Flexibility Potential of Residential Heat Pumps in the Power Grid of the Future

Wolf Bracke **Sam Hamels, PhD** **Mohsen Sharifi, PhD** **Jelle Laverge, PhD**
Member ASHRAE

ABSTRACT

Renewable energy sources such as solar and wind power will play an increasing role in the power grid. While generating low carbon electricity at an attractive cost, their intermittency poses challenges to the balance of our electrical system. During moments of high energy use but low availability of renewable energy, e.g. winter evenings, the most polluting fossil energy generators need to be active in order to fulfill the peak consumption. Conversely, during moments of low energy use but high availability of renewable energy, e.g. summer days, the excess energy will have to be curtailed.

With the rise in heat pump adoption, the electrification of heating systems might increase these challenges if we fail to devote adequate attention to the power consumption pattern. Yet, using intelligent control strategies can turn heat pumps from a system liability into a system asset. The success of large-scale industrial flexibility contributions to the energy system demonstrates that intelligent demand-response plays a key role in our current and future energy supply. Extending that role to small-scale distributed assets such as heat pumps is however not yet thoroughly investigated.

In this paper, the flexibility potential of heat pumps in the Belgian residential building stock is explored. The flexibility is expressed as the electricity which can be postponed by turning off the heat pumps during a given period of time. User comfort is taken into account, and minimum thresholds for the room temperature are defined.

Dynamic building energy simulations are run for buildings with different parameters using RC grey-box models. We investigated dwellings of different typology and size. Multiple insulation levels were applied, as well as different heat emission systems (radiator vs. floor heating) and heating schedules. A cold, average and warm climate year are used for the simulations, as well as different minimum temperatures.

Based on data from government agencies, the building stock is divided into categories of building typologies and insulation levels. Using various data sources and making several assumptions, we defined new built rates, renovation rates and heat pump adoption to estimate the building stock in the year 2030 and 2040. The results from the individual building simulations are extrapolated to the building stock level and different climate and comfort scenarios are evaluated.

According to our analysis, deactivating all Belgian heat pumps during a December month results in a initial load reduction of 2500 MW (8530 MMBtu/h) for the 2040 scenario. This value gradually reduces in the hours after the flex event, since certain buildings reach their minimum temperature threshold and restart the heat pump. After around 9 hours, a period of load increases takes place since the building stock requires additional heating compared to the baseline scenario. Load increases up to 1000 MW (3412 MMBtu/h) are registered. These values are largely influenced by assumptions regarding the building stock, as well as boundary conditions such as climate and minimum temperature threshold.

INTRODUCTION

Phasing out our fossil energy use is essential for the success of the energy transition. This implies a complete electrification of the final energy consumption, with the required electricity being generated from sustainable energy sources. The combination of growing electrical consumption combined with ever increasing intermittent renewable energy generation, however, poses challenges to the balance of our electrical system and the security of our energy

Wolf Bracke & Mohsen Sharifi are research fellows at the Department of Building Physics, Ghent University, Ghent, Belgium. **Sam Hamels** is a research fellow at the Department of Energy Economics, Ghent University, Ghent, Belgium. **Jelle Laverge** is a professor at the Department of Building Physics, Ghent University, Ghent, Belgium.

supply. During moments of high energy use but low availability of renewable energy, e.g. winter evenings, the most expensive and polluting fossil energy generators need to be active in order to fulfill the peak consumption. Conversely, during moments of low energy use but high availability of renewable energy, e.g. summer days, the excess energy will have to be curtailed.

The growing electrification, driven by assets such as heat pumps, electric vehicles and battery energy storage systems, also contains the root of the solution to these problems. If these assets can be made intelligently controllable and responsive to energy market signals, they can be turned from a system liability into a system asset.

In this paper, we evaluate the flexibility potential of all heat pumps in the Belgian building stock in a 2030 and 2040 scenario. To do so, we first need to define what we will consider as 'flexibility' and what indicators which will be used to evaluate the 'flexibility potential'. Next, we use dynamic building simulations to calculate the flexibility of individual buildings with a large variety in building attributes. In a final step, we estimate the future characteristics of the Belgian building stock and aggregate the results on the national level.

METHODOLOGY

Flexibility definition and indicators

During normal operation, the electricity consumption profile of a heat pump is spread across the hours of the day in a particular way. Depending on the building and the indoor temperature requested by the user in each hour, this profile may be relatively 'flat' – with a more or less equal amount of electricity being consumed in every hour – or contain significant peaks and valleys. The observation that – whatever the profile is –, it can probably be changed to a certain degree to meet certain private or societal goals, or in other words that "heat pumps are flexible", is not new. For example, one may attempt to exploit heat pump flexibility to concentrate the consumption profile into the hours with the lowest electricity price. Assuming that the user has an electricity contract using dynamic hourly prices, this would cause a reduction in the electricity bill paid for operating the heat pump. Similarly, a user may want to self-consume as much of the electricity produced by his own solar panels. In such a case the goal would be to concentrate the heat pump's consumption profile as much as possible into the hours when the production of solar power takes place. In this paper, the focus lies on the degree to which changes in a heat pump's consumption profile can contribute to a national electricity system's security of supply. This means that we are primarily interested in the ability to temporarily reduce a heat pump's electricity consumption, questioning for example how long it can be turned off before a certain comfort threshold is reached.

In recent years, various researchers touched upon heat pump flexibility. Junker et al. studied shifting energy demand peaks from hours with high prices to hours with low prices (Junker et al. 2018). They used a penalty function to enforce a heat pump's control system to shift around its electricity consumption. Considering this penalty function, the control system then shifted consumption away from the hours with a 'high penalty' and towards the hours with a 'low penalty'. In similar work focused on the Italian context, Vigna et al. attempted to change a heat pump's electricity consumption profile in order for it to match the production of solar panels as well as possible (Vigna et al. 2021). They did this by using a "smart" set-point for the desired indoor temperature. Reynders et al. assessed the heat pump flexibility by first overheating the building above the desired set-point temperature, to enable a longer period of reducing energy demand afterwards (Reynders et at. 2017). Through this kind of 'active demand response', the building's thermal inertia is used as a kind of battery, whereby the amount of energy that can be stored and shifted in time is dependent on the building's physical characteristics and the choices made in terms of the boundary conditions such as the preheating setpoint. Crawley et al. studied heat pump flexibility focusing on the amount of time over which a building can shift its entire heating demand without causing discomfort (Crawley et al. 2022). Temperature measurements were carried out for 193 buildings where the heating system was turned off, and the relationship between time and the drop in indoor temperature was studied.

In our study, we adopt Crawley's flexibility methodology, where heat pump flexibility is defined as the ability to deviate from its typical electricity consumption while remaining within whichever comfort boundaries are deemed acceptable. Note that we strictly focus on the electricity demand for space heating, and do not evaluate the flexibility potential for domestic hot water production nor cooling.

To quantify the flexibility, we focus on two parameters. The first is the duration of flexibility interventions, which is the amount of time – expressed in a number of hours – that it takes for a building to cool down to the predefined 'threshold temperature' after the heat pump was turned off. The second is the load reduction made possible by flexibility interventions, which is expressed in Watt. For this parameter, we compute the value for several time horizons, more specifically the 1h, 2h, 4h, 8h and 24h period. For each time horizon, the value represents the minimum amount of Watt by which the heat pump's load can be reduced compared to the reference consumption profile. After the initial period of load reductions, the threshold temperature is reached and the building is heated back up to the original setpoint. As a result, the building experiences a period of higher electricity use compared to the reference consumption, which is defined as a load increase during the recovery period. In Figure 1, the flexibility indicators are illustrated on a heat pump's load curve during a flexibility event.

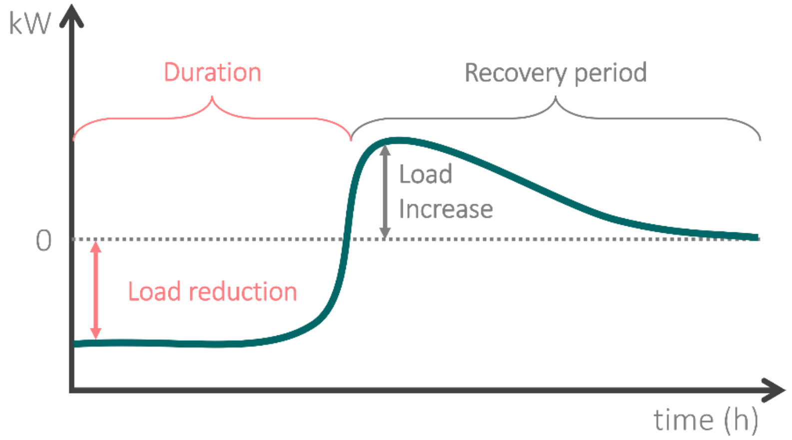

Figure 1 Simplified visualization of heat pump flexibility as conceptualized in this paper

Individual building flexibility

The flexibility indicators we focus on in this report are affected by two groups of parameters. The first group consists of building properties and user profiles: building geometry, building insulation level, heat pump type, heat emission system and heating schedule. In this study, the Belgian building stock is broken down into clusters with a unique combination of these properties. In a next part of this research, we will estimate the amount of buildings in each cluster, and aggregate the individual results. The second group of parameters can be used in a sensitivity study, where the minimum temperature threshold and outdoor climate can be varied.

Table 1. Parameter variation

Geometry	Insulation Level	Heat Pump Type	Heat Emission System	Heating Schedule	Threshold	Outdoor Climate
detached small	A	air-water	underfloor	24h	16°C (60.8°F)	cold
detached average	B	geothermal	radiators	16h	18°C (64.4°F)	average
detached large	C	air-air		8h	20°C (68.0°F)	warm
semi-detached small	D					
semi-detached average	E					
semi-detached large	F					
terraced small						
terraced average						
terraced large						
apartment middle						
apartment roof						

Since we investigate the ability to shift energy demand to a later moment in time for buildings with all unique combinations of parameter values, we need to use a dynamic simulation model which is mathematically simple to keep the simulation time within reasonable limits.

To this end, we've selected the grey-box modelling approach using resistor-capacitor (RC) models. Grey-box modelling offers flexibility; it allows for tailoring model complexity based on the specific application at hand, and simplifies many modelling tasks. However, ensuring the model's accuracy remains a manual task.

The selection of the model architecture is influenced by multiple considerations such as the model's intended use, the acceptable level of mathematical complexity and accuracy, and the characteristics of the building. Determining the most suitable model architecture often becomes a significant part of the modelling task. The configuration and quantity of resistors and capacitors can profoundly affect the results, either marginally or substantially. However, for this study, we opted for a generic model structure based on findings from prior research (Bacher et al. 2011, Allegrini et al. 2015, Reynders et al. 2016). We selected a single-zone model, incorporating 5 capacitors and 8 resistors.

The parameter values of the R-C model must be estimated for each building with a unique set of building characteristics. This is done in a model training step, where the heat demand of a white-box model is simulated during an entire year with a one year timestep using the EnergyPlus software. Subsequently, the CTSM tool, which is implemented in R, is used for parameter estimation (DTU Compute 2023).

Finally, dynamic building simulations are performed using a 1-hour timestep. The heating demand of the heat pump is calculated in a Python script using the R and C-values found in the previous step. To come up with the final electric demand, as well as the heat pump flexibility, we used a heat pump model representing a heat pump frequently encountered in the European market. The model calculates a COP at each timestep for the specific heat source temperature as well as required heating medium temperature.

Building stock flexibility

The total energy flexibility of the residential Belgian building stock in the target years of 2030 or 2040 can be regarded as the sum of the energy flexibility of every individual residential building in Belgium at that time. The most precise methodology would be to calculate the energy flexibility of every individual dwelling, which is too computationally heavy and would require detailed geometric and physical properties of the buildings, which is not available. As an alternative, a clustering methodology was developed, where the building stock is grouped in clusters which are represented by archetypical buildings with a variation in parameters as discussed before.

To extrapolate the results of the individual simulations to building stock level, we have to estimate the amount of buildings in each specific cluster. This requires a bottom-up approach where step by step, more details are added until we reach the detail level of the clusters.

We first need a comprehensive understanding of the present building stock. To determine the total number of residential buildings, their typologies - be it detached homes, apartments, or other forms - and their sizes, we used land registry statistical data (Statbel 2023) To gain insight in the current insulation level of these different groups of buildings, we analyzed public reports about the energy properties of the building stock (Vlaams Energieagentschap 2016, Heylen et at. 2019).

Next, we factor in new constructions using statistical data about building permits (Statbel 2023). To take into account building renovations, not only the amount of renovations are important; we must also predict the distribution between buildings' insulation level both before and after their respective renovations. To estimate the latter, a methodology was developed based on energy grant and building permit data (VEKA 2023)

Finally, we estimate the number of heat pumps of different types that will be in use, adopting the predictions of Belgium’s electricity grid operator (Elia 2023). Lacking reliable data sources, we had to make assumptions to determine what building typologies and insulation levels will likely have a more significant amount of heat pumps and forecast the expected heating schedules for the different buildings.

Our building stock model estimates the total number of buildings to be 6.0 million in 2030 and 6.6 million in 2040. The number of heat pumps increases from 0.8 million in 2030 (13.9% of buildings) to 2.4 million in 2040 (36.3% of buildings).

RESULTS

Duration

The duration on the individual level building was defined as the time it takes for the building to cool down to the minimum threshold, ending the load reduction phase and starting the load increase phase, or the 'recovery period'.

In a building stock with a large variation of building properties, some buildings will cool down faster compared to others, resulting in a mixed situation of some buildings undergoing a load reduction, while others are already in the load increase phase. On the building stock level, all loads are aggregated, and the period of a net load reduction is defined as the duration of the flex event.

Table 2 offers insight in the average duration outcomes for of December, presenting the results for the different parameters examined. December was chosen, since it represents a typical winter month for the average climate year. For the cold climate year, the month of December turns out to be the most critical month.

Table 2. Duration in December (hours)

	2030			2040		
	Cold	**Average**	**Warm**	**Cold**	**Average**	**Warm**
16°C (60.8°F)	11.6	16.1	17.5	11.6	16.0	17.5
18°C (64.4°F)	6.2	8.2	8.7	6.2	8.2	8.6
20°C (68.0°F)	2.1	2.2	2.3	1.9	2.1	2.3

The following conclusions can be drawn from the results in Table 2:

1. The minimum temperature threshold is the most critical factor impacting the duration of the flex event.
2. During a colder December month, the duration is significantly reduced. This effect is more pronounced with the lower temperature thresholds. The latter is related to a fast initial temperature drop when the heating system in a building is deactivated.
3. The higher amount of heat pumps in 2040 does not lead to a longer duration. Given our assumption that all buildings undergo the same flex event, they initiate the cooldown simultaneously. Intriguingly, 2040 shows a marginally shorter duration, which could be due to the adoption of heat pumps in buildings with inferior insulation in our proposed scenario.

While December's average monthly values might not perfectly capture the entirety of the year, a broader look at the percentile distribution of the yearly duration is offered in Figure 2. Here, we focus on the building stock projections for 2040 in an average climate year, using the 18°C (64.4°F) threshold. We observe a correlation between duration and outdoor temperature. In the typical heating months, we see a concentration of low-duration values with an average value around 8h. During shoulder season, the average value increases to roughly 20h, but with significant fluctuations that coincide with varying outdoor conditions.

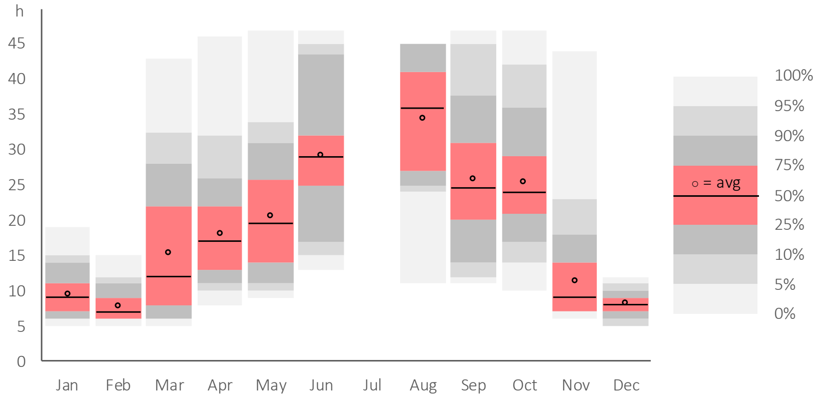

Figure 2 Percentile distribution of the duration (2040 / average climate year / 18°C (64.4°F) threshold)

Load reduction

The load reduction of the aggregated building stock is examined for periods of 1h, 2h, 4h, 8h, and 24h post a flex event. The load reduction is quantified as the minimum amount of electricity which can be avoided during every hour of the specified timeframes. Table 3 showcases the average load reduction for December during a 1h, 2h, 4h, 8h and 24h period, respectively.

It’s worth noting that the 1h load reduction for the 16°C (60.8°F) threshold is virtually identical to the total electricity consumption of all heat pumps within the Belgian residential building stock, since very few buildings will experience a temperature drop from the 21°C (69.8°F) setpoint to the 16°C (60.8°F) minimum temperature within a single hour.

Table 3. Load reduction in December (MW (MMBtu/h))

		2030			2040		
		Cold	Average	Warm	Cold	Average	Warm
1h	16°C (60.8°F)	1612 (5500)	1255 (4282)	1206 (4115)	3240 (11055)	2525 (8616)	1612 (5500)
	18°C (64.4°F)	1443 (4924)	1158 (3951)	1123 (3832)	2948 (10059)	2357 (8042)	1443 (4924)
	20°C (68.0°F)	1133 (3866)	906 (3091)	875 (2986)	2414 (8237)	1930 (6585)	1133 (3866)
2h	16°C (60.8°F)	1342 (4579)	1105 (3770)	1065 (3634)	2766 (9438)	2258 (7705)	1342 (4579)
	18°C (64.4°F)	1134 (3869)	952 (3248)	932 (3180)	2425 (8274)	2000 (6824)	1134 (3869)
	20°C (68.0°F)	124 (423)	363 (1239)	322 (1099)	265 (904)	775 (2644)	124 (423)
4h	16°C (60.8°F)	1128 (3849)	975 (3327)	945 (3224)	2391 (8158)	2026 (6913)	1128 (3849)
	18°C (64.4°F)	938 (3201)	819 (2795)	796 (2716)	2036 (6947)	1757 (5995)	938 (3201)
	20°C (68.0°F)	5 (17)	1 (3)	4 (14)	6 (20)	1 (3)	5 (17)
8h	16°C (60.8°F)	779 (2658)	768 (2621)	748 (2552)	1740 (5937)	1649 (5627)	779 (2658)
	18°C (64.4°F)	19 (65)	229 (781)	228 (778)	38 (130)	492 (1679)	19 (65)
	20°C (68.0°F)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
24h	16°C (60.8°F)	0 (0)	4 (14)	55 (188)	0 (0)	8 (27)	0 (0)
	18°C (64.4°F)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	20°C (68.0°F)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

Based on the data presented in the preceding table, we conclude the following:

1. Longer timeframes tend to result in smaller load reductions.
2. The 20°C (68.0°F) threshold provides a marginal load reduction after the initial hour.
3. During a colder December month, higher load reductions can be achieved on short timeframes compared to the average December month. Since the buildings cool down faster, we observe the inverse phenomenon for longer timeframe load reductions.
4. A higher load reduction is observed in 2040 relative to 2030, attributed to an increased number of installed heat pumps.
5. The 24h load reduction is negligible in most scenarios.

In concordance with our analysis of the duration, we explore the percentile distribution of the load reduction values during each month to learn more about the load reduction values expected during varying climate conditions. We focus again on the building stock projections for 2040 in an average climate year, using the 18°C (64.4°F) threshold. To avoid repetition, we only present the 1h load reduction results. Figure 3 illustrates how higher load reductions are possible during months with colder outdoor temperatures.

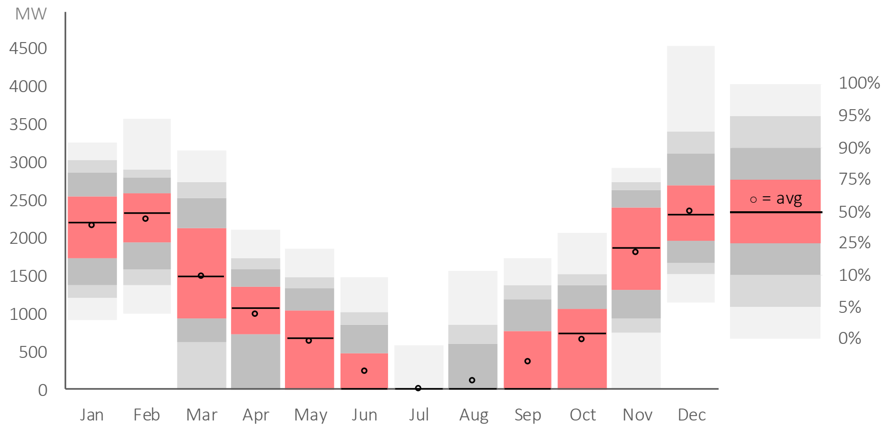

Figure 3 Percentile distribution of the 1h load reduction (2040 / average climate year / 18°C (64.4°F) threshold)

Detailed analysis

For a more detailed analysis of the building stock flexibility under various climate and threshold assumptions, we introduce the flexibility curve as illustrated in Figure 4. These curves aggregate results for potential flexibility events that could arise at any hour within a month. For each flexibility event, the consequent load increase or reduction is determined for a span of 48 hours. Each post-event hour provides a percentile distribution, shedding light on both typical and extreme values.

To illustrate, we assess the flexibility curve for the building stock projected in 2040, referencing December in an average climate year, with an 18°C (64.4°F) threshold.

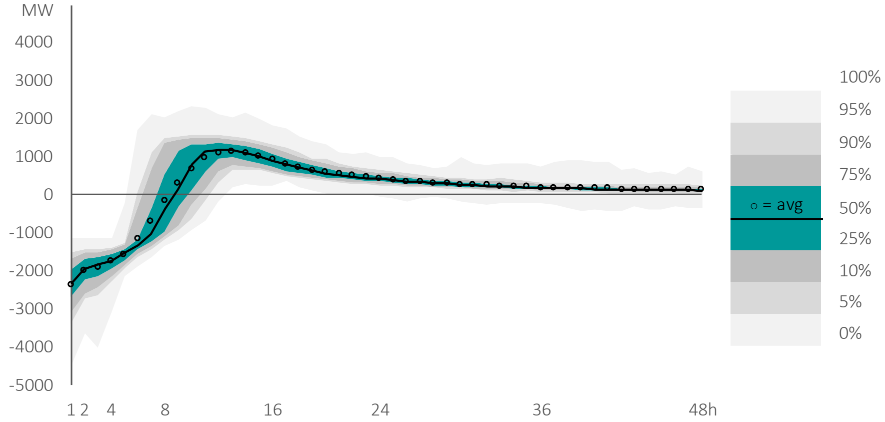

Figure 4 Flexibility curve December (2040 / average climate year / 18°C (64.4°F) threshold)

Figure 4 reveals several insights:

1. **Initial response**: The initial load reduction averages 2500 MW (8530 MMBtu/h), but extreme values range between 1250 and 4250 MW (4265 and 14502 MMBtu/h),. The core results, lying between the 25th and the 75th percentiles, are displayed in cyan. They are relatively concentrated between 2000 and 3000 MW (6824 and 10236 MMBtu/h).
2. **Subsequent load**: Over the subsequent hours, the load reduction exhibits a declining trend, corresponding to certain buildings achieving the minimum temperature, prompting the heat pumps to reactivate.
3. **Flex event duration**: On average, a flex event in December spans roughly 9 hours. However, specific events may last as briefly as 5 hours or extend up to 13 hours.
4. **Recovery phase**: After the load reduction period, the recovery period begins where we observe load

increases compared to the baseline scenario with normal heat pump operation. The average load increase peaks around 1000 MW (3413 MMBtu/h), but extreme values go up to 2000 MW (6824 MMBtu/h).

5. **Extended recovery**: An extended 'tail' of minimal load increases is observed, extending beyond the 48-hour post-flex event period studied. Since the thermal mass of the buildings is cooled down during a flex event, it can take a long time to bring the building back to the original temperature.

CONCLUSIONS

The flexibility potential of the future Belgian residential building stock was evaluated in this report. A clustering methodology was developed to group all residential buildings according to specific attributes such as building geometry, insulation level, heat pump type, heat emission system and heating regime. Though we capitalized on existing data repositories to envisage the upcoming building stock, it's imperative to recognize that projections inherently embody certain assumptions - specifically concerning renovation trajectories, heat pump adoption rates, and the employment of particular heat emission systems.

Next to the uncertainties in the building stock model, the individual building simulations are impacted significantly by assumptions made in the building model. Consequently, the most important take-aways of this research are the relative variation across the scenarios we studied, and the overarching trends identified. When interpreting the results of the flexibility indicators, it's more prudent to consider the order of magnitude rather than fixate on the exact numerical values.

The 18°C (64.4°F) threshold is regarded as a realistic lower temperature limit before reactivating the heat pumps. It results in a limited comfort loss, yet offers in a significant amount of flexibility. This threshold ensures a balanced compromise – ensuring comfort isn't extensively compromised while still reaping appreciable flexibility benefits. Taking the December month in a typical climate year as an example, we noted an immediate load reduction approaching 2500 MW (8530 MMBtu/h) for the 2040 scenario. This value progressively diminishes, eventually nullifying after a span of approximately 9 hours. Following this phase, a discernible load increase materializes relative to the standard scenario, peaking at 1000 MW (3412 MMBtu/h) around 4 hours into the recovery. This surge tapers off, extending well beyond the flex event's inception. In the context of the 2030 scenario, it's appropriate to reduce these values by half.

Studying a large variation of building stock scenarios, we highlighted the importance of the temperature threshold and outdoor temperatures. Lower thresholds are related to flexibility events with a longer load reduction and load increase phase. Lower outdoor temperatures amplify the load reduction potential, but result in flexibility events with a shorter duration.

ACKNOWLEDGMENTS

This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 893240 "REScoopVPP" (Smart Building Ecosystem for Energy Communities), and was supported by the "FlexSys" (A Flexible electricity System contributing to security of supply) project funded by the Energy Transition Fund of the Belgian federal government, managed by the FPS Economy, SMEs, Self-employed and Energy.

REFERENCES

Allegrini, J., Orehounig, K., Mavromatidis, G., Ruesch, F., Dorer, V., Evins, R. 2015. A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renewable and Sustainable Energy Reviews* 52:1391–404.

Bacher, P., Madsen, H. 2011. Identifying suitable models for the heat dynamics of buildings. *Energy and Buildings* 43:1511–22.

Crawley J, Manouseli D, Mallaburn P, Elwell C. 2022. An Empirical Energy Demand Flexibility Metric for Residential Properties. *Energies* 15(14):5304.

DTU Compute. 2023. https://ctsm.info.

Elia. 2023. Adequacy and flexibility study for Belgium 2024-2034

Heylen, K., Vanderstraeten, L. 2019. Wonen in Vlaanderen anno 2018. Leuven: Steunpunt Wonen.

Junker, R.G., Azar, A.G., Lopes, R.A., Lindberg, K.B., Reynders, G., Reland, R., Madsen, H. 2018. Characterizing the energy flexibility of buildings and districts. *Applied Energy* 225:175–82.

Reynders, G., Diriken, J., & Saelens, D. 2014. Quality of grey-box models and identified parameters as function of the accuracy of input and observation signals. *Energy and Buildings* 82, 263–274.

Reynders G, Diriken J, Saelens D. 2017. Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings. *Applied Energy* 198:192–202.

Statbel. 2023. https://statbel.fgov.be/en/open-data/cadastral-statistics-building-stock

Statbel. 2023. https://statbel.fgov.be/en/themes/housing/building-permits

VEKA. 2023.https://apps.energiesparen.be/energiekaart/vlaanderen#premies-residentieel.

Vigna I., Lollini R., Pernetti R. 2021. Assessing the energy flexibility of building clusters under different forcing factors. *Journal of Building Engineering* 44:102888.

Vlaams Energieagentschap. 2016. Cijferrapport: 10 jaar energieprestatieregelgeving. Procedures, resultaten en energetische karakteristieken van het Vlaamse gebouwenbestand – periode 2006 – 2015.