and accounts for about 20% of the available flexible heat pump electricity demand. A comparison of different modelling approaches and a deterministic sensitivity analysis of key input parameters complement the modelling. The most important input parameters impacting heat pump flexibility are the flexible capacity (determined by installed capacity and share of control), shifting time limitations, and cost assumptions for the flexibility provided. Heat pump flexibility contributes more to increasing low residual loads (up to 22% in the assessed scenarios) than decreasing residual load peaks. Wind power integration benefits more from heat pump flexibility than photovoltaics because of the temporal correlation between heat demand and wind generation.

Keywords Heat pumps · (Open-source) energy system modelling · Flexibility · Sector coupling · Power-to-heat · Storage

Introduction

Decarbonising our energy system requires rising shares of electricity generation by variable renewable electricity (vRES), integrating them into the overall system, and electrifying former fossilfuelled processes. Increased shares of vRES lead to more fluctuating generation behaviour on the supply side of the electricity system and the need for flexibility options to balance supply and demand. The primary flexibility options in the power system are storage, dispatchable generation technologies, trade and transmission, and demand response (DR). The use of these flexibility options may consequently contribute to (i) the avoidance of vRES curtailment and increase of vRES share (Kirkerud et al., 2021; Olkkonen et al., 2018), (ii) system integration of vRES and an increased market value of vRES generation (Härtel & Korpås, 2021), and (iii) the reduction of residual peak loads which would alternatively have to be covered by additional power generation capacities and grid expansion (Kiviluoma et al., 2018; Nagel et al., 2022). While flexibility options historically have focused on the supply side, DR is a balancing option to adapt electricity demand to variable generation patterns. To a certain extent, the electricity consumers' demand is elastic, dependent on the framework conditions and market design. DR can provide flexibility potential to the electricity system either in the form of physical storage or indirect storage, like the thermal inertia of buildings or the willingness to adapt the demand behaviour (Gils, 2016).

Increased sector coupling caused by the decarbonisation of other sectors, like renewable power to heat (P2H), is another promising option for flexibility provision to the electricity system, specifically in countries where e-mobility or e-heating is rapidly growing. For achieving fully decarbonised energy systems, smartly integrated system design is vital to benefit from the flexibility provided by sector coupling (Kiviluoma et al., 2018; Mathiesen et al., 2015). Decarbonising the heating sector requires increasing capacities of heat pumps (HPs) that enable efficient conversion of electricity into thermal energy, which is usually cheaper and storable for extended periods. HPs can be deployed as central (traditionally linked to district heating networks) and decentral units and are projected to play a significant role in the decarbonisation of the heating sector (Hilpert, 2020). In this paper, we focus on decentral HPs used to heat single apartments or buildings in Austria's residential and commercial sectors. These technologies can provide flexibility to the electricity system in future energy systems by exploiting the thermal inertia of the building mass or linked buffer tanks to shift electricity demand to hours of higher renewable energy production in the electricity grid.

There are different ways to implement HP flexibility in models (see the "State of the art" section). On the one hand, in many studies, bottom-up building sector models are used to represent heating technologies in a high level of detail. These models simulate HPs and storage systems with techno-economic parameters like the coefficient of performance (COP), storage loss, building type, and temperature dependency in high granularity (see, e.g. Mascherbauer et al., 2022a; Moser et al., 2015; Weiß, 2019). Still, they often do not explicitly consider the overall electricity system but feed in electricity price signals as exogenous inputs. On the other hand, many analyses use energy system models that cover several sectors, like electricity, heating and cooling, transport, fuel markets, and industrial processes (see, e.g. Gils, 2016; Kirkerud et al., 2017; Olkkonen et al., 2018). Whereas detailed building sector models simulate the flexibility potential in a high degree of detail, energy system models must break down the information from building sector models to the minimum necessary data. That means modellers have to simplify the electricity demand profile of HPs and the assumed characteristics of the flexibility option HP. We applied a detailed building technology operation model to derive central HP flexibility indicators (step 1), which we then used as input for an energy system analysis (step 2). This enabled us to reduce the complexity of HP operation dynamics so that they can be implemented in large energy system models, evaluating their impact on the overall electricity system.

This paper addresses the research question of the flexibility potential of HPs in decarbonised electricity systems. Additionally, our methodological approach sheds light on how we can adequately model the flexibility potential in energy system models without losing critical information on HP technology characteristics. We identified the potential flexibility that residential HPs for space heating can offer a decarbonised electricity system by combining a detailed bottom-up building technology operation model and an energy system model instead of focusing on one side of the analysis. We analysed the system-wide effects in hourly resolution for an entire year. We further investigated the impact of the choice of techno-economic attributes in more detail and conducted a deterministic sensitivity analysis to derive the factors that most impact the potential in modelling. That enables us to draw conclusions on the choice of the modelling approach and provide general advice for the modelbased assessment of flexibility provision by HPs in energy system models. Austria's electricity system in 2030 serves as a case study to provide answers to the research questions stated above because Austria's target of 100% electricity from renewable sources by 2030 (nationwide, at a yearly balance) and the topography of a rather cold country with high penetration rates of (recently) installed HPs. Therefore, the lessons learned from Austria can provide interesting insights for countries with similar characteristics or policy intentions. They may also offer valuable insights for the path towards full decarbonisation of other sectors within Austria or elsewhere since the value of flexibility measures increases with more ambitious climate targets (Nagel et al., 2022). Also, HP flexibilisation becomes especially relevant in energy systems with renewable energy shares above 80% (Hedegaard & Münster, 2013; Hilpert, 2020), which is expected to be achieved by only a few countries within the next decade which can then serve as case studies.

The remainder of this paper is structured as follows: the "State of the art" section gives an overview of the existing literature, divided into studies based on building sector and energy system models. The "Method, models, and data" section describes the applied method, the two coupled models, and the data underlying the scenario analysis. The "Results and discussion" section presents the results, comparing different flexible scenarios to the reference case of an inflexible scenario. The "Conclusions" section discusses the results and concludes this paper.

State of the art

A broad range of literature describes the flexibility potential of DR applications and HPs as one flexibility option. The literature dealing with HP flexibility in general and, more specifically, with a focus on Austria can be divided into two fields: On the one side, there are bottom-up, very detailed, technology-focused studies on HPs at the building and applications levels. On the other side, studies use integrated energy system modelling to cover several sectors like electricity, heat, and transport and their interactions through sector coupling. Because of Austria's target of covering 100% of its domestic electricity consumption by renewables by 2030 and climate neutrality by 2040, HPs are expected to play a significant role in the decarbonisation of the heating sector. Literature for Austria is, therefore, interested in the potential effects of HPs on the electricity system, and some findings are transferrable to other countries following similar decarbonisation strategies. Many of the studies in the field deal with HPs in the Nordic European countries because of high decarbonisation ambitions and geographically caused high heating demand (Ding et al., 2022). Also, those countries show Europe's most mature HP markets (Bayer et al., 2012).

Several preconditions must be met for HPs to provide flexibility to the electricity system. First, flexibility options used for load shifting rely on the availability of a buffer system and a utilisation rate of less than 100%, enabling both a downward and upward regulation of the demand profile (Lund et al., 2015). A further precondition for the efficient use of this flexibility option is the automation of the control system and communication interfaces with the overall electricity system, requiring as little interaction as possible with the end user. Increasing shares of installed HPs have control systems that can also be accessed externally, e.g. by using a cloud system provided by the component manufacturer and used by aggregators or grid operators (Globisch et al., 2020). Another precondition is that end users see time variable tariffs as an incentive to provide flexibility to the system (Fitzpatrick et al., 2020; Patteeuw et al., 2016).

Several studies have focused on the potential role of HPs and electric heating as flexibility options in the electricity system using energy system models. The literature shows a consensus that power-to-heat can contribute to decarbonisation and integrate variable renewable electricity generation. The motivation for demand shifting can be manifold: Minimisation of CO₂ emissions, maximisation of the integration of vRES into the system, maximisation of self-consumption of decentral generation, peak shaving, or overall system cost reduction (Khorsandnejad & Malzahn, 2021). Kirkerud et al. (2017) analysed the Northern European power system, characterised by a high share of power-to-heat sector coupling in 2030. They find that power-to-heat in district heating can increase system flexibility in the short- and long-term perspectives. Since district heating (with large storage tanks) is the prevailing space heating technology in urban parts of the Nordics, district heating HPs can also cover seasonal variability in electricity generation. Hedegaard and Münster (2013) show that HP penetration and HP flexibility support wind power integration and reduce peak/reserve capacity in their analysis of Denmark in 2030. Kirkerud et al. (2021) analysed the economic potential of various DR technologies for the Nordic power market, finding that DR may contribute to 18.6% of the total peak load in 2050 in this area. In their analysis, most of this potential is provided by the household and tertiary sector, while electricity-to-heat is the flexibility option that contributes the most. On the contrary, Schill and Zerrahn (2020), analysing the German 2030 energy system, state that short-term electric storage heaters are unsuitable for balancing inter-annual supply because of the seasonal mismatch of heat demand and renewable generation. Only minor benefits for the short-term operation can be seen in their study. So, the storage tanks' size and application in decentral buildings versus central seasonal storage facilities are essential when analysing HP flexibility potential.

In the heating sector, opposing decarbonisation trends leading to a strong increase in installed HP capacities, higher standards in temperature comfort and housing space on the one side, improved energy efficiency and better building standards on the other are expected (Kirkerud et al., 2017). These trends are the basis for any assumed HP capacities and respective electricity demand for heating in modelling, which lay the foundation for their flexibility potential. Olkkonen et al. (2018) stress the importance of considering the varying availability of flexibility options over seasons and daytime. They find that Finland's demand-side flexibility resource capacity varies significantly, resulting in an available capacity between 80 and 5600 MW. They state that the results are very sensitive to constraints of shifting time intervals of the considered demand-side flexibility options. Studies have found that the resulting flexibility needs in energy system modelling are very sensitive to the choice of method for time aggregation (Koduvere et al., 2018). Gils (2016) developed a novel DR application providing a transferable approach for any linear optimisation model and applied it to the case study of Germany. He stresses that DR is most suited for providing power, not energy, making the appropriate representation of temporal resolution even more critical.

Patteeuw et al. (2016) modelled the electricity generation system and residences with HPs in an integrated modelling approach. They compare a direct-load control scenario and several dynamic time-of-use pricing scenarios and identify better performance for the former, especially at high levels of residential HP penetration. This finding implies the importance of appropriate tariff structures, price signals to the customers, control automation, aggregation entities, and high-quality forecasts for efficient use of demand-side flexibility provided by HPs. Østergaard and Andersen (2021) evaluated the impact of electricity taxes on (i) the incentive to increase HP and thermal energy storage capacities and (ii) the alignment of HP operation with the dynamic electricity system needs. They do not find incentives for more HP capacity but for tentatively 20% more thermal storage and, therefore, more flexible operation according to the electricity prices. Higher thermal energy storage utilisation leads to higher losses and energy consumption. Fitzpatrick et al. (2020) find an overall primary energy consumption increase of up to 9.1% when HPs operate flexibly. They state that real-time pricing is the most suited tariff structure for offering energy flexibility with the lowest associated electricity costs. For their case study of a residential building in Germany, they state a building's potential energy flexibility of up to 1370 kWh_{el} over the heating season with average specific (marginal) costs of between €0.024 and 0.035 per kWh_{el} of flexibility provided. The effects of sector coupling on electricity price formation have been studied. It could be shown that sector coupling can reduce low or even negative prices in future electricity markets.

That cross-sectoral demand bidding will be crucial for the price formation in future electricity markets (Härtel & Korpås, 2021), increasing the market value and competitiveness of vRES producers (Kirkerud et al., 2017).

Literature focusing on HP flexibility potential in Austria presents rather heterogeneous findings, mainly due to the assumptions made to assess the flexibility potential. These assumptions are related to the assumed market penetration of HPs in the future electricity system, shifting potential depending on the building stock, and renovation rates in the country.

Haas et al. (2022) identify in their analysis of how to integrate high amounts of variable renewable energy sources in Austria the critical relevance of flexibility options. Besides the need for business models fostering their investment, they see the need for (i) establishing smart infrastructure to control flexibility options like HPs and (ii) coordinating entities for aggregating various flexibility options in Austria. Moser et al. (2015) analysed the flexibility potential of various applications in the residential sector. They find a maximum load shifting potential of 1.3 kW per household HP for Austria's residential sector. This value is the average of a broad range of different households. They also stress the negative impact of increased COPs on flexibility potential and the positive effect of increased market penetration of HPs in the heating sector. They state a maximum shifting time of 1 h, for which 85% of this potential is available. Weiß (2019) conducted a very detailed analysis of the impact of building design parameters on energy flexibility, focusing on high-performance buildings in Austria. By developing a simulationbased methodology to quantify energy flexibility, he included the perspective of building designers, owners, and grid operators. His case studies show the impact of building design on energy flexibility. He states possible load shifting times of HPs for more than 24 h due to his focus on zero and plus energy buildings. Spreitzhofer (2018) focused more specifically on HP owners' perspectives. She analysed the economic potential of the flexible use of HPs in single-family houses for the Austrian balancing market for manual frequency restoration reserve. She simulated 400 single-family houses with varying thermal characteristics to derive a technically feasible flexibility range and achievable economic revenues. As the most critical factors for the flexibility potential, she identifies building insulation, electric power of the installed HPs, and inhabitants' convenience. Interestingly, she also finds that the impact of an additional storage tank on the flexibility potential is low compared to those factors. The highest potential lies in existing buildings because of their high heat load, followed by low-energy houses with air HPs. She shows that the highest potential for all building types lies in winter, followed by autumn and spring. The flexibility potential in summer for most building types is negligible. For the heat shifting time, she finds a high dependency on the building type and values between 4 and 8 h and 12 h (for a passive house). To make this potential accessible, she emphasises the importance of affordable and standardised automation of the control system and communication infrastructure. Mascherbauer et al. (2022b) analysed the response of individual households' energy consumption to variable real-time electricity prices with an hourly technology operation model. They find that the economic incentive to shift load is higher for older buildings with higher energy demand. For different price profiles for 2030, they find an annual amount of shifted electricity between 11 and 26 GWh_{el} by the thermal mass alone in Austria's single-family houses.

Suna et al. (2022) analysed Austria's electricity and district heating system in 2030, evaluating various flexibility needs and options, including HPs, for different timescales (daily, weekly, monthly, and annually). They assumed an installed HP capacity of 2909 MW_{el} for space heating in the residential and commercial sectors, with 30% of the HPs being controllable for DR. The power system's associated storage size (representing buffer tanks and building mass considering new buildings and refurbished existing buildings) is 2494 MWh_{el}, corresponding to a shifting time of 2.9 h. After considering simultaneity effects, they state a maximal potential of 526 MW_{el} of flexible HPs in Austria in 2030. They found that most of the flexibility contribution of HPs takes place on the daily time scale. In contrast, HPs do not contribute to balancing weekly or seasonal mismatches of supply and demand. On the daily time scale, residential and commercial HPs provide around 10% of the flexibility needed to balance hourly fluctuations per day according to their integrated power and district heating modelling. That corresponds to approximately 480 GWh_{el}/a shifted by HPs in Austria in 2030.

Methodologically, there is a gap in the literature about heat pump flexibility between detailed building technology simulations and energy system analyses. In some cases, the flexibility potential of detailed case studies is aggregated or extrapolated (see, e.g. Sperber et al. (2020) for Germany) to retrieve quantitative results on the energy system level. This study bridges the gap by combining both approaches—a detailed building technology operation model and integrated energy system modelling-for the specific case of Austria. Most of the studies done so far for Austria focus on case studies and the building perspective of HP flexibility. This paper condenses these findings and evaluates their impact on the overall electricity system in Austria in 2030. For other countries (Denmark), it could be demonstrated that wind power integration benefits from HPs (Hedegaard & Münster, 2013), but this has not been analysed for Austria, which has lower wind power and much higher hydropower shares. Several studies point out the relevance of shifting time limitations (Olkkonen et al., 2018) and high temporal resolution of the modelling (Gils, 2016; Koduvere et al., 2018), which is often only partly considered in energy system analyses due to reduction of calculation complexity. We analyse the limitation of shifting time in a sensitivity scenario and model the flexibility in hourly resolution over the whole year, capturing short- and long-term dynamics of flexibility provision.

Therefore, the contribution of this study is threefold. It shows how information from detailed building technology operation models can be used in an energy system model to adequately represent HP characteristics in the overall electricity system and bridges a gap between the two approaches. Furthermore, it fills a research gap about the quantitative potential of HP flexibility in the Austrian electricity system. It provides insights into the possible flexibility provision for the Austrian electricity sector by decentral HPs and shows their system-wide effects in hourly resolution for an entire year. And finally, we shed light on the impact of the choice of assumptions on the results. This serves as a deterministic sensitivity analysis for the results derived for the Austrian electricity sector. The modelling approach and lessons learned may provide valuable insights for other modellers that strive to enhance energy system modelling capabilities following recent energy sector trends.

Method, models, and data

The primary method applied in this paper is energy system modelling, which models decentral HPs as a flexible component of the electricity demand, considering certain techno-economic limitations (described in the "Flexibility parameters" section). These limitations, e.g. heating profiles and flexibility parameters, have to be given as inputs to the energy system model in a simplified way, reducing the complexity of the preconditions in a natural system. Therefore, as a first step, the flexibility potential of the building stock heated by HPs was modelled in a detailed building technology operation model to identify the central characteristics of the flexibility provided (based on the method developed by Mascherbauer et al., (2022a, 2022b)) and convert them to indicators used as inputs for the energy system model. The information derived from the detailed building technology operation model was fed into the energy system modelling (second step). That enables us to represent HP flexibility adequately in the energy system model. In the energy system modelling, we applied a deterministic sensitivity analysis and evaluated relevant energy system output variables, with pessimistic and optimistic techno-economic HP values of each uncertain variable (Chelst & Bodily, 2000). That allows us to identify the most sensitive input variables and draw conclusions on which energy modellers should focus. We modelled the electricity and district heat sector and decentral HPs in Austria's residential and commercial sectors. The investment and dispatch optimisation of the electricity system was conducted in the open-source energy system modelling framework Balmorel (The Balmorel Open Source Project (2019), Wiese et al. (2018)), minimising overall system cost in hourly resolution for the year 2030 in Austria. We derived generation mix, overall system cost, electricity spot prices, and emission levels as output.

The energy system model

For this study, the energy system model Balmorel was used. Balmorel (the BALtic Model for Regional

Electricity Liberalisation) is an open-source, partial equilibrium energy system model (Wiese et al., 2018) following a bottom-up approach to model the electricity and district heat system. The model is built modularly, continuously being further developed (Balmorel Community, 2022).

Balmorel was one of the first open-source energy system models. The theoretical background was first described by the developers Ravn et al. (2001) and Ravn (2001). Following a deterministic bottom-up partial equilibrium approach, Balmorel can model several sectors, including electricity, district heating, individual heating, and transport. It can co-optimise energy dispatch and investment in the considered sectors using linear programming in GAMS. On the supply side, various technology types can be implemented, characterised by primary fuel type, input/ output efficiency, operation and maintenance costs, and investment costs for new capacity. For our analysis, we focussed on the electricity and district heat sectors and included individual heating by HPs in the residential and commercial sectors. Using a perfect foresight approach, the model's objective function (Eq. (1)) minimises the system cost¹ associated with the modelled technologies g: annualised investment costs of new investments c^{Inv} (\in /MW), fixed operation and maintenance (O&M) costs c^{Fix} (ℓ/MW) of existing units C^{Ex} (MW) and new investments C (MW), and variable operation and maintenance costs (including fuel and emission costs) c^{Var} ($\in *h/$ MWh) of existing units and new investments (for further details on the selected equations, see Münster and Meibom (2011) and Bramstoft et al. (2020)). The perfect foresight approach is commonly used in energy system optimisations. It means that the optimiser—in contrast to real systems—knows all future developments like resource availability and prices, leading to the lowest total system cost by definition (Lambert et al., 2023). Q (MW) represents the level of the commodity produced or consumed; Q^{el} denotes the commodity of electricity, Q^{dh} denotes the commodity of district heat. This is done for the different regions ($r \in R$), areas ($a \in A$), technologies ($g \in G$), and time steps ($t \in T$). Areas a are aggregated into transmission regions r. We modelled the energy system of Austria and the EU neighbouring countries in hourly resolution, considering every country as one region (one node), disregarding innernational transmission and distribution bottlenecks.

$$\min\left(\sum_{a\in A}\sum_{g\in G}c_g^{Inv}C_{a,g} + \sum_{a\in A}\sum_{g\in G}c_g^{Fix}\left(C_{a,g}^{Ex} + C_{a,g}\right) + \sum_{a\in A}\sum_{t\in T}\sum_{g\in G}c_g^{Var}Q_{a,t,g}\right)$$
(1)

The optimisation constraints are imposed by a set of linear relations reflecting the characteristics of the technologies, such as capacity, energy, and operational constraints of generation units and storage. The most important ones of them are displayed below (Eqs. (2)-(5)).

It is ensured for every time step *t* that electricity demand d^{el} (MW_{el}) is covered in every region *r* considering export and import Q^{trans} (MW_{el}) (including losses e^{loss} [-]) of electricity between regions and loading and unloading of storage technologies G^{St} (Eq. (2)). $Q_{rt,r,t}^{trans}$ and $Q_{r,r,t}^{trans}$ (MW_{el}) denote the electricity imported to and exported from region *r* and from a neighbouring region $r' \in R^{imp}$ or to a neighbouring region $r' \in R^{exp}$. Similarly, Eq. (3) ensures that the district heat demand d^{dh} (MW_{th}) is covered in each area *a*, but without the possibility of heat transmission between areas.

$$\sum_{i \in A_{r}^{R}} \sum_{g \in G^{el}} Q_{a,l,g}^{el} + \sum_{r' \in R_{r,r}^{imp}} ((1 - e^{loss}) \cdot Q_{r',r,t}^{trans} + \sum_{a \in A_{r}^{R}} \sum_{g \in G^{St}} Q_{a,l,g}^{el,exSt}$$
$$= d_{r,t}^{el} + \sum_{r' \in R_{r,r'}^{exp}} Q_{r,r',t}^{trans} + \sum_{a \in A_{r}^{R}} \sum_{g \in G^{St}} Q_{a,t,g}^{el,inSt} \ \forall r \in R, t \in T$$

$$\sum_{g \in G^{dh}} \mathcal{Q}_{a,t,g}^{dh} + \sum_{g \in G^{St}} \mathcal{Q}_{a,t,g}^{dh,exSt} = d_{a,t}^{dh} + \sum_{g \in G^{St}} \mathcal{Q}_{a,t,g}^{dh,inSt} \ \forall a \in A, t \in T$$
(3)

$$Q_{a,t,g} \le av_{a,t,g} \left(C_{a,g}^{Ex} + C_{a,g} \right) \forall a \in A, t \in T, g \in G^{dis}$$
(4)

$$Q_{a,t,g} + Q_{a,t,g}^{curt} = av_{a,t,g} \left(C_{a,g}^{Ex} + C_{a,g} \right) \forall a \in A, t \in T, g \in G^{ndis}$$
(5)

(2)

¹ That is, maximising social welfare when assuming inelastic demands.

The level $Q_{a,t,g}$ (MW) of electricity or district heat is constrained by the installed capacities $C^{Ex} + C$ (MW) and the availability av [-] of the technology plant at that specific time step t for dispatchable technologies G^{dis} (Eq. (4)). For non-dispatchable technologies G^{ndis} , i.e. wind, hydro runoff-river, and solar, the production is determined by the availability of resources/generation profiles, but with the possibility of curtailing generation Q^{curt} (Eq. (5)).

Endogenous optimisation results in the hourly electricity and heat generation of all technology components, including storage and flexibility options, the installed generation capacities, and the overall system cost per year (considering the discount rate and economic lifetime) under the premise of minimising the annualised cost of the energy system. Besides the total costs of the system, all variables are non-negative.

Wiese et al. (2018) describe the model structure, including the wide range of developed model extensions and how the open code enables usage in a broad geographic range. Performed analyses range from regional case studies only in the electricity sector (e.g. Barragán-Beaud et al. (2018) and Fedato et al. (2019)) to integrated studies comprising the electricity, heat, and transport sectors for several countries (e.g. Hedegaard and Balyk (2013)).

For our analysis, we focussed on the electricity and district heat sectors and included individual heating by HPs in the residential and commercial sectors. The electricity and district heat sectors of the neighbouring countries Czech Republic, Germany, Hungary, Italy, and Slovenia were modelled to capture export and import dynamics. HP flexibility was only assumed for Austria since this was the focus of our study. The scenario with flexible HP operation is compared to a reference case where inflexible electricity demand of the HPs is assumed to evaluate the flexibility potential of HPs.

Implementation of heat pump flexibility

In energy system modelling, the (relatively new) aspect of HP flexibility is often modelled as a wellknown type of electricity storage that has been implemented in energy system models for a long time. A storage capacity (MWh) and a charging/ discharging power (MW) characterise this type of functional storage, which is, in the case of HPs, equal to the installed HP capacity and able to provide flexibility to the system. Adding certain techno-economic constraints for shifting time and availability, e.g. the frequency of the application (cycling) and the shifting time, can refine the representation of HPs as functional storage in the energy system. In reality, these parameters are not static but change over time because they depend, e.g. on outside temperatures. For example, in winter, more negative flexibility can be provided by HPs because a higher load can be shifted. Still, when it is freezing, the possible shifting time differs from summer situations (Sperber et al., 2020). Implementing time-dependent parameters and temporal sums leads to increased complexity and runtime of energy system models, with DR often being only one of the system's multiple aspects to be analysed. When modelling flexibility options, the most important properties are (i) the shifting time, (ii) the amount of shiftable energy or power, and (iii) the associated cost or efficiency loss (Marszal et al., 2019). The provided flexibility to the system thereby depends on the heating demand (depending on outside temperature, comfort level, and building standards), the losses (depending on outside temperature and insulation), the comfort level (acceptable deviation from standard indoor temperature), and thermal mass of the building. In reality, the forecast accuracy of renewable electricity generation and electricity prices will also be decisive for the used shifting potential. We minimised overall system cost and derived results for the potential of HPs to shift peak load periods, reduce system cost, price variability, and curtailment of wind and solar generation.

Demand-side flexibility was implemented in Balmorel via the add-on "demandresponse" (Balmorel Community, 2022), which was developed by Kirkerud et al. (2021) for Balmorel following a theoretical concept close to Gils (2016). The add-on enables the model to endogenously optimise the demand profile of flexible consumers under given restrictions. In times of high marginal costs of the supply side of the electricity system, i.e. high electricity spot prices, the demand will decrease. In contrast, electricity demand will increase in times of low electricity prices. The add-on was used and further developed for this study. The heat demand profile was provided in one profile for the whole year in this study compared to a combination of seasonal and weekly patterns in the original add-on. Furthermore, thermal losses were only applied for preheating, not for precooling.

A share of the installed decentral HPs was assumed to be controllable (see Table 3), and their demand profile could be modified according to certain technoeconomic limitations. The modelling of load shifts was done by utilising a virtual storage concept, meaning that the DR flexibility was implemented as an indirect storage potential (Gils, 2016) in the modelling. The following parameters and variables describe this storage and were developed by Kirkerud et al. (2021) and adapted for the purpose of this study:

The load shifting $P_c(t)$ (MWh_{el}) describes the difference between the scheduled electricity demand $L_c(t)$ (MWh_{el}) and the realised electricity demand $R_c(t)$ (MWh_{el}) (Eq. (6)) at time step t.

$$P_c(t) = L_c(t) - R_c(t) \tag{6}$$

The upward or downward demand shifting $P_c(t)$ (MWh_{el}) of technology *c* determines the energy content $E_c(t + 1)$ (MWh_{el}) of the virtual storage, which can take negative and positive values, meaning the load could be shifted to a previous or a later point in time (Eq. (7)).

$$E_{c}(t+1) - E_{c}(t) = P_{c}(t)$$
(7)

There are two options to define the limitations of the virtual storage within those the model can optimise the shifting of flexible loads: Either by defining (a) a rigid shifting time Δt_c (h) or (b) a fixed limit of $E_c^{max}(t)$ (MWh_{el}).

In the case of (a), the upper limitation of the virtual storage is the sum of all loads within Δt_c (h) and is, thus, time-dependent since it depends on the scheduled loads of the considered time frame, which is set by Δt_c (h) (Eq. (8)).

$$E_c^{max}(t) = \sum_{tt} L_c(tt) \ \forall t \le tt \le t + \Delta t_c \tag{8}$$

The maximal possible demand reduction (downward shift) $P_c^{max}(t)$ (MWh_{el}) is the load to the extent scheduled at time step *t* (Eq. (9)).

$$P_c^{max}(t) := L_c(t) \tag{9}$$

The maximal possible demand increase $P_c^{min}(t)$ (MWh_{el}) (upwards shift) is the difference between the scheduled load and the maximal demand (defined by the installed capacity) of the technology Λ_c (Eq. (10)).

$$P_c^{min}(t) := L_c(t) - \Lambda_c \tag{10}$$

Equation (9) and Eq. (10) are ensured by:

$$P_c^{min}(t) \le P_c(t) \le P_c^{max}(t) \forall t, c.$$
(11)

The described equations are presented to understand the basic functioning of the energy system model add-on in combination with the detailed building technology operation model. For a more detailed description of the model add-on, see the explanations of the developers Kirkerud et al. (2021).

In the baseline scenario, the electricity demand of the HPs was part of the overall electricity demand in Austria and was assumed to be inflexible as the general electricity demand. In the flexibility scenarios, the electricity was handled separately and could be shifted in time, given the techno-economic constraints.

Figure 1 shows the main variables and parameters describing the load-shifting potential of HPs in the case of a limitation by shifting time. It describes the theoretical concept developed by Gils (2016) and implemented in Balmorel by Kirkerud et al. (2021).

Heating profiles

A crucial element when assessing the flexibility of HPs is the nature of the heating profile, which determines the profile of the electricity demand for HPs. Following the seasonal patterns of heating degree days, heat demand is highest in winter and lowest in summer in Austria, which has an effect on the flexibility potential provided by power-to-heat technologies.

For the purpose of this study, we used the hourly heat demand profile for space heating in the residential sector for the year 2010, provided by Pezzutto et al. (2018). The profiles are based on hourly profiles for typical day types depending on the

Fig. 1 Parameters and variables describing the flexibility potential of load shifting of HPs in Balmorel by using shifting time Δt_c as a limitation



— Realized load after load shifting

country-specifics and the temperature, resulting in a yearlong assembled demand profile (unitless and normalised). The original data is on NUTS2 level and was aggregated for Austria.² The weather year was chosen because of the data availability in high temporal and spatial resolution (Pezzutto et al., 2018) and because 2010 is a year also chosen as representative conditions for Austria in literature (Suna et al., 2022). The heating profile follows a seasonal pattern as well as daily patterns. The hourly profile during one week follows the typical day structure with higher demand during the night than during the day (see Fig. 2). This pattern is more distinct during the winter than during the summer: The profile is rather flat during the summer and shows more fluctuations during the winter. The HP demand profiles used do not consider cooling demand. Figure 2 shows the heat demand profiles of different selected weeks in 2010.

Flexibility parameters

The technical flexibility or load shifting potential of HPs is dependent on various factors like outdoor temperature, COP, or building type. This section shows the impact of these different factors on the load shifting potential of HPs.

A detailed hourly technology operation model was used to model individual households' load

shifting dynamics using a simplified five resistance one capacity (5R1C) approach following the DIN EN ISO 13790 (for the European Standard, see CEN (2008)). For further details of the approach applied in this paper, see Fig. 14 (description in the Appendix) or Mascherbauer et al., (2022a, 2022b). The model simulates the hourly heat and cooling demand of a building based on outside temperature, solar radiation, and building characteristics. The five resistances represent different aspects of the thermal insulation



Fig. 2 Heat demand profiles for the residential sector for weeks 3, 13, 23, 33, and 43 (normalised) in Austria for the year 2010. (Source: Own illustration based on Pezzutto et al. (2018))

² Even weight for all NUTS2 regions.

of the building, while the one capacity simulates the building's thermal capacity. Although models with more than one capacity (e.g. EN ISO 52016, see CEN (2017)) improve the representation of the thermal dynamic behaviour of the building significantly (Cirrincione et al., 2019; Sperber et al., 2020), their computational complexity increases when implemented into an optimisation algorithm. The main advantage of the higher-order models is that the thermal mass of the building (zone) can be specified per building element. As applied in this paper in the 5R1C approach, model reduction and simplification methods aim to represent the building behaviour with smaller equation systems and fewer input parameters. Since this paper seeks to present a method that reduces the complex building-level information and uses it on an aggregate level in energy system modelling focused on the electricity sector, the authors chose this condensed approach. This approach has been tested against results from Energy Plus, Invert/EELab, and the VDI 6007 (Lauster et al., 2014; Michalak, 2014; Zangheri et al., 2014),³ showing that the heating demand is reasonably accurate. The authors are researching the thermal response of a building modelled with only one capacity compared to multiple capacities.⁴ The first results show that the load shifting potential, as is the thermal inertia, is underrepresented when using only one capacity. Higher-order models are known for better representation of transient behaviour, with first-order models underestimating heat flow (Lauster et al., 2014). Thus, modelling the thermal response of a building due to load shifting with the 5R1C model as applied in this paper provides a lower benchmark of the actual capability of a building to shift demand and provide flexibility.

Newer or better-insulated buildings can shift the demand for a longer time but have a lower heat demand. To visualise the impact of the building type, we compared two single-family building types: house 1 (see Fig. 3, panel (a) and (b)) has a low insulation status but has a high thermal mass. House 2 (see Fig. 3, panel (c) and (d)) is well insulated but has only a medium thermal mass. The buildings were chosen from the Invert/EE-Lab building stock database (Mueller, 2021) to represent typical single-family houses in Austria with (i) low insulation and high thermal mass, which corresponds to older buildings within the stock, and (ii) newly built buildings which usually have lower thermal mass but are well insulated. With these two edge cases, we show how the building parameters influence the possibility of shifting load. The analysis shown in Fig. 3 is done for a winter day at - 5 °C; constant room temperature without interference should be 20 °C. The continuous heating power to achieve this indoor temperature under given conditions is around 10 kW_{th} for house 1 and about 6 kW_{th} for house 2, which are representative values for single-family houses in Austria. The used parameters for the 5R1C model of each house are given in Table 8 in the Appendix.

Figure 3 (panels a and c) shows the heating power, the thermal mass, and the room temperature for the case with and without load shifting ("constant"). In the example, the building is preheated for 3 h, which results in a room temperature of 22 °C instead of 20 °C. The thermal mass temperature continuously increases during the first 3 h and decreases in the following hours since the energy is stored in the thermal mass and discharged during the following hours. Consequently, the electricity demand can be reduced in the following 3 h compared to the constant heating profile. The additional thermal energy is consumed in three ways (Fig. 3, panels b and d): (i) the thermal energy that is used for heating in the following 3 h, (ii) the energy remaining in the thermal mass, and (ii) the thermal losses. The longer the shifting process takes, the higher the share of the thermal losses. Because of these thermal losses, using the storage capacity for longer storage durations is not economical. The calculations are similar to the finding of Wolisz et al. (2013), who identified a heating demand reduction of 20% for the 4 h following a 2-h preheating phase.

The stored energy which can be used to shift the electricity demand of HPs depends on the outside

³ Lauster et al. (2014) compared the performance of a firstorder model (ISO 13790) and a second-order model (VDI 6007) for a test case of a two storey single-family dwelling with a living area of 150 m². They found the heat capacity in the first-order model to be about 10% smaller than the capacity in the second-order model. Michalak (2014) compared the ISO 13790 method to a detailed simulation programme (EnergyPlus) for ten Polish test cases and found an error of up to 12.2% for the annual and up to 13.4% for the monthly heat demand.

⁴ Results will be provided by the authors upon request, the respective study should be published within 2024.



Fig. 3 Heating power (kW_{th}), thermal mass and room temperature (°C), shifted energy (kWh_{th}) when preheating for 3 h to 22 °C instead of 20 °C at -5 °C outside temperature for two different building types. Panels **a** and **c** show the heating

power, the thermal mass, and the room temperature for the case with and without load shifting ("constant"). Panels \bf{b} and \bf{d} show how the additional thermal energy (from preheating) is consumed

temperature. The colder, the more energy is needed for heating, and the more energy can be shifted (see Fig. 4). This relationship is the same for all building types assessed (see Appendix, Fig. 13). Additionally, the interference time accepted to deviate from the desired room temperature of 20 °C is an essential factor. This depends on the users' willingness to reduce comfort for a specific period. The longer they are willing to deviate



Fig. 4 Stored energy (kWh) divided by installed heat pump power (kW) in dependence of outdoor temperature (°C) and preheating hours (h) (accepted time of interference to increase the room temperature from 20 to 22 °C). Houses 1 and 2 are single-family houses differing in thermal insulation status (in increasing order from 1—low to 2—high)

from their desired room temperature (22 °C instead of 20 °C), the higher the amount of energy which can be shifted (see Fig. 4). The same analysis can be done for reduced room temperature (load delay = precooling).

The associated storage capacity in the assessed cases lies between 0.5 and 4 kWh stored energy per kW installed HP capacity, considering only the thermal mass of the buildings. Suna et al. (2022) find a capacity of 2.9 kWh/kW, including a buffer tank of 250 l. As input for our standard flexibility scenario in the energy system model, we derived from the detailed building model a capacity of 3 kWh/kW, representing the thermal mass of the building as well as a buffer tank. Considering the relations in Fig. 4, this value of 3 kWh/kW appears high. However, we took into account that the calculations underlying Fig. 4 do not consider a buffer tank and represent a first-order model representing the lower boundary of the flexibility potential (as explained earlier in this section).

In the energy system model, the temperature dependence is partly implemented in the modelling by the heating profile, but dynamic thermal losses are not explicitly modelled. In contrast to the detailed building model, simplified assumptions had to be taken, which were derived from the detailed building model described in this section. In reality, the losses vary depending on the building type, insulation, and outside temperature. In the energy system modelling, a constant efficiency loss per hour of 5% is assumed because of the thermal storage effect (Kirkerud et al. (2021) estimate 3%). The energy system modelling was conducted in hourly resolution, and there was no minimum runtime assumed (i.e. the HP can completely switch on and off within one hour).

In our standard flexibility scenario, the indoor temperature could not fall below 20 °C. This implies that only preheating is possible since regulating the demand downwards first and making up for the demand difference afterwards would imply a temperature drop below the intended level. No variable or fixed costs were assumed in the standard flexibility scenario because load shifting does not cause a utility loss for the consumer when operated within the given constraints. However, a sensitivity analysis with variable shifting costs was conducted.

Energy system data

This section describes the overall assumptions of the energy system. The electricity system was modelled in hourly resolution for the year 2030. The generation profiles for photovoltaics (PV), wind, and hydro generation represent the weather year 2008. The CO₂ price is 52.8 ϵ_{2015} /t CO₂ (Distributed energy scenario from ENTSO-E, 2021).

The assumed electricity and district heating demand and installed conventional capacities stem from the AURES II project (AURESII, 2022). Assumptions on the renewable deployment of PV, wind, and hydro run-of-river were aligned with the TYNDP 2020 National Trends Scenario (ENTSO-E, 2021). The assumptions for Austria were taken from the national energy and climate plan (WAM scenario) (Environment Agency Austria, 2020), and renewable capacities were refined according to the 100% renewable target until 2030. Austria targets to cover 100% of its domestic electricity demand by renewables by 2030 (Republic of Austria, P, 2021). That implies 27 TWh of additional annual electricity generation from renewable sources by 2030, adding significant amounts of fluctuating solar and wind generation to the system. We modelled the public grid in Austria. Austria's overall electricity demand (without storage losses, transmission and distribution losses, and self-consumption) is 74.6 TWh, whereas 2.6 TWh is consumed by electric cars. The electricity is generated by the power plant stock shown in Table 1.

MW	Austria (AT)	Czech Republic (CZ)	Germany (DE)	Hungary (HU)	Italy (IT)	Slovenia (SI)
Coal		5768	19,563	884	5084	
Geothermal	8		37	56	967	7
Lignite		763	16,370	220		
Natural gas	3349	1262	58,980	3318	27,856	877
Oil	15		558	170	1240	
Waste	150	100	1661	59	580	38
Nuclear		2660		1887		727
PV central	776	1165	35,093	2902	17,452	400
PV decentral	10,751	3735	94,299	3743	30,796	1690
Hydro reservoirs	3531	758	1065	32	4550	
Hydro pump storage	4800	1172	9422	-	7276	180
Hydro run-of-river	6807	395	4036	57	10,653	1206
Biogas	73	275	4682	121	1417	45
Biomass	349	604	4312	628	1550	53
Wind offshore			16,717		1236	
Wind onshore	6870	960	81,501	376	20,962	150
Sum	37,479	19,617	348,296	14,453	131,619	5373

Table 1 Installed electricity generation capacities in MW_{el} for the modelled countries

The assumption on transmission capacities is displayed in Table 2, assuming a possible utilisation of 80%.

Scenarios

There were eleven scenarios assessed (see Table 3): First, we modelled the reference scenario where the residential HPs were assumed to be inflexible, following the given heat demand profile ("Reference"—"REF"). This scenario serves as a reference to evaluate the flexibility potential of the residential HPs in all other scenarios.

Based on the literature assessed (see the "State of the art" section), the most important factors influencing HP flexibility were identified and considered in the scenario design. A deterministic sensitivity analysis evaluated their impact on the results of the energy system modelling.

Table 2 NTC capacities (MW) between countries in 2030. Values are taken from the National Trends Scenario of the TYNDP (ENTSO-E, 2021), assuming a possible utilisation of 80%

MW	CZ	DE	HU	IT	SI
AT	720	4320	640	544 (export)/400 (import)	760

The installed HP capacity for heating was assumed to be 2900 MW_{el} in Austria in 2030, and the flexible, controllable share was 30% (Suna et al., 2022). This resulted in an installed flexible HP capacity in the standard case of 870 MW_{el}, leading to an annual flexible electricity demand of 957 GWh (1100 fullload hours, according to Suna et al. (2022)). The energy demand of HPs was represented in the model as an electric demand profile, which was defined by the installed capacity and the full-load hours. That means that the underlying technical assumptions, like COP, are not directly implemented in the energy system analysis but only indirectly. In the standard flexibility case, an associated storage capacity of 3 kWhel was assumed per kWel installed HP capacity ("Standard flexibility"-"Flex1"). As deterministic sensitivity analyses, this was varied by 50% in the "Flex2"/"Flex3" scenarios (4.5 kWh/kW in the "Thermal storage+" and 1.5 kWh/kW in the "Thermal storage -" scenario) as this value can change and depends on assumed building stock etc. (see the "Flexibility parameters" section). Another critical but uncertain parameter is the installed HP capacity in the future since this depends on the penetration rate, technology development, price paths, national strategies, etc. We assessed this in the sensitivity

altered in the rest	pective scenario cc	mpared to th	he standard	flexibility s	cenario						
Model inputs	Inflexible sce- nario	Flexible s	cenarios								
	Reference	Stand- ard flex- ibility	Thermal storage +	Thermal storage –	HP capacity +	HP capacity –	Control +	Control –	3-h shifting time restriction	Cooling allowed	Shifting costs
Scenario ID	REF	Flex1	Flex2	Flex3	Flex4	Flex5	Flex6	Flex7	Flex8	Flex9	Flex10
Installed HP capacity (MW _{el})	2900	2900	2900	2900	4350	1450	2909	2909	2909	2909	2909
Controllable share (%)	ı	30%	30%	30%	30%	30%	45%	15%	30%	30%	30%
Flexible HP capacity (MW _{el})		870	870	870	1305	435	1309	436	870	870	870
Storage capacity (MWh/MW installed HP capacity)	1	3.0	4.5	1.5	3.0	3.0	3.0	3.0	Time-depend- ent	3.0	3.0
Precooling allowed	ı	x	х	X	x	x	x	X	x	>	x
Var. shifting costs ($\varepsilon_{2015}/$ MWh)		0	0	0	0	0	0	0	0	0	29.5

Energy Efficiency

analyses where the installed capacity was varied by 50% in the "Flex4"/ "Flex5" scenarios (4350 and 1450 MW_{el} – "HP capacity ±"). Besides the installed capacities, the share of HPs communicating with the grid and thus able to provide flexibility to the overall system is decisive for the flexibility potential. This aspect was evaluated in the scenarios "Flex6"/ "Flex7", where the controllable share of the HPs was varied ("Control ±" refers to 15 and 45% controllable share). As described in the "Implementation of heat pump flexibility" section, shifting limitations in modelling can be implemented via a storage capacity as done in our analysis (3 kWh/kW) or by a hard shifting time restriction. In the scenario "3 h shifting time restriction", a hard time restriction was implemented to analyse the impact of the two different model approaches ("Flex8"). It was assumed that only preheating is possible because the indoor temperature level has to be kept above 20 °C, i.e. precooling and reheating at a later point in time was not possible due to the comfort losses that reduce the acceptance of the demand shifting by users. However, in one scenario ("Cooling allowed"-"Flex9"), we assessed the impact of the acceptance of such a measure. In the standard case, no costs were assumed for the shifting behaviour because HP owners have an economic incentive to shift demand to times of lower electricity prices and reduce their expenses. However, there can be costs and utility losses due to deviations from the desired heating profile for controlling, aggregation, and equipment. Also, Mascherbauer et al. (2022b) showed that the economic incentive for single-family house owners is very low. Therefore, we conducted a sensitivity analysis where variable shifting costs of 29,5 \in_{2015} /MWh (Fitzpatrick et al., 2020) were assumed ("Shifting costs"-"Flex10").

Results and discussion

This section presents and compares the results for the different scenarios. First, the results of the inflexible scenario are presented (section "Reference scenario: the inflexible case"), serving as the reference scenario to which the various flexible scenarios are compared (section "Flexible scenarios"). The effects of heat pump flexibility on the electricity system are displayed in terms of shifted electricity, avoided curtailment of renewable electricity generation, and system impacts like system cost reduction, electricity price developments, and emission reduction.

Reference scenario: the inflexible case

In the reference scenario, the HPs operate in an inflexible mode. That means the HP electricity demand is coupled inflexibly to the heating demand it covers. These scenarios serve as a reference to analyse the impacts of HP flexibility in the different flexible scenarios done. Table 4 shows the electricity generation mix in the reference scenario. In Austria, 11.49 TWh of electricity are generated from natural gas. Considering the national target of 100% renewable generation (annual, national balance), this is only possible by Austria becoming a net exporter of electricity.

Based on the generation mix and transmission between the countries, average hourly electricity prices of 56.68 (Germany) and 70.23 \notin /MWh (Hungary) can be observed (see Table 5).

Flexible scenarios

In the flexible scenarios, HPs can shift their electricity demand according to the method presented in the "Implementation of heat pump flexibility" section and according to scenario-specific limitations. Introducing flexible electricity demand by residential HPs in the model, this part of the demand can react to Austria's endogenously generated market price signals. In hours of lower electricity prices, the HPs reduce their electricity demand considering the given boundaries, and in times of higher electricity prices, they increase electricity demand.

As the standard flexibility scenario, the scenario with assumed heat storage of 3 kWh/kW was chosen (see Table 3). Figure 5 shows the load shifting behaviour of the residential HPs in a randomly chosen week (week 2) of 2030 in the standard flexibility scenario.

In times of (relatively) lower electricity prices, the HPs increase their electricity demand compared to the scheduled demand; in times of (relatively) higher prices, they reduce their demand. Since only preheating is possible due to the minimal temperature requirement, the load peaks take place first (and are more distinct) than the load reductions, which are

Table 4	Electricity	generation	per modelled	country and	l fuel
---------	-------------	------------	--------------	-------------	--------

Electricity gen- eration (TWh)	Wind	PV	Hydro	Natural gas	Coal	Lignite	Nuclear	Bioen- ergy + waste	Geo-thermal
AT	16.29	10.93	48.51	11.49	-	_	_	3.22	0.06
CZ	2.51	4.29	3.48	3.58	13.20	0.65	22.43	3.64	-
DE	185.26	113.57	35.46	18.29	94.47	53.97	-	22.85	0.30
HU	0.87	6.81	0.37	10.08	6.57	0.36	16.10	2.10	0.49
IT	56.26	62.17	46.64	107.76	38.92	-	-	3.93	8.28
SI	0.30	2.13	4.76	2.98	-	-	6.27	0.30	0.05

Electricity price (€2015/MWh)

AT

62.44

CZ

60.70

DE

56.68

HU

70.23

IT

69.68

SI

68.69

Table 5Average hourlyelectricity price in thereference scenario percountry



Fig. 5 Load shifting behaviour of the installed residential heat pumps (right axis) and electricity price (left axis) in 80 randomly chosen consecutive hours of the modelled year. Standard flexibility scenario (3 kWh/kW heat storage)

distributed over more hours. The shifting behaviour is not dependent on an absolute threshold but can be observed relative to the electricity price in the previous and following hours.

The following sections give an overview of the various effects of the load shifting of HPs on the electricity system in the assessed Austrian case. The results are presented as an explorative, deterministic sensitivity analysis, evaluating the impact of input choice on the analysed output variable. In the presented tornado charts (Figs. 6, 7, 8, 9, 10, and 11), the axis shows the value in the standard flexibility case (3-kWh storage capacity/kW installed HP capacity). The bars show the sensitivities for the (i) \pm 50% thermal storage, (ii) \pm 50% installed



Fig. 6 Shifted electricity downwards (GWh) for the flexibility scenarios compared to the standard flexibility scenario. In the standard flexibility scenario, the shifted electricity amounts to 194.01 GWh

HP capacity, (iii) $\pm 50\%$ share of controllable HPs, (iv) the introduction of a hard shifting time restriction, (v) the possibility of precooling (additionally to preheating), and (vi) the consideration of variable shifting costs (for the scenario assumptions, see again Table 3).

Shifted electricity demand

First, the amount of shifted electricity demand is a measure of flexibility provided to the system. The values presented in Fig. 6 show the sum of the downwardly regulated electricity demand, i.e. the reduction of peak load. The upwards-shifted electricity amounts to the same number plus efficiency losses caused by the shifting process.



Fig. 7 Avoided wind curtailment (GWh) (panel **a**) and avoided PV curtailment (GWh) (panel **b**) for the flexibility scenarios compared to the standard flexibility scenario. In the

standard flexibility scenario, the avoided wind curtailment is 19.16 GWh, and the avoided PV curtailment is 20.79 GWh

In the standard flexibility scenario, 194.01 GWh_{el} are shifted, i.e. 19.7% of the previously identified flexible HP electricity demand. In the sensitivity analyses, that amount varies between 89 and 648 GWh_{el} . In general, pessimistic sensitivity analyses have a slightly more significant impact than positive ones (see scenarios "Thermal storage", "HP capacity", and "Control share"). Additional thermal storage can barely be utilised, whereas a reduction of thermal storage capacity is clearly visible with 30 GWh less shifted electricity. The variation of the HP capacity and the control share



Fig. 8 Austria's solar generation, wind generation, hydro runof-river generation, and heating demand profiles (normalised)

has higher implications than variations in the thermal storage capacity. A hard shifting time restriction reduces the amount of shifted energy compared to the modelling approach of associated storage capacities (3 kWh/kW). This also aligns with the literature (Olkkonen et al., 2018) that finds flexibility potential quite sensitive regarding the assumed shifting time limitations. Considerably, assuming variable shifting costs of 29.5 ϵ_{2015} /MWh reduces the flexibility provided to the same extent as halving the available HP capacity.

The amount of shifted electricity is highest in the scenario, where (in addition to preheating) precooling was also allowed. This means an increase in consumers' acceptance of deviations below the intended indoor temperature (below 20 °C as assumed in the "cooling allowed" scenario). Then, around 2.5 times more electricity is shifted than in the standard flexibility scenario



Fig. 9 Overall system cost reduction (%) for the flexibility scenarios compared to the standard flexibility scenario. In the standard flexibility scenario, a - 0.011% reduction is achieved



Fig. 10 Panel a: Residual load boxplot and duration curve for the reference scenario, the standard flexibility scenario; panel b: Duration curve for the reference scenario for all hours with a residual load below -2 GW

(454 GWh). The reason for this is that, in contrast to preheating, precooling has no losses because there is no additional heat stored but temperature reduced (i.e. comfort loss). For preheating, an hourly loss of 5% was assumed (see the "Flexibility parameters" section), i.e. an efficiency loss caused by the shifting process. This is not the case for precooling and leads to higher utilisation of flexibility when precooling is possible.

Comparing our results to the literature, we find that the amount of shifted electricity in the standard flexibility scenario is in the medium range. Mascherbauer et al. (2022b), who considered only the thermal capacity of single-family houses without buffer tanks, found an amount of shifted electricity between 11 and 26 GWh_{el} for Austria when only the house-owners perspective is considered. Suna et al. (2022), who modelled more countries and all relevant flexibility options in Austria in a system optimisation approach, found 480 GWh_{el}/a to be shifted by HPs in Austria in 2030, considering thermal mass as well as typical buffer tank sizes of all buildings heated by HPs.

Curtailment

The results show that HP flexibility reduces curtailment of wind, PV, and hydro run-of-river generation (see Fig. 7 for wind and PV). The avoided curtailment in the standard flexibility case amounts to 19.16 GWh (wind) and 20.79 GWh (PV) in Austria. Numbers for hydro run-of-river can be found in the Appendix (see Fig. 14) and amount to 17.40 GWh compared to the standard flexibility scenario. This corresponds to 0.12% wind generation and 0.19% PV generation.

The hard shifting time restriction is a more relevant limitation for wind than for PV, i.e. -18.87 GWh compared to -11.62 GWh in the case of PV. That shows that wind generation could more often make use of more extensive storage than this limitation of the HP flexibility compared to PV. Kirkerud et al. (2017) also found that the flexible use of heat boilers is correlated positively with wind speed levels.

Figure 7 shows that wind power can benefit more from increased HP flexibility than PV generation, i.e. additional flexibility provided by HPs can mainly be used by wind generation. That is due to the higher temporal correlation between wind generation and HP utilisation (see Table 6) because wind generation and HP demand are higher during winter

Table 6 Correlation between heating demand and solar, hydrorun-of-river, and wind electricity generation in Austria

Correlation coefficient	Solar	Run-of-river	Wind
Heating demand	-0.299	-0.057	0.280

and night than during summer and the day. Increasing the storage capacity in the "Thermal storage +" scenario does not benefit PV curtailment because the heating demand in times of high solar generation is low, and additional storage cannot be used. Wind shows a positive correlation with heating demand in Austria (0.280), but PV (-0.299) and run-ofriver hydro (-0.057) generation show a negative correlation.

Especially for PV generation, a distinct, inverse seasonal pattern is observable compared to the heating demand (see Fig. 8), indicating a negative correlation.

These patterns show that HPs contribute to shortterm flexibility (hours to days), whereas the seasonal mismatch has to be covered by other flexibility options like export and import and HPs cannot be used for that. However, on the daily time scale (hourly fluctuations within a day), the contribution can be considerable in terms of power. Suna et al. (2022) show in their analysis that HPs provide up to 10% of the flexibility needed within a day (hourly fluctuations within a day, aggregated over the whole year).

System impacts

In general, overall system cost is reduced by HP flexibility since the model only chooses this option when the objective function of minimising overall system cost is reduced. The highest reduction can be seen in the scenario when precooling is allowed (-0.014%)(see Fig. 9). The reason for that is again that there are no thermal losses in the case of precooling but comfort losses.

Overall, system cost reductions are relatively low. However, it has to be kept in mind that six countries and their aggregated system cost were modelled, and Austria is a relatively small part of it.

In all flexible scenarios, the average electricity price of the reference scenario (62.44 ϵ_{2015} /MWh) is increased to between 62.49 ϵ_{2015} /MWh ("3-h shifting time restriction") and 62.70 ϵ_{2015} /MWh ("HP capacity+" and "Control+"). This means that hours of low prices are reduced, improving market values for renewable and helping their integration. Also, the standard deviation of the electricity price is reduced, creating a more stable market environment (see Table 7).

This result shows that HP flexibility can decrease price variance, which is expected to increase with a high share of fluctuating renewable electricity generation, especially in systems lacking sufficient transmission or large storage capacities (Schöniger & Morawetz, 2022). This balancing effect of HP flexibility is also visible when analysing the residual load (defined as exogenous load - wind generation - PV generation - hydro run-of-river generation) in Austria in different scenarios. Figure 10 panel a shows the residual load for the reference scenario and the standard flexibility scenario, which ranges between about 10 and -10 GW over the year with the given energy mix and export/import dynamics of the year 2030. It shows very similar characteristics for both scenarios, i.e. the maximal values and distribution of hourly residual load are barely impacted by the modelled HP flexibility.

However, evaluating the single hours in greater detail reveals some differences: Fig. 10 panel b shows the residual load duration curve for the standard flexibility scenario and three flexible scenarios. While changes in the overall load duration curve are barely visible, scenarios differ on the part of the curve with negative residual load. This means that the system profits from HP flexibility, especially during high renewable generation and the flexibility provision is mainly the uptake of surplus renewable generation, not the reduction of load during peak demand times. This flexibility provision by HPs mainly affects wind generation during winter since the highest PV generation occurs in summer. These results are also supported by literature which finds that HPs (Rinaldi et al., 2022) or, more generally, DSM (D'hulst et al., 2015) and sector coupling (Schill, 2020), mainly provide flexibility by consuming surplus renewable generation.

In hours when a positive residual load is decreased, the average reduction is $-2.6\%^5$ in the standard flexibility scenario and -3.8% in the "HP Capacity+" scenario (upper bound scenario). The downregulation shapes up to 4.6% of the Austrian exogenous load in the standard flexibility case.

In the hours when a negative residual load is increased, the average increase is 15.8% in the standard flexibility scenario and 21.6% in the "HP Capacity +" scenario. The shifting takes place mainly in the

 $^{^{5}}$ The stated average reduction and increase values are 5% trimmed mean values since in single hours, the values can be very high (in hours of a residual load close to 0).

 Table 7
 Standard deviation of the electricity price in selected modelled scenarios

	Reference	3-h shifting time restriction	HP capacity +	Standard flexibility
Standard deviation electricity price (ϵ_{2015} /MWh)	17.95	17.83	17.18	17.40

form of additional high peaks in times of low prices (shortly before they increase again; see Fig. 5) and then continuous reduction over several hours. In reality, the heat transfer coefficients are of crucial relevance regarding possible maximal heat transfer into and out of the thermal mass.

The assumed fossil fuel prices and CO_2 price lead to the result that overall CO_2 emissions are reduced in all flexibility scenarios compared to the reference scenario without flexibility (see Fig. 11).

However, this depends on the technology mix and the assumed carbon and fossil fuel prices because the objective function minimises costs, not emissions. Also, spill-over effects are observable, and CO_2 emissions in some countries are increased. This shows that flexibility always has to be analysed in the context of neighbouring energy systems and their interrelations.

Another result is that the necessary peak power capacity is not reduced in Austria, but this depends mainly on the district heat demand during winter provided by combined heat and power units.

Conclusions



We conducted an energy system analysis evaluating the flexibility potential that decentral heat pumps (HPs) for

Fig. 11 CO_2 emissions in the power and district heating sector in the modelled flexible scenarios compared to the inflexible scenario

space heating can provide to a decarbonised electricity system. Additionally, a detailed building technology operation model was used to derive central indicators of HP flexibility. The Austrian electricity system serves as a showcase for a high-share renewable electricity system because of its national target to increase renewable electricity supply so that renewable-based supply equals overall electricity demand at an annual balance by 2030. The country was modelled in the context of its neighbouring countries, considering import and export dynamics.

Former studies about HP flexibility can be divided into two fields: (i) Detailed building sector model analyses with a high-detail representation of techno-economic parameters like insulation status, technology, comfort level, and thermal losses, and (ii) energy system analyses in a broader context and consideration of various flexibility options and their interactions with the overall energy system. We bridged the gap between these two approaches in the literature and used a detailed building technology operation model to derive simplified input parameters for the energy system model (step 1) and fed them into an energy system analysis (step 2). Besides analysing the HP flexibility potential in Austria in 2030, we analysed the impact of the choice of input parameters by a deterministic sensitivity analysis. We ran eleven scenarios using the open-source energy system model Balmorel, implementing HP flexibility in ten scenarios with outputs being compared to one reference scenario.

Overall, positive system-wide effects of HP flexibility in Austria can be shown: reduction of system cost, renewable curtailment, and CO_2 emissions, as well as mitigating effects of the merit-order effect, smoothing of the residual load, and consequently, increased market integration of renewables. However, the respective amounts are relatively small. Avoided curtailment is about 0.2% of annual wind or PV generation (see the "Curtailment" section), reduced CO_2 emissions about 0.04% of the overall system⁶ (see the "System impacts" section). The reduction of emissions also depends on fossil fuel and carbon prices since the model minimises overall system cost, not emissions. This means that emissions do not necessarily decrease with HP flexibility in a different system (e.g. higher coal share and lower carbon prices).

However, in the short term, the impact in terms of power can be considerable. Installed overall peak load capacity is not reduced. This result confirms the findings of Kirkerud et al. (2021). HP flexibility shows its effect mainly in times of negative residual load when it increases electricity demand. In these hours, the increased electricity demand by the upward regulation of HPs amounts to, on average, 15.8% of the residual load (see the "System impacts" section), increasing the market values for renewables. System-wide effects are rather observable in terms of an increased residual load than in terms of reduction of peak load. In hours when the Austrian load is decreased by HP downshifting, up to 4.6% of the load is reduced. The average electricity price is increased in all flexibility scenarios, mainly due to the increase of residual load in times of high renewable generation. This economically fosters the integration of variable renewable energies since it reduces the merit order effect. Electricity price volatility is decreased by HP flexibility in all flexible scenarios compared to the inflexible case, leading to a more stable market environment. The amount of electricity shifted in the standard flexibility case is 194 GWhel, amounting to 19.7% of the identified available flexible HP electricity demand (see the "Shifted electricity demand" section). That amount varies between 89 and 648 GWh_{el} in the sensitivity analyses. An increase in consumers' acceptance of deviations below the intended indoor temperature (i.e. a comfort loss) increases the used flexibility potential significantly. We find that the flexibility potential provided by HPs is mainly concentrated in the heating season, meaning that the potential in summer is low. This is in line with other findings from the literature that find only minimal potential for balancing the seasonal mismatch of electricity demand and renewable generation (Schill & Zerrahn, 2020). The effect of HP flexibility is concentrated on the short-term balancing of the system (hourly). At the same time, other flexibility options have to cover the seasonal mismatch of electricity supply and demand. Our results show that HPs can foster wind integration better than solar integration due to the temporal correlation of heat demand (and associated flexibility potential) and wind power generation since both have their peak during the winter in Austria.

The conducted sensitivity analysis shows that the installed capacity of flexible HPs is the most critical assumption for the flexibility potential estimation. Installed HP capacities and share of controllable capacities show similar impacts since either one or the other parameter determines the installed, controllable capacity that can provide flexibility to the system. This stresses the importance of considering feedback mechanisms between energy efficiency and flexibility, which was also found by Rinaldi et al. (2022). The limitation of shifting time (in hours) is a parameter that reduces the potential compared to the modelling approach, where flexibility is provided via a storage capacity (kWh/kW) and thermal losses. Also, the assumption of variable shifting costs is a game changer: These costs reduce the (already small) economic business case considerably.

When analysing the flexibility that HPs can provide to the electricity system, the chosen model conditions are highly relevant: Generally, the more integrated and interconnected the modelled system, the lower the need for flexibility. This means the selected geographical scope of the analysis and the availability of other flexibility options, e.g. transmission capacities, demand side response, or investment options for large storage facilities in the electricity and district heat sector, impact the evaluated potential. We modelled Austria and its neighbouring countries, somewhat underestimating the flexibility potential of exports and imports beyond those countries' borders. Also, we did not explicitly model other demand side flexibilities, e.g. smart charging for e-vehicles. The availability of such options is expected to decrease the HP potential. However, the techno-economic assumptions for the HP flexibility were taken rather conservatively, considering the mentioned limitations

⁶ The overall system consists of the electricity and district heat sectors of six countries, with Austria contributing only a very small share to the overall costs and emissions. This is one reason why heat pump flexibility in Austria has a small effect on these two overall variables.

of the modelling approach. As done in our analysis, a joint optimisation approach serves as an upper bound for achievable operational cost savings (Patteeuw et al., 2016). In reality, real-time implementation will rely on price signals that can be either expectations or real-time pricing with suboptimal results compared to the overall system optimisation approach. Furthermore, HPs in district heating with large seasonal storage could help to mitigate the seasonal mismatch of electricity demand and supply (Kirkerud et al., 2021) but were not the focus of our study. For further analysis, it would be interesting to evaluate whether and how higherorder building models can improve the accuracy of the derived HP flexibility indicators and how this impacts the energy system model results.

This paper presents findings about the flexibility potential of demand shifting by heat pumps in Austria in 2030 that can provide useful insights for other countries on the path towards full decarbonisation. We further inform energy system modellers about which input parameters are most critical when condensing detailed building technology operation model information and using them as inputs for energy system models. We focused on a rather cold country and the heating sector. However, with the increasing impacts of climate change, demand for heating is expected to decrease, but demand for cooling is expected to increase (Viguié et al., 2021). The summer electricity system is characterised by high shares of fluctuating PV generation, increasing demand for flexibility during solar (off-)peak times. This development could lead to a more evenly distributed electricity demand for heating and cooling over the year, enabling easier balancing between solar generation and cooling on the one side and wind generation and heating on the other. This means that future research should emphasise the flexibility potential of cooling because it is negatively correlated with heating and positively correlated with the generation patterns of PV.

Nomenclature Indices a, A: Area, set of areas; A^R : Subset of areas in the region; c: Load shifting technology; g, G: Technology, set of technologies;

 G^{dis} , G^{ndis} : Subset of technologies that are dispatchable/non-dispatchable; G^{St} : Subset of storage technologies; r, R: Region, set of regions; t, T: Time step, set of time steps; tt: Timestep within the timeframe of load shifting; R^{exp} , R^{imp} : Subset of regions that can be exported to/imported from

Variables *C*: Newly invested capacity (MW); *E* : Energy content of the "virtual storage" (MWh); *P*: Shifted demand (MWh); *Q*: Commodity level (generation or consumption) (MW); Q^{curt} : Curtailed electricity (MW_{el}); Q^{dh} : District heat level (MW_{th}); $Q^{dh,inSt}$, $Q^{dh,exSt}$: Heat sent to/taken from storage (MW_{th}); Q^{el} : Electricity level (MW_{el}); $Q^{el,inSt}$, $Q^{el,exSt}$: Electricity sent to/taken from storage (MW_{el}); Q^{trans} : Transmitted electricity (MW_{el}); R: Realised demand after load shifting (MWh)

Parameters *av*: Availability of the technology (-); C_g^{Ex} : Existing technology capacity (MW); c^{Fix} : Fixed operation and maintenance costs (ℓ /MW); c^{Inv} : Annualised investment costs (ℓ /MW); c^{Var} : Variable operation and maintenance costs (ℓ /(MWh/h)); d^{dh} : District heat demand (MW_{th}); d^{el} : Electricity demand (MW_{el}); e^{loss} : Transmission loss (-); *L*: Scheduled demand (MWh); Δt : Maximal shifting time (h); Λ : Maximum electric demand (MWh) **Abbreviations** *COP*: Coefficient of performance; *DR*: Demand response; *HP*: Heat pump; *O&M*: Operation and maintenance; *P2H*: Power-to-heat; *PV*: Photovoltaics; *vRES*: Variable renewable electricity

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Data availability The datasets related to this article can be found at https://doi.org/10.5281/zenodo.7185318, an open-source online data repository hosted at Zenodo.

Declarations

Conflict of interest The authors declare no competing interests.

Appendix

Please see Figs. 12, 13, 14 and Table 8



Fig. 12 Stored energy divided by installed heat pump power in dependence on outside temperature when the room temperature is increased from 20 to 22 °C for 3 h (preheating). The installed HP power is designed to provide the heat needed for heating at -15 °C



Fig. 13 Avoided hydro run-of-river curtailment (GWh) in the flexibility scenarios compared to the standard flexibility scenario. In the standard flexibility scenario, the avoided wind curtailment is 17.40 GWh



Fig. 14 5R1C circuit representation (DIN EN ISO 13790)

The calculation of the circuit representation for the 5R1C model is described in the DIN EN ISO 13790 (for the European Standard, see CEN (2008)). The heat transfer through ventilation H_{ve} is directly connected with the node for the air temperature θ_{air} and the node representing the supply air temperature θ_{sup} . The heat transfer through transmission is divided into the window-related part $H_{tr,w}$, for which a thermal mass of zero is assumed, and the remaining part $H_{tr.op}$, which has the thermal mass and is further divided into two parts: $H_{tr,em}$ and $H_{tr,ms}$. The solar and internal heat gains are distributed across the node for the air θ_{air} , the mean node θ_s (a mix of θ_{air} and the mean radiant temperature $\theta_{r,mn}$), and the node representing the mass of the building zone θ_m . The thermal mass is represented by a single heat storage capacity C_m , which lies between $H_{tr,ms}$ and $H_{tr,em}$. A thermal coupling conductance is established between the node for the indoor air and the mean node. The heat flow due to internal heat sources Φ_{int} and the heat flow due to solar heat sources Φ_{sol} are distributed between the three nodes.

transmission coefficient for windows (W/K); H_{ve} , transmission coefficient ventilation (W/K); C_m , internal specific heat capacity (J/K); A_m , factor, effective mass-related area (m²)

Building	$A_f(\mathrm{m}^2)$	<i>H_{op}</i> (W/K)	H_{tr_w} (W/K)	<i>H_{ve}</i> (W/K)	<i>C_m</i> (J/K)	A_m factor (m ²)	Specific internal gains (W/m ²)	Description
1	180	200	200	45	300,000	3	3	Typical old single-family house
2	180	100	70	60	150,000	3	3	Typical new single-family house

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