

# Assessing flexibility offers of different building age classes utilizing thermal mass

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**Abstract.** This study investigates how building age classes influence thermal flexibility offers for demand-side management in power grids with increasing renewable energy integration. Using a model predictive control approach applied to simulation models, we analyze residential buildings from various age classes (1945-2025) with different heat transfer systems (radiators and underfloor heating) to quantify available energy flexibility and associated costs. Our analysis shows that energy flexibility reaches average values of up to 37 Wh/m<sup>2</sup>, with older buildings offering greater potential than newer ones. While newer buildings offer less flexibility, they can provide flexibility at lower average costs of approximately 5 ct/kWh to 10 ct/kWh. While radiators provide greater absolute flexibility due to faster response times, underfloor heating offers more cost-efficient energy storage. Heat pump modeling significantly impacts cost assessments, with Carnot models potentially overestimating efficiency losses. Based on these results, optimal flexibility portfolios from a grid operator perspective would combine numerous newer buildings providing cost-efficient flexibility with select older buildings capable of delivering larger flexibility volumes during high-demand periods.

## 1. Introduction

The increasing share of renewable energy in the power supply creates a growing need for flexibility to stabilize the power grid. With their high primary energy demand and growing electrification, building energy systems offer significant potential for providing flexibility [1]. Particularly, residential buildings are of interest due to their high demand for space heating [2]. To utilize this flexibility, buildings can trade their flexibility on flexibility markets. The necessary flexibility offers consist of the amount of available flexibility and the associated costs for flexibility activation. Understanding how these flexibility offers differ across various building configurations is crucial for accurately estimating the total flexibility resource available within the residential sector. A key factor influencing the available flexibility offers is the building age class and the corresponding transfer system. Depending on the age class, the thermal mass and insulation of the building vary. This also alters the available storage capacity and thus the flexibility quantity, as well as storage efficiency and the resulting costs. Moreover, building age classes are typically associated with specific heat transfer systems, which further influence the flexibility characteristics. Previous work has identified a significant influence of the age class on the available amount of flexibility [3, 4]. However, the associated costs have not yet been investigated, making the influence on flexibility trading unclear.

Therefore, this work examines how different building age classes, together with their typical



transfer systems, influence the available flexibility offers and their associated economic implications.

### *1.1. Related Work*

The literature contains numerous works investigating the flexibility of the thermal envelope of buildings. Askeland et al. investigate old and modern buildings and find that the flexibility potential provided by thermal mass is significant when compared to its equivalent battery storage [5]. Johra et al. examine two different building age classes, each with either radiator or underfloor heating as transfer systems [6]. They find that building insulation has a greater influence on flexibility than thermal mass. Additionally, older buildings, due to higher losses, also have more potential for load shifting. Reynders et al. investigate a variety of different building age classes, also with radiator and underfloor heating systems [7]. Their results similarly show the significant influence of insulation and, additionally, the inefficiency of radiator systems for storing energy in thermal mass. In further work, van der Heijde et al. examine different age classes based on the Belgian building stock and investigate these regarding available flexibility [8]. They find that radiator systems can achieve higher peak flexibility, but with significant fluctuations, whereas underfloor heating systems exhibit more predictable flexibility within a more constrained interval.

All works presented here demonstrate the significant influence of building age class and associated transfer systems on available flexibility. However, the costs of activating flexibility are not considered.

De Coninck et al. and Harder et al. determine not only the amount of flexibility but also the costs for activation, thus providing flexibility offers, using a quantification approach based on model predictive control (MPC) [9, 10]. However, they only examine individual buildings without variation of the age classes. In our previous work, we used a comparable MPC approach to estimate the influence of the thermal envelope on flexibility offers [11]. However, our analysis was limited to only two different envelopes of non-residential buildings and did not include a detailed examination of residential building age classes.

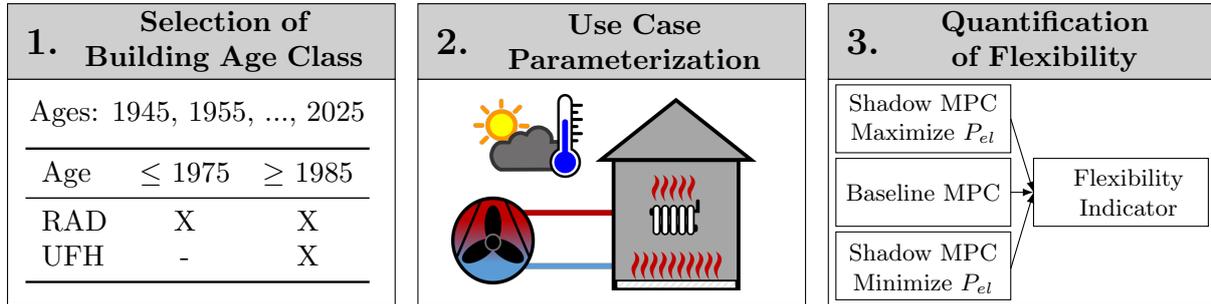
In summary, a significant influence of the building age class on available flexibility can be identified in the literature. Some works have also investigated the actual costs of activating flexibility. However, to the best of the authors' knowledge, no work has been published that systematically investigates the influence of the building age class on available flexibility offers. With this work, we aim to contribute to closing this gap.

## **2. Methodology**

The methodology applied in this work consists of three steps as illustrated in Figure 1. To clarify the relationship between the individual steps, the process steps are described in reverse order.

### *2.1. Quantification of Flexibility*

For the quantification of flexibility offers, we introduced an agent-based framework in a previous paper, which is based on multiple MPCs [11]. A baseline MPC is responsible for controlling the building. At the same time, two additional shadow MPCs maximize or minimize power during a defined flexibility event while keeping thermal comfort and without influencing the actual operation of the building. The defined flexibility event begins after a preparation time to maximize the potential for flexibility during the event. Through the rolling horizon approach of the MPCs, the available flexibility for the respective future event is predicted at each time step. This allows a continuous quantification of the maximum available flexibility during the operation of the building. For further details on the agent-based framework, readers are referred to [11].



**Figure 1.** Overview of the three-step approach for assessing flexibility offers of different residential building age classes

From the resulting predictions of the electrical power of the three MPCs, flexibility can be determined using various indicators. These indicators are each divided into positive (minimization of electrical power) and negative (maximization of electrical power). In this paper, the indicators energy flexibility  $\epsilon$  (Equation 1) and specific costs for activating that amount of energy flexibility  $c_{Flex}$  (Equation 2) are used.

$$\epsilon = \int_{t_{Prep}}^{t_{Prep}+t_{FE}} (P_{el,base}(t) - P_{el,shadow}(t))dt \quad (1)$$

$$c_{Flex} = \frac{|\int_{t_{Start}}^{t_N} c_{el}P_{el,base}(t)dt - \int_{t_{Start}}^{t_N} c_{el}P_{el,shadow}(t)dt|}{\epsilon} \quad (2)$$

$P_{el,base}$  describes the predicted power of the baseline, while  $P_{el,shadow}$  describes that of the respective shadow MPC. The preparation time  $t_{Prep}$  and duration of the flexibility event  $t_{FE}$  are used for calculating the energy flexibility, while the calculation of costs is performed over the entire prediction horizon ( $t_{Start}$  to  $t_N$ ) to include costs caused by the flexible operation before and after the event. To determine these costs, the difference between the total electrical energy consumption of the shadow MPC and the baseline MPC is multiplied by the electricity price  $c_{el}$ , effectively representing the difference in operational costs between the two control strategies, divided by the available energy flexibility  $\epsilon$ .

In [11], it was shown that calculating costs is challenging for inert systems. For inert systems, the operations of the shadow MPCs may not converge with those of the baseline, depending on the length of the prediction horizon. Thus, the shadow MPCs may possess a different amount of stored energy in the thermal mass compared to the baseline. This stored energy does not affect the available amount of flexibility, but it does affect the associated costs, as the energy difference can lead to further deviations in operations after the prediction horizon. To account for this, we introduce the corrected costs for flexibility:

$$c_{Flex,corr} = \frac{|\int_{t_{Start}}^{t_N} c_{el}P_{el,shadow}dt - \int_{t_{Start}}^{t_N} c_{el}P_{el,base}dt|}{\epsilon} - c_{el}\Delta E_{el}(t_N) \quad (3)$$

Here,  $\Delta E_{el}$  describes the difference in the thermal energy still stored within the thermal mass at the last time step of the MPC predictions, expressed in terms of equivalent electrical energy. Throughout the remainder of this paper, the term costs for flexibility  $c_{Flex}$  always refers to the corrected costs.

### 2.2. Use Case Parameterization

A simulation model of a residential building is used as a use case. The investigated building consists of a thermal zone, a heat transfer system, and a heat pump. All components are created

and parameterized using the Modelica library AixLib [12]. The zone is modeled as a single-family house and is based on a reduced order approach [13]. For heat transfer systems, this study employs radiators (RAD) and underfloor heating (UFH), the most common systems in practice. These are modeled using the AixLib components *PanelHeating* and *Radiator* respectively. A heat pump is also included to convert the thermal flexibility of the building envelope and the heat transfer systems into electrical flexibility. This is modeled in a simplified manner via a Carnot coefficient of performance (COP) with a constant efficiency factor representing the ratio of actual to Carnot performance.

Since multiple building age classes are investigated, each transfer system and corresponding heat pump must be properly sized depending on building characteristics. Therefore, the heat demand is calculated following the normative approach described in DIN EN 12831 [14], which determines the design heat load required to maintain indoor comfort conditions during extreme outdoor temperatures. This standard uses the location-specific design outdoor temperature to represent these extreme conditions, typically defined as the minimum two-day mean temperature that statistically occurs once in 20 years. To determine the standard heating load, the model is simulated using this design outdoor temperature as input. The resulting maximum heating load value is then established as the nominal output capacity for both the heat transfer system and the heat pump. The dimensioning of different heat transfer systems follows system-specific approaches: for radiator systems, this translates to calculating appropriate radiator lengths, while for underfloor heating, it means determining the required number of pipe loops based on the heat output per square meter. All other parameters of the heat transfer systems remain identical to ensure a valid comparative analysis.

The MPCs, needed for the flexibility quantification, control the zone air temperature by adjusting the supply temperature of the heat pump. To account for the delay in dynamics caused by the distribution systems, a first-order delay element is applied to the supply temperature. The associated time constant was determined through simulative investigations with the Modelica library BESMod [15]. The optimization models used by the MPC to calculate the optimal control decision are modeled as white box to provide the most accurate assessment of the available flexibility offers. For details on the equations, readers are referred to the open source library AixLib [12].

For the same reasons in choosing the white box approach, the MPCs in this study also operate with perfect forecast for their predictions. These predictions include the comfort boundaries, ambient conditions, and the electricity price. The comfort boundaries follow Wolisz's model [16], distinguishing between active and sleep phases. During the active phase (7 a.m. to 11 p.m.), temperature limits are set at  $T_{\text{upper,active}}=297.15$  K and  $T_{\text{lower,active}}=295.15$  K. The sleep phase uses more energy-efficient boundaries with  $T_{\text{upper,sleep}}=294.15$  K and  $T_{\text{lower,sleep}}=292.15$  K. Additionally, a constraint of maximum temperature rise at 2 K/h is implemented to ensure thermal comfort. For ambient conditions, the study focuses on a high-demand scenario. Weather data from 2023 for Aachen was clustered to select a week representing the 20th percentile of coldest temperatures combined with the 50th percentile of solar radiation, creating conditions with potentially high flexibility demands. To minimize the influence of other disturbance variables, a constant electricity price  $c_{\text{el}}=33.17$  ct/(kW h) is chosen, which is derived based on real data from a German electricity provider. All other relevant parameters for the MPCs are listed in Table 1, including the prediction horizon N and the sample time of the MPCs  $t_{\text{Sample}}$ .

**Table 1.** Relevant parameter values for the MPCs

N	$t_{\text{Sample}}$	$t_{\text{Prep}}$	$t_{\text{FE}}$
96	900 s	1800 s	7200 s

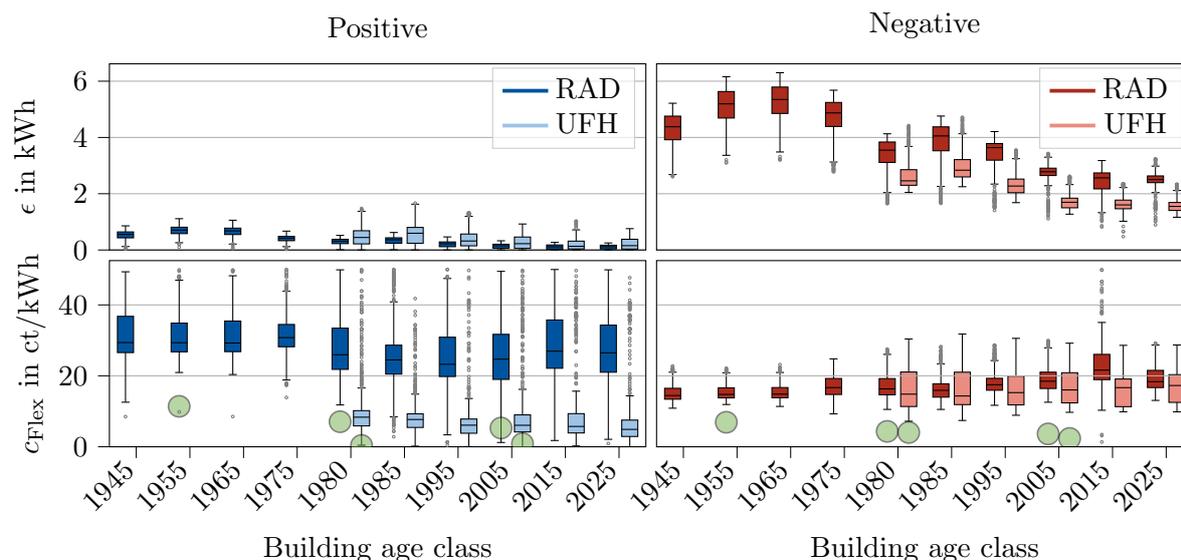
### 2.3. Selection of Building Age Classes

The different building age classes are selected using the TEASER tool [17]. TEASER uses data from TABULA for the German building stock, which specifies building age classes from 1945 to 2015 [18]. For the age class 2025, a reference house from the German Buildings Energy Act (GEG) is used [19]. For the usable area of the buildings, we assume the average area of approximately 134.5 m<sup>2</sup> for German single-family houses [20]. In addition to data for the building envelope, information on the heat transfer system is also selected. Since underfloor heating in buildings before 1979 is present in only 3.3% of buildings ([21]), both radiators and underfloor heating are used only for newer buildings.

After selecting the age class and the basic geometries of the building, the remaining process is automated. This includes the automatic creation of the Modelica models, the preliminary simulation for system dimensioning, the parameterization of the MPCs, and the performance of the quantification. The results of this process are described below.

### 3. Results

Figure 2 shows the flexibility quantification results across building age classes, divided into energy flexibility (top) and costs (bottom) for both positive (left) and negative (right) flexibility.



**Figure 2.** Positive and negative energy flexibility as well as costs for the different building age classes. The green markers represent mean costs for buildings with a constant COP for the heat pump.

Energy flexibility generally decreases with newer buildings due to their reduced heating loads from improved insulation. This results in smaller-sized transfer systems and heat pumps, limiting the absolute flexibility potential. Notably, there is significantly less positive flexibility available than negative flexibility. This occurs because baseline operation at constant electricity prices runs at the lower comfort boundary, leaving minimal room for further load reduction. Available positive flexibility potential is primarily generated through preheating during preparation time. Underfloor heating offers greater positive flexibility as it stores heat more efficiently, while radiators transfer more heat to room air which suffers greater losses, requiring earlier reheating. For negative flexibility, however, UFH provides less potential as its slow response may violate

comfort boundaries during transitions from active to sleep phases, while radiators can heat longer without comfort violations due to their faster response.

Flexibility costs remain relatively constant across age classes, despite the theoretical advantage that newer buildings with better insulation would have for cost-efficient preheating. However, while costs primarily reflect heat losses (directly related to insulation), older buildings operate with higher baseline supply temperatures. According to the Carnot principle, the relative COP reduction when increasing supply temperatures is less pronounced for higher values of the supply temperature. Therefore, newer buildings with lower baseline supply temperatures suffer a greater relative COP drop than older buildings, even though the absolute COP of older buildings is lower. To highlight the effect of the relative efficiency loss, the green markers in Figure 2 show the mean costs resulting from the quantification with a constant COP ( $COP = 3$ ) for three selected buildings. The selected buildings each come from a group with comparable flexibility offers (1945-1975, 1980-1995, and 2005-2025). For the constant COP, costs decrease with newer buildings as expected, with insulation effects predominating. These costs align with market flexibility prices of approximately 5 ct/kW h to 10 ct/kW h ([22]) enabling profitable market trading for flexibility.

Comparing transfer systems, radiators incur higher costs than UFH due to greater heat losses. UFH shows wider cost variability due to its thermal inertia, which sometimes prevents full utilization of stored thermal energy (e.g., when heating before comfort boundary reductions), increasing the associated costs.

#### 4. Conclusion

In this paper, we examined the influence of building age classes on flexibility offers. Our results align with literature, showing that available flexibility increases with building age [6] and radiators provide greater absolute flexibility [8] with higher losses [7]. We identified that buildings within three age groups (1945-1975, 1980-1995, and 2005-2025) exhibit similar behavior, potentially reducing simulation requirements for future studies. These groups demonstrate average negative energy flexibility per building area of approximately 37 Wh/m<sup>2</sup>, 26 Wh/m<sup>2</sup>, and 18.5 Wh/m<sup>2</sup>. Positive flexibility potential is generally lower but could be enhanced by adjusting comfort boundaries during flexibility events while considering user needs. Cost analysis revealed that heat pump modeling significantly impacts cost assessments. The Carnot COP tends to overestimate efficiency losses, resulting in costs of up to 25 ct/kW h, while constant COP models assume no losses, resulting in costs around 7.5 ct/kW h. Future work should implement more realistic performance characteristics to accurately evaluate flexibility costs and the trading potential of residential buildings.

Overall, our findings indicate that older buildings offer greater flexibility but at higher prices, while newer buildings are more cost-efficient. From a grid operator's perspective, an optimal flexibility portfolio would combine numerous newer buildings providing cheap flexibility with select older buildings for periods of high flexibility demand.

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