ISEC 2024 – 3rd International Sustainable Energy Conference
Promising Heat Storage Technologies
https://doi.org/10.52825/isec.v1i.1132

Published: 22 Apr. 2024

Thermally Activated Building Structures as Flexibility Option for the Electricity Market

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Abstract. Combined with heat pumps, thermally activated building structures (TABS) can serve as a resource of flexibility for electricity markets and the grid. This paper analyses the energy-economic value resulting from utilising the flexibility enabled by thermal building inertia. The scope of the study is the Austrian building stock by the year 2040. A specific business model for using the flexibility from heat pumps in buildings is being developed in the PnP Control TABS research project. This paper also gives insights into the controller logic developed and first results from a demonstrator.

Keywords: TABS, Flexibility, Optimal Dispatch, Electricity Market

1. Motivation: Flexibility as a cornerstone of the energy transition

The volatility of electricity generation from wind and PV will increasingly challenge grid stability and also lead to price peaks on the power exchanges. Beside typical controllable power plants, also new storage technologies and flexible end consumers ("demand response") are needed to meet the future demand for flexibility. In this context, the use of the thermal inertia of buildings as flexibility is still scarcely considered by the energy industry. This paper aims at quantifying the economic value when leveraging this flexibility potential in the Austrian building stock by 2040. It sums up the results from a study prepared by IIBW and e7 on behalf of the Austrian Ministry for Climate Protection [1] and gives directions for the ongoing research project PnP Control TABS [2].

In the case of thermal building inertia, the flexibility potential for the electricity system arises from thermally activated building structures (TABS) and also underfloor heating systems powered by heat pumps. It takes many hours and days for the concrete structures to warm up and just as long to cool down. The control of the heat pumps can thus be adjusted to the requirements of the grid or the electricity market.

Flexibility is needed for various purposes in the system. In this context, it is crucial to differentiate between the following perspectives [3]:

- **System-side flexibility** describes flexibility dispatched by the Transmission System Operator (TSO) in order to ensure stability of the whole grid, mostly for the purpose of frequency regulation.

- **Grid-side flexibility** serves the Distribution System Operator (DSO) to avoid critical situations at certain nodes in the grid. Hence, grid-side flexibility needs to be always characterised by a locational information.
- **Market-side flexibility** describes the use of flexibility by actors on the liberalised electricity market, e.g. for price optimization when electricity prices are volatile.

From this differentiation, it can be concluded that the goal and rational of these three perspectives are not equal and can even contradict each other. However, in this study, flexibility is considered as a resource to shift loads from times of high electricity prices to times of low prices (i.e. market-side flexibility). This also maximises the use of renewable energy, since in times of surplus production through PV and wind, prices on the power exchange are typically low.

According to this scope, the aim of this work is to explore and quantify the flexibility potential from TABS and underfloor heating in the Austrian building stock by 2040. The focus is on the so-called “energy-economic value”, which means that the flexibility potential modelled is expressed in monetary terms. It describes the cost savings the energy industry (and hence the end-users) can achieve when dispatching the flexible heat pumps in a market-oriented schedule.

The remainder of this paper is organised as follows: Section 2 describes in detail the methodology, especially the building simulation and the optimisation model developed. Section 3 presents the findings of a market analysis about the future market trends of TABS and underfloor heating in the Austrian building stock. Section 4 reveals the flexibility potential on individual building level and on the level of the whole building stock. Section 5 describes how an actual control algorithm could leverage this flexibility potential and gives insights in the ongoing work of the research project PnP Control TABS. Finally, conclusions are drawn in section 6.

2. Methodology: Market analysis, building simulation and optimisation model

In a first step, based on the experience of IIBW and conversations with stakeholders, estimates have been formulated for the expected new constructions and renovations of residential and tertiary buildings in Austria until 2040. Then, e7 has deployed a methodology featuring dynamic building simulation and optimisation modelling. Different reference buildings were modelled and then simulated over the course of a year, taking into account outdoor temperatures, solar radiation and comfort zones for heating and cooling. This modelling and optimisation workflow is described in the following sub-sections.

2.1 Reference buildings and location

Four reference building types were selected and simulated due to their relevance and prevalence in Austria: Single-family house, multi-family house, office building and industry hall. Moreover, the different building usages were analysed for three building standards: New construction, refurbishment, and existing buildings. As heat distribution systems, TABS and underfloor heating (UFH) systems were defined. Note, that in this study, UFH is only used for heating, while TABS is also used for active cooling.

The modelling parameters for each building type were determined using the Swiss standard SIA 2024 [4] and the "Tabula" database [5]. PV was also assumed for some model variants. The profiles were generated for a southern orientation with a 30° elevation using the online tool Renewables Ninja [6]. In addition, a room temperature band was specified for each building type, which can be utilised as thermal inertia in the controlled scenario. It is assumed that there is sufficient user comfort within this band. The surface heating systems are each operated with heat pumps. A distinction is made between air source heat pumps (more precisely air-to-water heat pumps) and ground source heat pumps (more precisely brine-to-water heat pumps or water-to-water heat pumps). Both types have a different coefficient of performance (COP). The COP for ground source heat pumps is assumed to be constant at 5 for both heating and cooling, regardless of the outside temperature. For air source heat pumps, the COP fluctuates with the outside temperature. In the heating mode it is between 2 (at 0°C) and 4 (at 25°C), in the cooling mode between 4 (at 14°C) and approx. 3 (at 30°C).

A representative location in Austria was selected for the building simulation in order to be able to use the same weather data for all reference buildings. The selected location should be approximately an average for the whole of Austria and represent both the majority of existing buildings and the potential for new construction. After analysing the heating degree days and evaluating the number of locations in different heating degree day ranges, four potential locations identified: Klagenfurt, Amstetten, Steyr and Linz. The weather data from these locations were then compared in terms of outdoor temperature, outdoor humidity and solar radiation. Based on the similar trends of the analysed parameters, Linz was selected as the representative location, as it has both urban and rural characteristics.

2.2 Dynamic building simulation and thermal reference cases

Based on the real weather data of Linz, the entire year was divided into seven typical reference days (very cold, cold, cool, moderate, warm, hot and very hot). To define these reference days, for each of these categories, a representative day was identified in the weather dataset based on the outdoor temperature. The temperature was then averaged over the entire day, in order to enable uniform reference cases that can be further used in the (linear) optimisation problem. The typical reference days were then distributed over the entire year, based on the real daily mean temperatures. The final reference days and their number of occurrence throughout the year are shown in Table 1.

Table 1. *Reference days with average outdoor temperature and frequency of occurrence in one year.*

Reference day	Average outdoor temperature [°C]	Number of days per year
very cold	-5.3	10
cold	-0.2	51
cool	4.6	77
moderate	10.0	68
warm	15.2	72
hot	20.0	65
very hot	24.7	22

In a next step, the thermal inertia of the buildings was investigated as part of the dynamic building simulation, using the software IDA ICE. After drafting a 3D model (including all thermal properties) for each of the building types, the heating patterns as well as the heat loss patterns were tested. This has been achieved by creating a simulated thermal test, meaning that the building was heated up until reaching a maximum comfort level (24°C) followed by a steady cooling down (due to thermal losses) until reaching a minimum comfort level (21°C). For active cooling, the same thermal tests have been conducted during summer days for a comfort interval between 24°C and 27°C. Figure 1 shows as an example the thermal test for the building type “single-family house with TABS” on the reference day “very cold”.

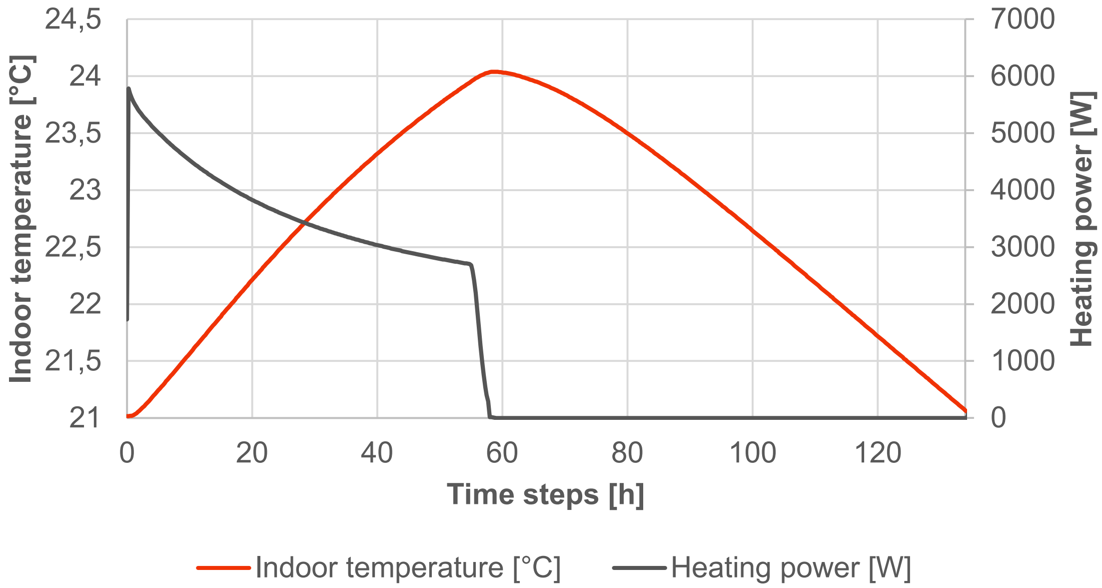

Figure 1. *Thermal test for the building type “single-family house with TABS” on the reference day “very cold”*

2.3 Optimisation: Economic Dispatch

In the next step, the results of the building simulation were integrated into an optimisation model. The model was formulated in the GAMS modelling environment and solved with the highly efficient optimisation solver CBC.

As an output, the mathematical optimisation model suggests a control strategy for the buildings’ heat pumps to minimise energy costs in a dynamic electricity pricing scheme. Note, that the main priority is always maintaining the users’ comfort boundaries, which means that price optimisation is limited by an indoor temperature range in the building. Comparing an uncontrolled scenario (business as usual) with a price-controlled optimised scenario (spot market prices on the day-ahead market with forecast prices and volatilities until 2040, based on [7]), the monetary energy-economic value of flexibility from TABS and underfloor heating systems is then calculated. The optimisation problem is formulated as described in the following paragraphs.

The objective function of the model minimises the electricity costs C over all time steps t of a year:

$$C = \sum_{t} p_{DA(t)} \cdot (E_{\sup(t)} - E_{fi(t)})$$

Here, p_{DA} represents the electricity price on the spot market, E_{sup} the amount of energy purchased for heating/cooling and E_{fi} the surplus PV generation that is not consumed by the heat pump for heating/cooling and fed in back to the grid. It should be noted that not all model scenarios include a PV system. In addition, although the revenues for the surplus feed-in are included in the optimisation, they are deducted from the selected cost savings. This guarantees that the energy-economic value actually only relates to the flexible control of the heat pump and not to the feed-in of surplus generation.

The results of the building simulation are incorporated into the optimisation model via the thermal test cases described before (for each building type and reference day). Following parameters are derived from this thermal test cases:

- Timespan for heating (from 21°C to 24°C in the heating period);
- Timespan of cooling down (from 24°C to 21°C in the heating period);
- Amount of heating energy required for the heating process.

This results in the following respective input parameters:

- on describes the increase in room temperature during a time step t if heating is on during this time step;
- off describes the decrease in room temperature during a time step t if heating is off during this time step;
- q_{HP} describes the heating energy that needs to be provided by the heat pump in a time step t if heating is on in this time step.

The room temperature T_{ia} can therefore be calculated as a variable as follows:

$$T_{ia(t)} = T_{ia(t-1)} + Switch(t) \cdot on(t) + \left(1 - Switch(t)\right) \cdot off(t)$$

The variable $Switch$ describes whether or not heating is on at the relevant time step. The variable can therefore be defined as a binary variable or as a linear variable with values from 0 to 1. The linear simplification generates only negligible deviations compared to the solution in the binary programme, but is clearly superior in terms of calculation performance.

Finally, the temperature comfort band must be defined by

$$T_{\min} \leq \mathrm{T_{ia(t)}} \leq \mathrm{T_{max}}$$

and also the COP of the heat pump $eta_{HP(t)}$ needs to be considered for calculating the amount of electrical energy required:

$$\mathrm{E_{sup(t)}} = \mathrm{Switch(t)} \cdot \frac{\mathrm{q_{HP(t,a)}}}{\mathrm{eta_{HP(t,a)}}}$$

3. Market trend for TABS and underfloor heating

In order to answer the research question of this study about the future significance of TABS for the energy industry, an estimation model was developed for the expected new construction of residential and tertiary buildings in Austria by 2040 as well as the renovation of existing buildings. First insights of this analysis have already been published in [8]. Based on previous new construction rates and the forecast of household development, a variety of input variables were taken into account, such as the development of vacancy rates, the development of demolition and replacement construction, the trend towards renovation of existing buildings, investment trends, and many more. With the support of a network of experts, a plausible penetration of the new technology of TABS and (also activated) underfloor heating was assigned to the estimated values for new construction and renovation, and on this basis a market trend for thermally activated building area was estimated by 2040. The results were subjected to multiple plausibility checks and sensitivity tests.

Under the assumptions made in the model, it is estimated that the market penetration of TABS in Austria will increase rapidly in view of the many advantages of the system. From about 500,000 m² of newly installed space today, the annual output is expected to increase to over 2.5 million m² by 2040. Cumulatively, this is then close to 30 million m² (residential and tertiary buildings, new construction and renovation combined), whereby not the entire potential is operated with heat pumps. Underfloor heating (which can be activated to a lesser extent to serve the grid) will start with a significantly higher volume of currently about 2.5 million m², which will increase to about 4 million m². Cumulatively, this will be over 50 million m² (without existing stock). Together, this will be almost 12% of the building stock in 2040. In view of the rapidly spreading smart-ready heat pumps, a significant volume of thermally activated space will be available in Austria in the foreseeable future. The results of the market analysis are shown in Figure 2. This forms the basis for scaling up the results of the optimisation model for the whole Austrian building stock.

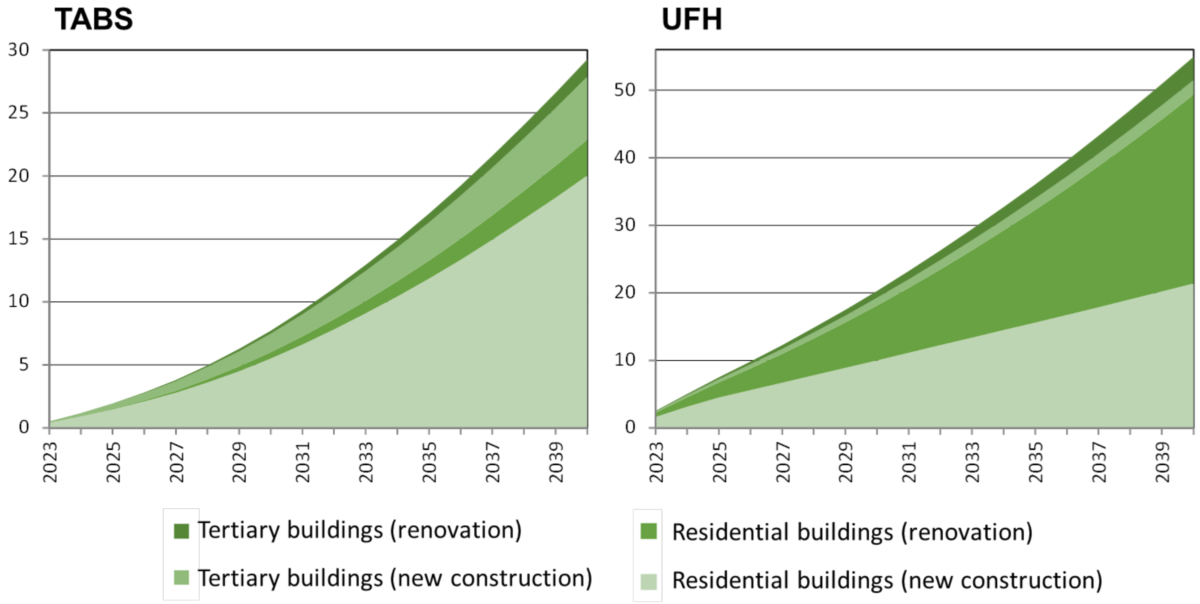

Figure 2. *Estimated cumulative development of TABS- and UFH-activated area by 2040 (million m²)*

4. Energy-economic value of TABS

As described above, a dynamic building simulation has been conducted for the following building types: single-family homes (SFH), multi-family homes (MFH), offices and industry halls, each with different construction standards and with TABS and UFH. For the model scenarios in the optimisation model, the building types hotel, retail and culture/education were also added, as these also appear in the building statistics, but only with small total areas. For this reason, the MFH building model was used for hotels and the office building model was used for the retail and culture/education categories. The following sub-sections present the results of the energy-economic value firstly on the level of individual buildings and secondly on the level of the whole Austrian building stock.

4.1 Flexibility potential at building level

As a representative example of all model variants, the results of the optimisation are now presented in detail using the example of a new-build flat in an MFH with TABS. Essentially, the aim is to show how the heat pump control is orientated towards the spot market price and what cost savings are possible as a result.

Figure 3 shows the control signal of the heat pump in the model. A week (Monday to Sunday) in March 2040 was selected for visualisation. It can be seen that in the controlled scenario (OPT), the heat pump is activated when the electricity price is particularly low. In the uncontrolled scenario (BaU), the heat pump is activated at any time so that the specified temperature range is maintained.

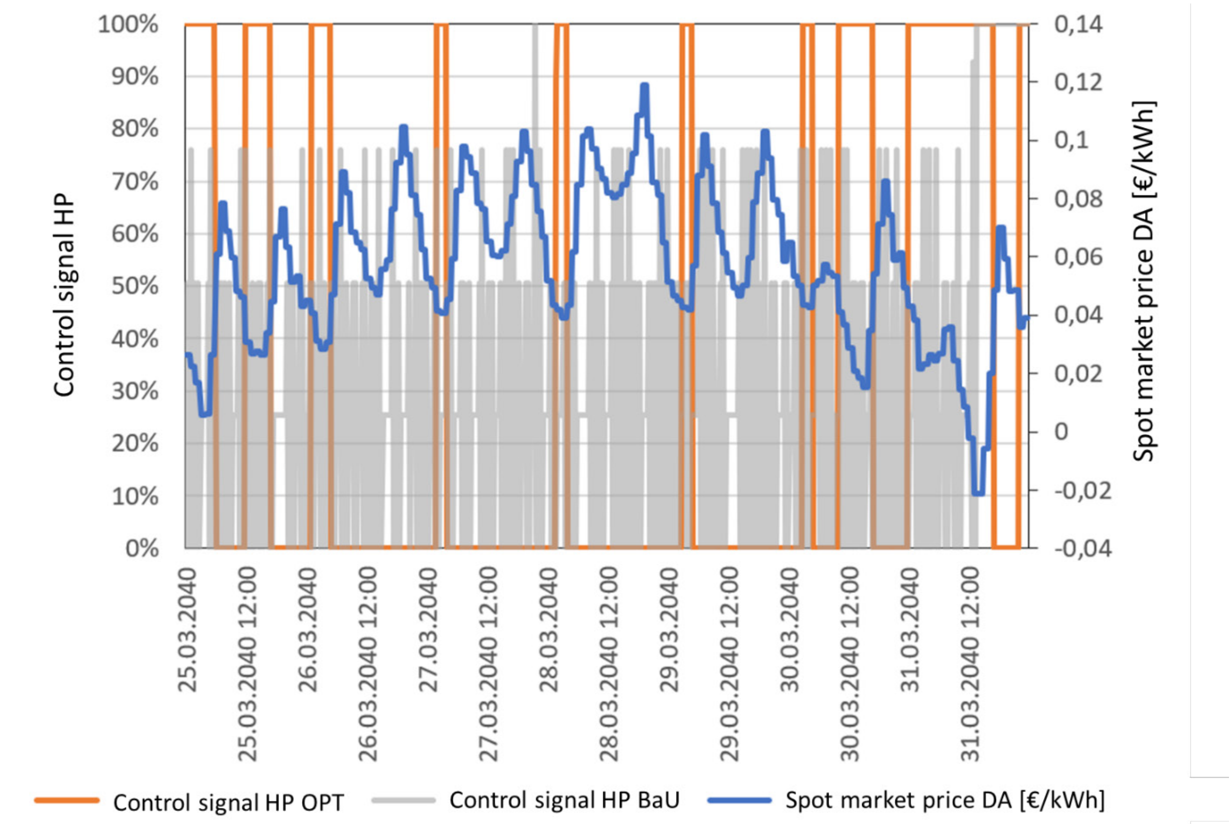

Figure 3. *Control signals oft he heat pump in the simulation for the scenarios BaU and OPT for the example of a MFH (new construction) with TABS*

Looking at all the various model scenarios (building type, building standard, heat output system, PV, heat pump), it can be concluded that the cost savings from price-optimised operation of heat pumps at an average amount to around 22 % in 2025, but 50-75 % in 2040, depending on the building type. The savings are higher for buildings with air source heat pumps than with ground source heat pumps, which is due to the greater efficiency of the ground source heat pump. Electricity from PV reduces the benefit from price-optimised electricity procurement from the grid, as it leads to higher independence form grid-supplied electricity and thus lower cost saving potential. The cost savings achieved for individual building configurations in the 2040 scenario are shown in Figure 4.

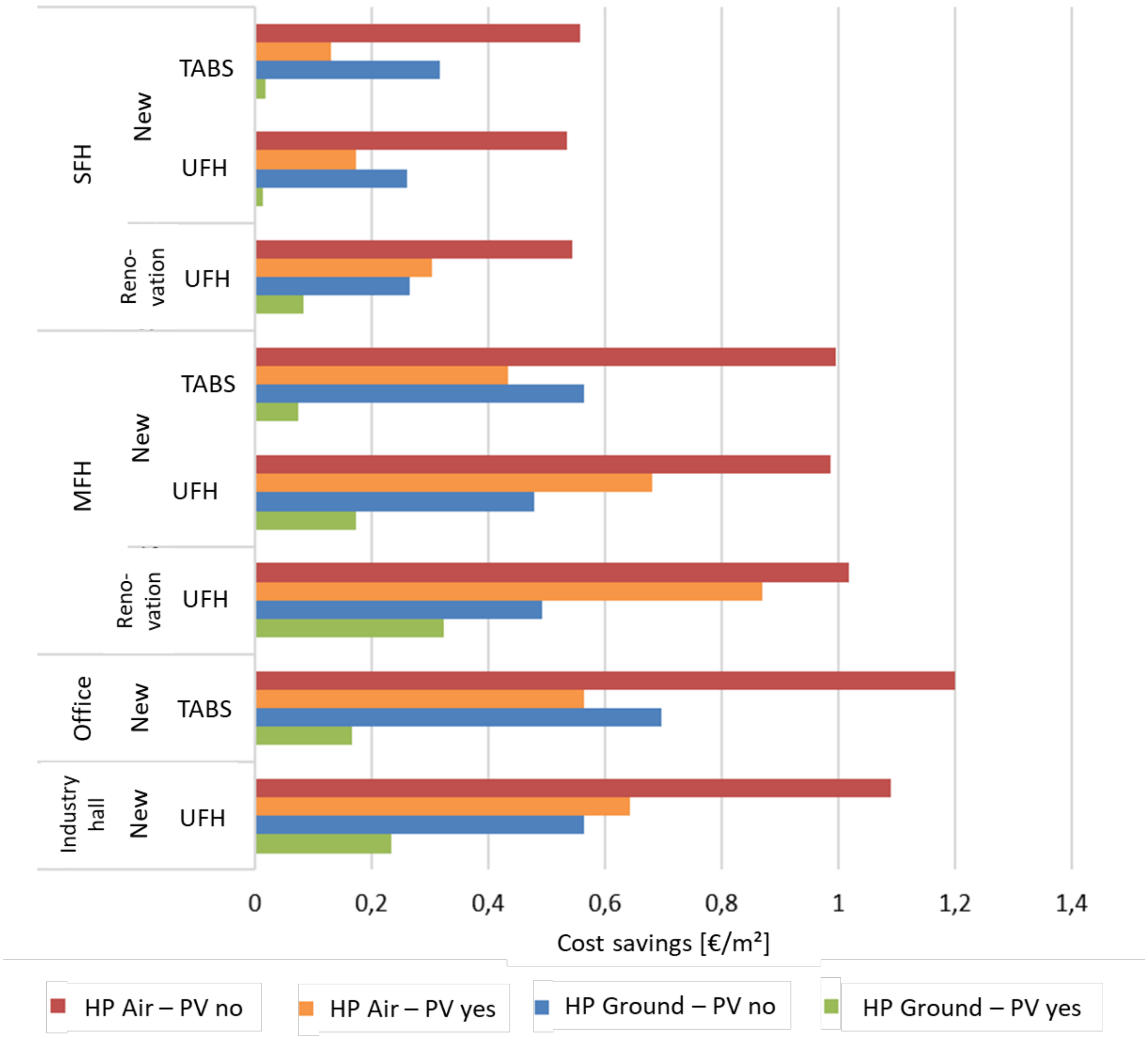

Figure 4. *Specific cost savings in €/m² by utilising the flexibility potential in 2040 for individual building types*

4.2 Flexibility potential of the Austrian housing stock by 2040

If these results are combined with the results of the market analysis, the potential for the entire thermally activated building stock in Austria can be calculated. The achievable cost savings thus reach around € 23 million in 2040, with large-volume residential buildings being by far the most important. Also, underfloor heating in new builds and refurbishments is more relevant than TABS. The overall cost savings for the year 2040 are shown in Figure 5.

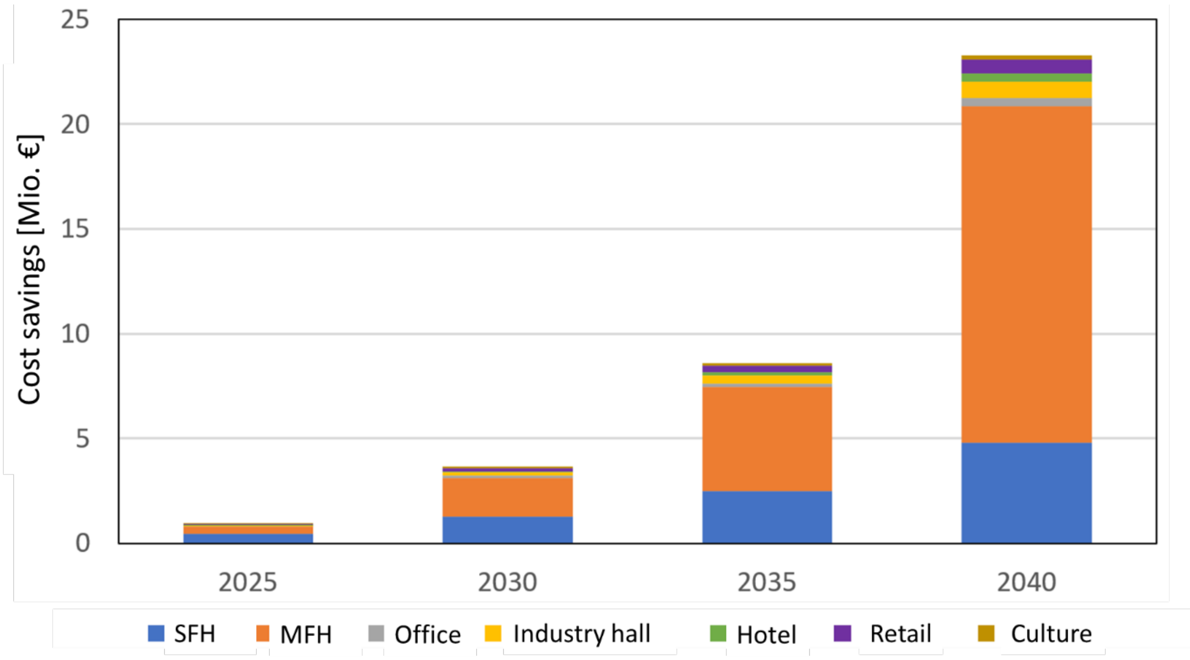

Figure 5. *Cost savings in million € in 2040 by utilising the flexibility potential of the entire thermally activated building stock, differentiated by building type*

To understand the only moderate cost savings, it should be added that only the energy for heating and cooling, but not for hot water, was taken into account. Furthermore, only the pure energy costs are included, not network charges, taxes and levies. In addition to the direct cost advantage, there are many other benefits of optimised heat pump control for energy suppliers and grid operators, but these are difficult to quantify in monetary terms. After all, load shifting during low-price periods contributes to better utilisation of renewable energy sources and thus to achieving climate targets.

5. Development of a Plug-and-Play control strategy

In order to realise this flexibility potential in practice, the necessary technical requirements for controlling heat pumps are needed on the one hand, but also corresponding offers on the market on the other hand. A specific business model for using the flexibility from heat pumps in buildings is being developed in the PnP Control TABS research project. The aim of the project is to design a standardised plug-and-play control strategy in which an optimisation algorithm reacts to dynamic day-ahead price signals and the predicted local photovoltaic production. In addition, the DSO is capable to activate positive or negative short-term flexibility calls to compensate for errors in the production and consumption forecasts and balance its portfolio. The required electricity price and weather forecasts are provided by a cloud-based grid-data-manager which clusters and manages the flexibility calls for the DSO.

Starting the control design in simulation environments, the developed procedure was continuously reduced in complexity to meet, in its current version, the requirements for practical implementation in various demonstration buildings. In its core, the developed control procedure is based on forecasts of internal and external operational boundary conditions like

i) the outdoor air temperature (nowadays widely available from commercial and non-commercial providers),
ii) the availability of local renewable energy (photovoltaic power forecast either direct from specific providers or estimated from solar radiation predictions),
iii) the domestic electricity consumption to calculate the excepted surplus power (done by data-driven approaches or simple by standard load profiles) and

iv) the future electrical energy costs like the day-ahead market prices blended with the local network tariff, fees and taxes and overlaid with short-term flexibility calls by the DSO if required (in particular the minimal 12-hour future horizon of the day-ahead market prices needs to be extended with additional simple market estimations to achieve sufficient long control horizons).

Together with a thermal building model, the future boundary conditions, estimate the dynamic thermal comfort within in the building. To maximise the scalability, a trade-off between a simple model structure, with minimal required parameters and inputs, and a sufficient control performance was made. The model parameter estimation can be done by data-driven identification methods, although an intuitive manual tuning is possible and allows to adjust the control behaviour during operation without the need of high-quality building data. A further simplification is to split the model in its dynamic and steady part. The novel approach allows to estimate the future thermal losses of the building purely based on the steady state model parameters, whereas the dynamic parameters are used to assess the flexibility of the thermal comfort.

The optimal future operation plans for the heating system are derived by numerical optimization combined with the receding horizon principle, considering the respective objective function and the thermal constraints within the building. Since a linear model structure could be found, mixed-integer-linear-programming is applied to solve the optimization problem. The resulting operation plans, basically an on/off signal, needs to be further translated to e.g. setpoint offsets and/or blocking commands on different levels of the hydraulic system (heat pump, optional puffer storage, heating circuit or even room temperature controller).

In its simplest form, the procedure can be reduced to a straight feed-forward formulation without the need of any live information of building itself, like the indoor air temperature. Provided that an accurate building model is available, the complex, computationally intensive calculations are no longer necessary on site and software-as-a-service business models can further enhance the urgently needed market penetration of sophisticated load shift algorithms.

The developed control strategies are demonstrated in multiple test buildings under real world conditions and first results from October to December 2023 of the ongoing practical evaluation in a domestic application (single-family house) are presented. The building fulfils the actual regulations according to thermal insulation and has a rather heavy construction with brick walls and concrete ceilings. An air-to-water split heat pump supplies directly (without puffer storage) the under-floor heating system and prepares the domestic hot water. A south oriented, roof-mounted 15 kWp photovoltaic systems provides local renewable energy and an electricity contract based on the day-ahead prices of the Austrian bidding zone with typical processing fees, taxes and the local network tariff is assumed. The OeMAG feed-in tariff for 2023Q4 with 0,1246 €/kWh is applied to consider the opportunity costs if the heat pump operates on photovoltaic energy. The hot-water strategy is simple rule-based with one fixed forced charging period in the hour with the expected highest photovoltaic output between 12:00 and 13:00.

For the presented evaluation the total photovoltaic energy is available for the heat pump and only the electrical consumption of the heat pump is taken into account, the domestic consumption is not considerate. In the three months October, November and December 2023, the first half of the heating season, the heat pump consumes 990 kWh electrical energy with 62 % direct solar consumption. The remaining 372 kWh are consumed from the grid, either with simultaneously solar consumption or with 100 % grid consumption at low price time periods. Figure 6 shows the resulting heat pump operation for a (cold) representative calendar week at the beginning of December. Primarily the heat pump consumes photovoltaic energy since the import price is above the export price for most of the time. Since the time periods with available photovoltaic energy are not sufficient to cover the heating demand, additional energy is consumed from the grid, preferably at the lowest possible costs.

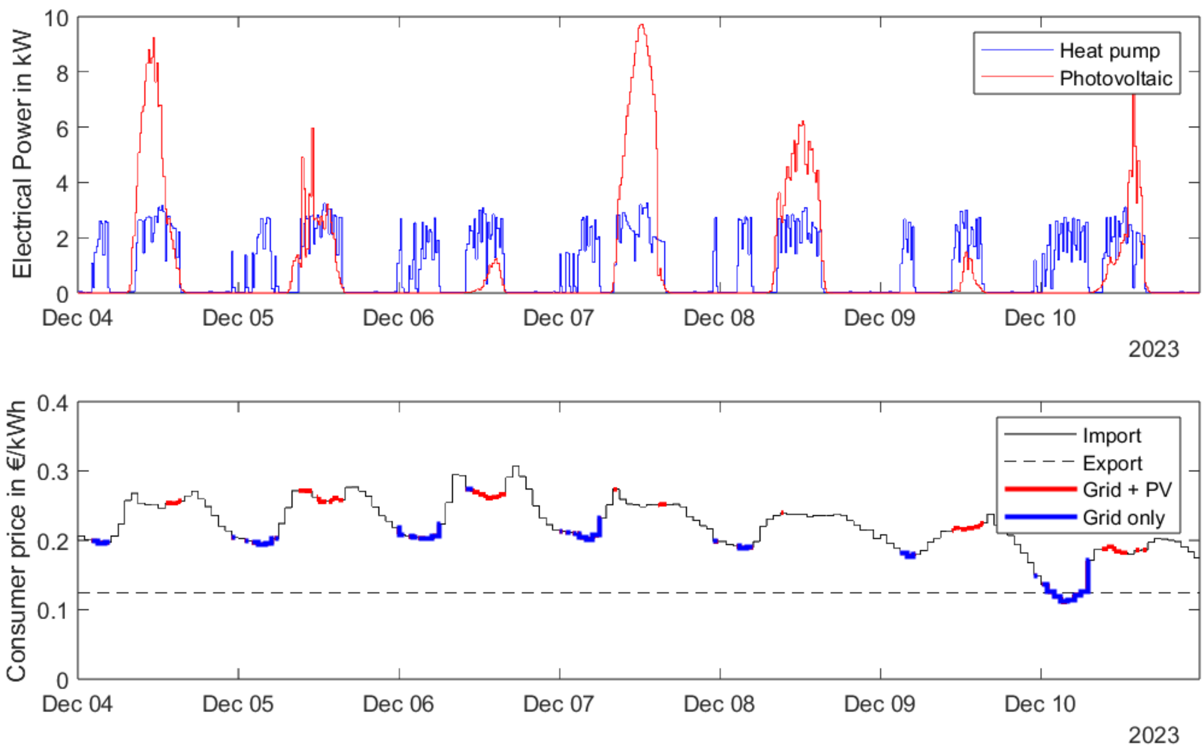

Figure 6. *Experimental results of the controlled heat pump to account for local photovoltaic energy (top) and flexible electricity prices (bottom) in a residential demonstration building. The utilised prices are marked in red if the heat pump runs partly on solar and blue if it runs purely on grid energy.*

The realized total heat pump operation costs for the three months are 139,84 € if the solar opportunity costs are considered and 62,72 € when solar energy is free of charge. Assuming an evenly distributed energy consumption with the mean day-ahead electricity price, the benchmark operation costs would be 198,24 € resulting in costs savings of around 30 % to 70 %, depending on the solar energy feed-in tariff.

6. Conclusion: How to unleash the flexibility potential of TABS?

Building on a comprehensive methodology consisting of an explorative market analysis, dynamic building simulation and optimisation modelling, this study has quantified the future flexibility potential of thermally activated buildings (TABS and UFH) in the Austrian building stock by the year 2040. This potential can be utilised for the electricity system through smart operation of heat pumps. The energy-economic value of such applications can be calculated by modelling a market-oriented control strategy of the heat pumps.

The results show that the load shifting potential is significant, however, the cost savings achieved (either by end-users or specialised service providers applying respective business models) tend to be small. The main reasons for this can be summarised as follows:

- When optimising towards prices on the spot markets, savings can only be achieved regarding energy costs, but not regarding grid tariffs and taxes. Typically the latter are responsible for two thirds of the end-users' total energy bill.
- Smart ready heat pumps capable of implementing flexible control strategies are mainly in newly constructed or refurbished buildings, which generally are already very efficient. This means the potential of cost savings is small compared to older and less efficient buildings (which are typically still operated by fossil-fuelled heating systems).
- This study focussed on market-oriented use of flexibility. There might be additional benefits when using the flexibility for grid support and frequency regulation. However,

these benefits are hard to quantify, partly due to a lack of mechanisms in which demand side assets can participate.

There is certainly a need for further research and awareness raising for testing such concepts in large-volume residential buildings, in which TABS will play an increasingly important role. In this context, real estate developers should be made aware of the advantages of using flexibility and the technical requirements that need to be taken into account during construction and renovation.

Author contributions

Guntram Pressmair: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Visualization, Software. **Wolfgang Amann:** Conceptualization, Methodology, Formal analysis, Data curation, Project administration, Funding acquisition. **Alina Stipsits:** Conceptualization, Methodology, Formal analysis. **Sama Schoisengeier:** Formal analysis, Data curation, Validation, Writing – review & editing, Software. **Florian Wenig:** Chapter 5 - Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Visualization, Software

Competing interests

The authors declare that they have no competing interests.

Funding

The work published in this paper has been financially supported by the Austrian Research Promotion Agency (FFG) through the study "Bewertung der Bauteilaktivierung als Option für Flexibilität im Strommarkt" and the project PnP Control TABS. The knowledge gained is disseminated to international stakeholders through active participation in the technology collaboration programme IEA ES Task 43 - Standardized use of building mass as storage for renewables and grid flexibility.

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