Energy Flexible Buildings - The impact of building design on energy flexibility

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Abstract. Thermal load management has substantial theoretical potential for energy flexibility. To use the inherent flexibility in buildings, for example, district heating companies could temporarily control the heating system of buildings to switch-off or preheat dwellings in the morning to avoid using peak load gas boilers. The »thermal flexibility« in this study indicates the tolerance of buildings towards the changes of its heating system operation according to an external signal. The focus of this investigation is to give an overview of »thermal flexibility« of residential buildings in Austria from 1920 – 2020 with different envelope qualities, construction types and heating systems. Existing residential buildings in Austria usually have a high thermal mass within their massive brick or concrete primary structure, and therefore their indoor thermal conditions react slowly to operative changes in the supply of thermal energy. Depending on the buildings ability to retain or store heat inside the building envelope, space heating can be used to offer energy flexibility. Among other factors, especially the quality of the thermal envelope, the thermal capacity of the building, the sluggishness of the heat delivery system and passive solar gains are crucial for keeping indoor thermal comfort. Dynamic building simulation in IDA ICE is used to evaluate the potential of selected building typologies to shift heating loads away from peak demand periods. Potentials of various building archetypes according to the EU-Tabula building database to time-shift the operation of the heating system are pointed out respecting occupants’ comfort.

1. Background and objectives
Domestic space heating is responsible for about 45% of the total household energy demand in Austria [1]. Especially old buildings before the 1970ies with a high domestic space heating demand have the highest share in the overall heating energy consumption. Still due to their high heat storage capacity, if they have a certain thermal envelope quality, they can stay pleasantly warm for some time after the heating system has been switched off. Austrian buildings before 1970 were often heated by single furnaces as heating systems, and the air-temperature control was depending on how the air supply was adjusted and how the fuel was added to the furnace. Under these conditions, a large heat storage capacity of old buildings was highly desirable and helpful. It reduced the increase in air temperature when there was an excess of thermal heating energy and slowed down the drop in temperature when the furnace was turned off. The heat storage capacity has a »temperature-equalising« or »temperature-stabilising« effect especially useful for uneven or so-called transient-heat-delivery-systems like old furnaces. Under these heating conditions, the heat storage capacity was thus able to compensate for the poor controllability of the heating systems in a certain sense. The larger the storage mass, the better [2]. Most of the old inefficient furnaces and heat delivery systems have been replaced in old buildings in the meantime, often by district heating grid connected heating supply systems or electric heat pumps. With today's low-temperature (compared to furnaces) heating systems and control options, the heat storage capacity has become less important for space heating. Mainly also because the charging
of the storage masses by convective heat transfer is incomparably lower than by radiation. With convective heat transfer, the storage mass can at best be charged with the air temperature of the room and not - as in the past - absorb the radiant heat of the furnace. However, with the arising challenge of integrating high shares of renewable energy in energy supply grids, particularly variable wind and solar puts the idea of the heat storage capacity of a building into a new perspective. The concept of flexibility of buildings is to manage their loads based on the requirements of the surrounding grids. In the context of heating flexibility, this means to heat-up the building when there is excess solar, and wind energy available in electricity grids, or renewable heating grids can be operated ideally and reducing heating power at other times. Especially during cold winter periods, control systems in residential buildings can be used to reduce peak demands and take stress from electricity and heating grids [3]. The energy flexibility of heating systems depends on the ability of a building to retain or store the heat inside the building envelope concerning comfort requirements. The amount of insulation, the thermal capacity and the passive solar gains of buildings are crucial for keeping indoor thermal comfort [4] and [5].

The focus is here a quantitative evaluation of the potentials of heating flexibility of residential buildings in Austria from 1920 – 2020 on the level of usable energy. The difference of envelope qualities, construction types and heating systems plays a crucial role in defining the possible heating flexibility of a certain building typology. Dynamic building simulation in IDA ICE is used to evaluate the potential of these building typologies to shift heating loads away from the peak demand periods. Potentials of various building archetypes to time-shift the operation of the heating system will be pointed out, with attention to occupant comfort. With the obtained data, it is possible to offer an estimation of the heating flexibility of prototypical residential buildings in Austria assuming that they are equipped with a grid-connected heating system like electric heat pumps, district heating or direct electric heating. Also, the effect of the insulation level applied to the building envelope as well as the effect of thermal mass on the heating flexibility is analysed.

2. Evaluation Methodology
Heating energy flexibility also referred to as »thermal load shifting« is here defined as the number of hours the energy system can be delayed or forced to operate considering the indoor comfort band as a constraint. For example, when space heating is switched off at the upper excepted limit of the indoor comfort temperature, the indoor temperature remains within the comfort zone for a certain period depending on the level building insulation, ventilation and thermal mass. As the thermal energy inside the building envelope is vanishing, the indoor temperature drops. ΔT denotes the time after which the temperature has fallen from the upper comfort limit to the lower comfort limit, yielding a temperature difference of ΔT [°C]. Other essential definitions are explained in Figure 1.

![Figure 1](image)

**Figure 1** Demand-side control of set temperatures, representation of the cooling-down curve (delayed operation- Δt1) and heating-up time (response - Δt2) (graph based on [9]).
3. Austrian dwellings - Simulation models

The calculation of thermal load management potentials for representative building typologies has been derived from the TABULA/EPISCOPE web database [6]. For the simulation, the weather conditions of the test reference year of Graz, from the 2013 ASHRAE [7] — see figure 2, has been applied. Four different detailed building models with different years of construction and controllable heating systems and defined user behaviour were modelled in IDA ICE. The ventilation and infiltration corresponds to 0.4 air change per hour in order to guarantee sufficient air renewal. All buildings are modelled as a single zone, with the exact physical characteristics derived from the TABULA/EPISCOPE database. Internal heat gains for multifamily buildings according to SIA 2024 [8] have been applied to the building models. The set-point for the indoor operative temperature is 22°C. The allowed temperature band is 22 ± 2°C, and the minimum allowed operative temperature 19°C matches to the PMV-PPD category II of the comfort standard EN 15251 (PPD < 15%, -0.7<PMV<0.7). The influence of different occupancy behaviour on the heat flexibility is not considered here.

4. Results

The resulting load shifting potentials for analysed building typologies defined in 'Table 1' are presented in the following.

4.1. Delayed operation – cooling down

The simulations were firstly carried out for a characteristic winter week, 16th – 23rd of January, using a simulation time step of 10-minutes. During the working days, the building is non-occupied from 8.00 am. to 17.00 pm. Each occupant emits 80 W due to the metabolism, and the assumed net floor are per person is 30 m². There are also internal gains from appliances during occupied hours resulting in internal heat gains of 13 W/m² as shown in table 1.2. Figure 3 shows the cooling down of the operative temperature after the heating system is switched off. The period it takes for the operative temperature to reach the lower comfort level of 19°C is referred to as the potential »delayed operation« of the heating system. The changes in of operative temperature after switch-off of the heating system on the 16th of January starting at 0:00 is shown in figure 3. When the heating is switched off, the operative room temperature drops rapidly at first and then more slowly. When the room air temperature drops during the first hour after the heat cut-off, the heat stored in the wall returns to the room, and the temperature drops more slowly. Throughout the day, the passive solar gains via the window surfaces lead to an increase in the temperature, which then drops again constantly during the evening and night-time. The positive effect of the passive solar gains during the daytime influences here only the newer better insulated cases (C and D) since the old buildings (A and B) cool down too fast in order to benefit from passive solar gains. If however the switch-off occurred during sunshine, building A and B would also benefit somewhat from the solar radiation.

![Figure 2](Image)

Figure 2 Climate chart of the chosen reference week 16th January to 23rd January, Graz (ASHRAE, Inc.: International Weather for Energy Calculations).
Table 1  Representative building typologies based on TABULA/ EPISCOPE database (retrieved from http://episcope.eu [6]).

| Building Class          | Tabula Code                  | Construction Period | Reference Floor Area | Net /Gross Energy need for heating | U-Value exterior Wall | U-Value Windows | U-Value Roof |
|-------------------------|-----------------------------|---------------------|----------------------|-----------------------------------|-----------------------|----------------|--------------|
| [A] Single Family House | ATN.SF.3.Gen                 | 1945 – 1960         | 198m²                | 134 kWh/m²a                       | 1,40 W/m²K           | 2,30 W/m²K   | 0,50 W/m²K  |
| [B] Multi-Family House  | ATN.MFH.5.Gen                | 1981 – 1990         | 590m²                | 90 kWh/m²a                        | 0,60 W/m²K           | 2,50 W/m²K   | 0,44 W/m²K  |
| [C] Apartment Building  | ATN.AB.8.Gen                 | 2010 -              | 906m²                | 47,8 kWh/m²a                      | 0,30 W/m²K           | 1,40 W/m²K   | 0,40 W/m²K  |
| [D] Single Family House | no                          | 2020 -              | 138m²                | 12,1 kWh/m²a                      | 0,10 W/m²K           | 0,60 W/m²K   | 0,10 W/m²K  |

Figure 3  Cooling down time of 4 case studies - delayed operation (Δt1).
It should be noted that the shiftable heating loads are not constant over time as can be seen in figure 4. Further, the average heating power needed to keep the buildings operative temperature at 22°C in this January week ranges from 55 W/m² in case A, 37 W/m² in case B, 18 W/m² in case C to less than 10 W/m² in case D. Buildings with lower heating loads, have longer delayed operation times. Passive solar gains have shown to increase the delayed operation time which is also noticeable in the reduced heating energy power during the daytime. These results lead us to the first conclusion: Old buildings, represented in simulation models [A and B], in contrast to new- and highly energy efficient buildings [C and D] have a higher specific performance due to the lower insulation standard. This leads on the one hand to a higher shiftable heating load, but shorter delayed operation periods as seen in figure 3 and figure 4. Figure 5 combines the simulation results of figure 3 and figure 4. The resulting curve displays the delayed operation time (the time that it takes for the room to cool down from 22°C to 19°C) on the x-axis and the shiftable heating power (the average heating power that can be switched off during this period) on the y-axis. The curve shows how long the average specific heating power [W/m²] of the four different building typologies (A to D) can be switched-off while the operative temperature inside the building stays in the specified comfort band of 19°C-22°C operating temperature after the heating system has been switched off.

![Figure 4](image4.png)

**Figure 4** Heating power demand to keep the temperature of the building at a 22°C setpoint temperature (without load shifting) for case B and D.

![Figure 5](image5.png)

**Figure 5** Load duration curves of cases showing the potential of shiftable domestic heating load over time.
4.2. Delayed operation – Optimisation

The effect of thermal inertia in relation to energy flexibility has been investigated in detail by (Reynders et al., 2015). Buildings with high thermal mass embedded in the construction, have a huge potential to store heat over long periods. The specific heat storage capacity of the analysed TABULA case studies accounts for approximately 120 Wh/m²K since the buildings all have brick walls and concrete ceilings. Following the primary structure of the case study buildings is changed to a concrete construction (specific heat capacity of construction = 200 Wh/m²K) in the simulation model. Figure 6 shows the effect of increasing the thermal inertia of the building when the heating system is switched off. The larger the storage mass, the slower the building cools down. A heavyweight constructed building in combination with a high insulation standard (case C and D) extends the timespan for thermal load shifting drastically as shown in figure 6. The thermal mass of a concrete constructed building, in comparison to brick buildings, enables it to store more heat.

![Cooling down time of the case studies with increased thermal mass for case C and D.](image)

Figure 6 Cooling down time of the case studies with increased thermal mass for case C and D.

It turns out that the delayed operation time of case study C can be extended from 20 hours up to 32 hours by adding more thermal inertia. This effect becomes even more drastically when adding thermal inertia to the most efficient building, case study D. Here the potential delayed operation time rises by a factor 2.3 from 46 hours up to 102 hours. Figure 7 allows us to explore the influence of shiftable domestic heating loads between heavy and medium-weight constructions, as well as different insulation levels based on the year of construction. The possible off time for case study B, C and D increased considerably, while there is no increase for case A. The latter due to the large losses through the poor thermal envelope.

![Load duration curves of heavy weight cases - potential of shiftable heating power over time](image)

Figure 7 Load duration curves of heavy weight cases - potential of shiftable heating power over time
Even though the load shift period was determined for a typical cold January week, the resulting curve in Figure 7 can theoretically be used for any day/season of the year. If the heating power is known for a certain timespan, the ratio of the average shiftable heating power and the delayed operation time can be estimated depending on the thermal inertia.

In comparison to the investigated load shifting options by modulating the heating system (on/off), state-of-the-art thermal or electrical energy storage systems are a more common way of providing energy flexibility to heating systems. Based on the heating system a state-of-the-art thermal storage water tank of 0.15-0.6 kWh/m² can drastically extend the thermal load shifting potential/thermal storage potential. These capacities represent a 20-80 kWh thermal storage tank (200-1000 litres) for a typical single-family home in Austria.

The curves in Figure 8 show how long a specific thermal power [W/m²] can be provided by different thermal storage system [kWh/m²] after the heat cut-off. It is seen that the load duration curves can be extended drastically by adding thermal storage systems. Figure 9 shows how long a specific electrical power [W/m²] can be provided by three different sized electrical batteries [kWh/m²floor area] after the active power supply has been cut-off. Please notice that this potential seems to rather small because it is assuming a direct electric heating system using each electrical kWh directly as thermal energy for heating the building. If the heating system would be powered by for example, a geothermal heat pump operating at COP 3.5, the load duration curves can be extended drastically. It is essential to notice that batteries can be used all year round for electric energy demand of the building and not specifically only in winter for heating flexibility.

![Figure 8](image1.png)

**Figure 8** Load duration curves are showing the potential of storeable domestic heating load over time with three thermal storages

![Figure 9](image2.png)

**Figure 9** Load duration curves are showing the potential of battery storages to provide for electrical power after power cut-off

### 4.3. Response - heating-up

Due to the low-temperature heating systems in cases C and D with lower maximum heating capacity, the heating up timespan from the lower temperature setpoint of 19°C up to 22°C usually takes much longer. Also, the sluggishness of low temperature heating systems and modern PI controllers slow down the heating-up timespan. This timespan to reach the original temperature setpoint of 22°C again is referred to as the “response time of the heating system” in figure 10. It is heavily depending on the capacity and the control strategy of the heating system and much more difficult to assume in general than the cooling-down period, which is more related to the physical properties of a building. Figure 10 combines the load duration curves of the case studies showing the potential of shiftable domestic heating load over time for the cooling-down timespan on the right side (delayed operation) with an average predicted heating-up timespan (response) after the thermal load shifting operation on the left side. Also, we can see in figure 10 that from the end of the load shifting period till the heating system reaches the 22°C setpoint temperature again, there is an increase in heating demand since extra
power is needed. Old, poorly insulated buildings with slightly oversized heating capacities, can react more quickly and reach the upper setpoint temperature relatively quickly.

Figure 10  Rebound effect of shiftable domestic heating loads over time delayed operation (Δt1 – right) and response (Δt2 - left).

5. Conclusions
The potential for shifting domestic heat loads from the peak to low demand periods for Austrian building archetypes was investigated, and potentials for optimization were pointed out.

The findings are summarized as follows:

- Old buildings (cases A and B) in contrast to the new (cases C and D) have higher specific loads due to the lower insulation standard. This leads to a higher switchable load, but also a shorter shutdown period. Heat flexibility, therefore, is mainly determined by the buildings’ physics-thermal properties. Also, energetic refurbishments of existing buildings can unlock a high load management potential since old buildings usually have high heating loads.

- The total amount of heating energy that can be shifted is beside the thermal quality of the building envelope dependent on the heating set points and acceptable comfort range. Tolerating a larger deviation from the comfort band especially in unoccupied times can significantly extend the load shifting potential of domestic heat loads.

- An increase of thermal mass/heat capacity leads to a damping effect on temperature changes, resulting on average in a 20-30% higher load shifting potential. At least 50% of the domestic heating peak loads can be shifted to off-peak periods during the day for building after 1980 in Austria, also in January, and still reach the comfort band of EN 15251, category II.

- The expansion of electric heating systems on the other side also poses the risk of worsening the seasonal gap of renewables in the grid, leading to higher specific emissions per kWh.

- For all building types, large delayed operation times are possible on days with higher average outside temperatures and high solar irradiation. Also, it is concluded that for four prototypical buildings, it is possible to predict the heating flexibility based on weather conditions – namely outside temperature and solar irradiance. For the older dwellings, the outside temperature has a dominant impact on the heat flexibility, as cooling down times are so fast due to envelope heat losses that these buildings hardly benefit from passive solar gains due to solar irradiance. Especially when the switch-off occurs during periods without solar radiation.
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