# Flexibility deployment of a heating system with heat pump in residential towers

*Beatrix* Bos [a], *Pieter-Jan* Hoes [b], *Jan* Hensen [b], *Ingrid* van Prooijen [c], *Christina* Papachristou [c]

[a] Sustainable Energy Technology, Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, the Netherlands, b.r.a.bos@student.tue.nl.

[b] Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology, Eindhoven, the Netherlands, p.hoes@tue.nl.

[c] BAM Energy Systems, Royal BAM, Bunnik, the Netherlands, ingrid.van.prooijen@bam.com.

**Abstract.** The transition from fossil fuel energy sources to renewable energy sources requires flexible use of our energy consumption to prevent congestion in the electricity grid. The heating systems of buildings are large energy consumers and can play an important role in matching electricity generation and demand. This research evaluates the amount and value of the potentially available flexibility from the heat pump in a case study on the heating system of two residential towers in The Netherlands, named Stoker & Brander. The thermal mass of the buildings is used to store energy to prevent heating during moments when grid congestion is likely to occur or when renewable energy production is low while maintaining comfortable indoor temperatures. To assess the potential energy flexibility, a building performance model and a financial model are developed to compare the influence on the energy flexibility when using different thermostat setpoint schedules. The total heat demand, the shifted load, the comfort, and the saved costs when deploying flexibility are selected as key performance indicators. With the model, 9 different thermostat setpoint schedules are tested with varying preheating duration and with varying timing before peak hours. In general, the schedules with a 2-hour preheating duration show the best results in terms of comfort and potential saved costs, while the timing before the peak hours has less effect on the results. The analysis on the saved costs is done with electricity prices of 2019, representing the current market, and with 4 price scenarios for 2030, representing the future market. The savings significantly increase for 2030, showing a large future potential for flexible deployment. However, it remains difficult to make a correct estimation of the predicted future savings as the scenarios show large differences between each other due to large uncertainty about the future prices. Nevertheless, for all scenarios at least 20% of the electricity purchase costs can be saved in 2030.

**Keywords.** Energy flexibility, heat pump operation, thermal mass, thermostat setpoints, electricity price scenarios
**DOI**: https://doi.org/10.34641/clima.2022.295

## 1 Introduction

### 1.1 Background information

To mitigate the effects of climate change, The Netherlands has decided to gradually reduce the natural gas consumption of buildings to zero by 2050 [1]. Common alternatives for heating with natural gas are all-electric heat pumps, collective heating systems or green gas. The electricity for the heat pump can be provided by renewable energy sources like solar or wind energy. These sources are characterized by their intermittent nature, which can result in an energy surplus when the weather circumstances are beneficial, yet in zero energy production when the weather is less beneficial. Renewable sources are implemented decentralized in the electricity grid, which often leads to grid congestion at places with a large renewable energy penetration and low grid capacity. The combination of these two characteristics leads to an increased pressure on the electricity grid and eventually to grid congestion, which is increasingly becoming a problem in the Netherlands (see this map). To alleviate these electricity grid problems a certain flexibility is required in demand and supply of electricity. Electricity should be used *where* it is generated and *when* it is generated. One way to offer this energy flexibility is by using Demand Side Management (DSM) in which the demand loads are adapted to the grid requirements [2]. Examples of Demand Side Management are load shifting and peak shaving of the peak electricity demand. In this research the focus lies on shifting the building energy demand to *when* electricity is generated.

The ability of a building to manage its energy demand according to local climate conditions, user needs and grid requirements is addressed as the Energy Flexibility of a building [3]. In this research we focus on the energy flexibility that can be offered by using the heating system of a building in combination with the building's thermal mass. The working principle is based on the thermal inertia of a building, i.e., the indoor temperature responds relatively slow due to thermal energy buffering in the thermal mass [4]. When (green) electricity is available or cheap, heat can be produced and stored in the thermal mass without changing the indoor temperature too much. When generation from renewable energy sources is low or when congestion is expected, the stored heat in the thermal mass can be used to maintain a comfortable temperature, while reducing to building's heating energy demand [5]. This is referred to as load shifting. However, it is important to keep in mind that the operative temperature should always be kept within the limits of the occupants' thermal comfort.

### 1.2 Case description: project Euroborg - Stoker & Brander

In this research, the potential of using a heat pump for energy flexibility deployment is investigated by using a case study building. Royal BAM Group, hereafter indicated with BAM, has constructed two residential towers in Groningen, named Stoker & Brander. Each of these towers is home to 90 apartments with different lay-outs divided over 25 levels [6]. BAM acts as an Energy Service Company (ESCo), and is therefore responsible for the design, installation, and maintenance of the heating & cooling system of the towers. The system consists of a large heat pump that uses an underground heat and cold storage as thermal energy source (an Aquifer Thermal Energy Storage (ATES) system). The heat pump provides space heating to all apartments through an underfloor heating systems. For domestic hot water, the installation of gas boilers was required to achieve higher temperatures

### 1.3 Research objective

The main research objective of this project is to *quantify and value the potential energy flexibility of the heat pump in the heating system of two residential towers, Stoker & Brander, by utilizing the thermal mass of the buildings as heat storage medium*. This research explicitly focuses on making use of the existing heating system to keep additional investment costs in new infrastructure and storage capacity as low as possible. Next to that, this research is restricted to the condition that thermal comfort of the residents should always be guaranteed.

The following three main questions are formulated to support the research objective:

1. What is the current performance of the heating system in Stoker & Brander?
2. What is the energy flexibility of the current space heating system? Additional sub-questions can help to answer this question: What Key Performance Indicators are relevant? How can the energy flexibility be modeled and which building performance simulation models are suitable? What model complexity is appropriate?
3. What are the current and future monetary savings when the energy flexibility is deployed or not deployed?

## 2 Methodology

### 2.1 Research steps

In this research the flexibility of Stoker & Brander is quantified and valued by using a computational model that consists of multiple parts. To create this model, several steps are taken.

In the first step an analysis on historical data of the buildings is executed as well as having multiple conversations with BAM's management and operations team working on these buildings leading to detailed information about the current performance of the buildings. Second, the architectural drawings are taken as starting point to find an appropriate spatial resolution for the model. The appropriate spatial resolution is identified for one apartment by experimenting with certain modeling resolutions and their impact on the KPIs, after which the choices are converted to the geometries of the other apartments. In step 3 information about the occupant behavior, lighting settings, heating system and its settings, and the simulation periods are added to the model by using an iterative process. In the 4th step, varying temperature setpoint schedules are tested on one apartment to investigate the flexibility deployment by using the heat pump. In the next step, all different apartment types are simulated. In the last step, the results of all apartment types are combined with the outputs of the first step. Besides the quantification of flexibility, the valuation of this quantity requires a financial analysis. This analysis looks at both the current expected value and the future expected value.

### 2.2 Simulation workflow

In order to execute the research steps, different software tools are used that complement each other. An overview is presented in Figure 3. On the left side, the used inputs for the software tools are shown, in the middle is shown which part of the model is made with which tool and on the right side the outputs are represented. In red is indicated if and where the output is used as input for another software tool.

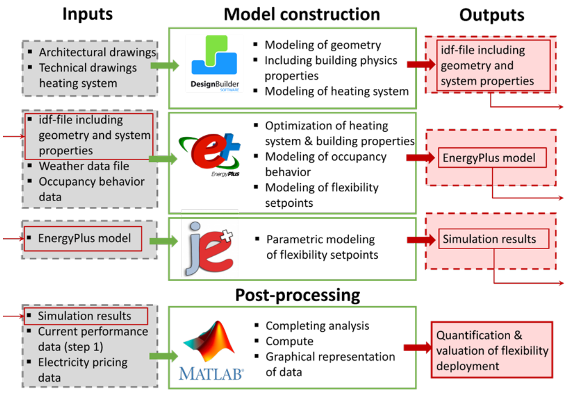


**Fig. 1** - Graphical representation of the used software tools and their in- and outputs.

# 3 Case study description

As explained previously, BAM acts as an Energy Service Company for the buildings Stoker & Brander. The benefits of an ESCo are that the building owners (and tenants) are care-free and not responsible for the heating and cooling provision. A key component of the relation between the owner(s) and the ESCo is the energy performance contract. Generally, in these contracts, long-term guarantee of the performance is secured and, optionally, agreements are made on the energy savings. The ESCo agreement on these buildings, that runs for 30 years, provides an incentive for optimization of the system and its operational costs. Residents pay a fixed amount to BAM for their consumed heat. If BAM can generate the delivered heat more efficiently, they can benefit from higher profit margins while the clients pay a flat, predictable rate. However, the risk of producing heat against higher costs is also for BAM. Making smart use of the heat pump and the expected fluctuating electricity prices could save on the operational costs. Based on their point of view, the Key Performance Indicators are formulated.

## *3.1 Key Performance Indicators*

The quantification and valuation of the flexibility deployment is assessed by using a set of Key Performance Indicators (KPIs). To assess the energetic performance of the system when deploying flexibility, the shifted load and the total energy consumption are evaluated. The amount of increase or decrease of the electricity demand after a (price) signal is the shiftable load for one signal. The summation of the shifted loads of all signals during one heating seasons is used as the *total shifted load*, which can be used to express the amount of flexibility [7]. Besides the shifted load, it is good to keep an eye on the *total energy consumption* to make sure that the energy consumption when deploying flexibility does not increase. The KPI's value can be seen as a boundary condition that should be satisfied. The valuation of the flexibility deployment is expressed in the saved operational costs of the heat pump. The operational costs mostly consist of the electricity costs. These *saved costs* are expressed in absolute saved costs in [€] and relative to the total electricity costs in [%] for the heating system. As is the case with the total energy consumption, the *thermal comfort* also places limits to the amount of flexibility that can be deployed. Therefore, thermal discomfort is defined as the number of hours when the occupants are present of which the operative temperature falls outside the 90% bandwidth of the Dutch adaptive comfort limits.

## *3.2 Building characteristics*

As real-life buildings function as case buildings, a lot of information is known. Three aspects are of interest: the (thermal) building properties, the functioning of the heating system and information about the residents. Based on the architectural drawings, most building properties have been deduced. Second, information about the installed heat system is analyzed and converted into more simple, schematic overviews showing the main components of the installation and their connections. Due to privacy laws, not much information is known about the residents. Therefore, demographic information of the neighborhood gives an indication of the residents' profiles. Five different household types are identified: 1-adult household (39%), 2-adult household (13.9%), 1-senior household (21%), 2-senior household (15.1%), Family household (11%).

# 4 Current performance analysis

As described in the section Research steps, the first step entails the analysis of the current performance of the case buildings. The results of this analysis are used as inputs to construct the model. Key figures that are of interest are the energy flows, distribution losses and the performance of the heat pump. To get an idea of the total performance of the system, the total energy flow over one heating season is presented in a Sankey diagram, see Figure 4.

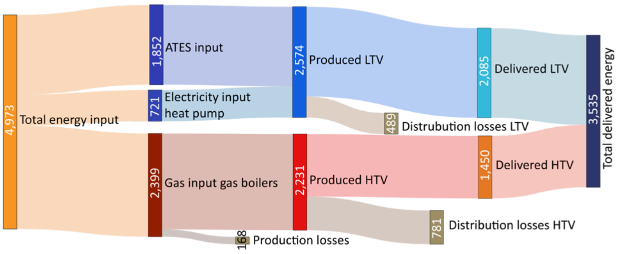


**Fig. 2 -** Sankey diagram of the energy flow in Stoker and Brander for 2019

The total amount of produced thermal energy for Low Temperature Heating (Lage Temperatuur Verwarming - LTV), which is used for space heating, is the combination of the electricity consumed by the heat pump and the thermal energy extracted from the ATES source. During the delivery of the LTV from the installation room to the apartments, the distribution losses are 18 to 19%. The total amount of produced thermal energy for the High Temperature Heating (Hoge Temperatuur Verwarming - HTV), which is mainly used for Domestic Hot Water (DHW), depends on the gas consumption and the efficiency of the gas boilers, which is assumed to be 93% and is common for gas boilers. Due to the higher temperatures of the HTV, higher distribution losses are found of 35 to 36%. For both streams, the losses are lower than the design values of 20 and 40% respectively. Though, it should be kept in mind that the losses vary over the years. As no significant amount of electricity is used to supply cooling to the apartments, the energy flows for cooling are not regarded in this analysis and thus, the thermal energy from the cold source is not included.

The heat pump is a crucial asset of the heating system. At moments where the heat pump does not function as designed, the gas use increases enormously, having a negative effect on the environmental and financial costs. Over the years that the heat pump was in normal operation, an average COP of 3.6 was found. Histograms of the data show that most of the time, the COP was even higher than 3.6 but the average performance is decreased by some low outliers (that can occur during malfunctioning of the heat pump).

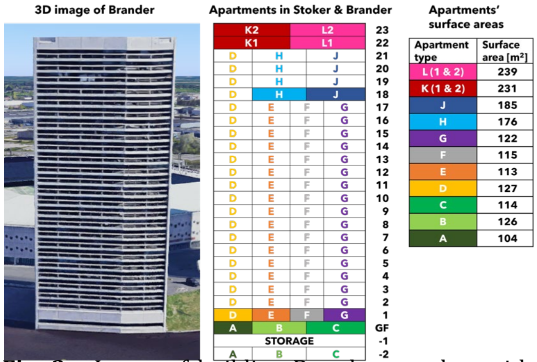
# 5 Model construction

The construction of the simulation model is split into three sections. The first section focuses on the modeling of the geometry of the building, the second on the simulation settings and the third section explains the financial model.

## *5.1 Geometric modeling*

Stoker & Brander are similar in terms of most building properties and floor plans, moreover they are connected to the same heating system. The largest difference between the towers is the orientation of the buildings. Stoker is oriented 36.6° relative to the north axis, where Brander is oriented -2.5° relative to the north axis. This difference results in a varying solar incidence per wall. To check whether the orientation influences the thermal heat demand, the smallest and the biggest apartment are simulated for both orientations. The difference between the smallest apartments is 5.8% and between the largest apartments 1.9%. As the differences are small, it is assumed that the differences are insignificant, and this research continues with the modeling of one of the two buildings.

Within one building there are 90 apartments for which 11 different apartment types can be identified based on their position, size and floor plan. The types are indicated with the letters A, B, C, D, E, F, G, H, J, K and L. For every apartment type, at least one apartment should be simulated to investigate the impact of the apartment type on the results. To prevent creating 90 different models per building, the model is simplified by using the method of [10] In Fig. **5** the colored apartments indicate how this method is translated to the apartments of Stoker & Brander. Note that level -2 is uninhabited due to leakage problems.
To decrease the complexity of the geometries within the apartments, different thermal zone designs are tested for one type of apartment to find an optimum between the complexity of the model and accuracy the results. Four common zone configurations are modelled [9]: *single-thermal zone*, where the entire apartment is modelled as one thermal zone, *zone per orientation*, where there are always five zones, one for each orientation and one in the middle, *zone per function*, where rooms with the same function can be combined, and *zone per room*, which entails the highest complexity. Simulations show that single-thermal zoning has the highest deviation in the relevant KPIs, and is therefore less suited, which is in accordance with the literature on multistorey buildings [9][10]. A choice is made for the *zone per function* as this can result in the simulation of the least thermal zones with comparable results.



| | | | | |
|---|---|---|---|---|
| K2 | | L2 | | 23 |
| K1 | | L1 | | 22 |
| D | H | | J | 21 |
| D | H | | J | 20 |
| D | H | | J | 19 |
| D | H | | J | 18 |
| D | E | F | G | 17 |
| D | E | F | G | 16 |
| D | E | F | G | 15 |
| D | E | F | G | 14 |
| D | E | F | G | 13 |
| D | E | F | G | 12 |
| D | E | F | G | 11 |
| D | E | F | G | 10 |
| D | E | F | G | 9 |
| D | E | F | G | 8 |
| D | E | F | G | 7 |
| D | E | F | G | 6 |
| D | E | F | G | 5 |
| D | E | F | G | 4 |
| D | E | F | G | 3 |
| D | E | F | G | 2 |
| D | E | F | G | 1 |
| A | B | | C | GF |
| STORAGE | | | | -1 |
| A | B | | C | -2 |

| Apartment type | Surface area [m²] |
|---|---|
| L (1 & 2) | 239 |
| K (1 & 2) | 231 |
| J | 185 |
| H | 176 |
| G | 122 |
| F | 115 |
| E | 113 |
| D | 127 |
| C | 114 |
| B | 126 |
| A | 104 |

**Fig. 3** - Image of building Brander together with a schematic overview of the apartment types, their floor level and surface area.

## *5.2 Simulation settings and assumption*

With the geometry of the buildings being modelled, a representation of the heating system is chosen. As this study is interested in shifting electricity consumption, only the space heating system is modelled as the DHW-system is mostly consuming natural gas. The space heating system can be modelled in three parts: the underfloor heating system to release the heat, the distribution system of heat and the heat generation in the installation room. As the efficiency of the heat pump and the distribution system of the case buildings are known (see Section 4), this part can also be calculated during the post-processing of the results to decrease the complexity of the simulation model. Therefore, the heat generation and distribution system are represented in the models by a district heating system that directly delivers its heat to the apartment, while the underfloor heating system is modelled per apartment in more detail.

However, the consumption of the heating system depends greatly on the behavior of the occupants, that is characterized by personal preferences and lifestyle. Similarities between these characterizations can be grouped in different household types that are common in the Dutch housing stock, as defined in Section 3.2. Per group, characteristics like occupant presence and desired temperature setpoints can be assigned in the form of profiles. The data for these characteristics is extracted from the WoonOnderzoek Nederland (WoON) [11] and composed to profiles in previous work [10][12]. These profiles show the presence or desired temperature setpoint per hour of the day. When the presence is 0, an occupant is not at home at that hour, when the presence is 1, an occupant is at home, and in between 0 and 1 the occupant is present at that moment for a part of the week. The temperature profiles show when the setpoint temperature is preferred (20°C or for seniors 22°C), or when the setback temperature is preferred (16°C or for seniors 18°C), which is the minimal value for the room temperature that must be maintained. By means of simplicity these profiles are equal for the weekends and the weekdays.
Next, it is determined in what level of detail the simulations should take place. As the time span of heat storage in thermal mass is relatively small, this study requires a large level of simulation detail. Therefore, the 5-minute interval shows the most realistic results and is therefore used for all further simulations.

Due to this large level of detail, simulating the entire heating season would require large calculation load.

To reduce the computational load, three different weeks in the heating season are simulated and translated back to the heating seasons. These three weeks are chosen by their different weather characteristics for several consecutive days to represent the different outdoor circumstances that could occur during the heating season. The characteristics of the weeks are shown in Table 1.

**Tab. 1** - Characteristics of the three weeks chosen as simulation periods.

| | **Average year based on E+ weather file** | **Colder year** | **Warmer year** |
|---|---|---|---|
| Week A | 8 | 10 | 4.5 |
| Week B | 11 | 10 | 13 |
| Week C | 15.5 | 14.5 | 17 |

During preliminary simulations of one entire heating season, the energy demand during the chosen three weeks is compared to the other weeks of the heating season, based on the EnergyPlus weather file for Groningen [13]. This gives an indication of how many times each week should be included in the model to represent one heating season. Though, as not every year is identical - one year can be colder or warmer than other years – a warmer and a colder year is created to cover the differences per year. To generate the colder and warmer variations on the average year, the reference years in NEN5060 are used.

**Tab. 2** - Translation of simulated weeks to entire heating season showing how many times a week occurs.

| | **Dates** | **$T_{out,m}$ [°C]** | **Total GHI [W/m²]** | **Average wind speed [m/s]** |
|---|---|---|---|---|
| Week A | 9-15 Feb | -3.7 | 6353 | 2.76 |
| Week B | 16-22 Jan | 5.2 | 4531 | 6.52 |
| Week C | 7-13 Nov | 8.3 | 3714 | 3.74 |

Generally, it shows that their 2018 reference climate year is significantly warmer than the weather file of Energy Plus for Groningen. It is more likely that the future years getting warmer than colder. This is also expressed through their 1% & 5% exceedance probability reference years. Though, NEN5060 also shows that extreme cold consecutive days with similar temperatures as week A are not rare and could still occur. Therefore, based on this information a slightly colder year than the average year is constructed but a significantly warmer year than the average year is included, see Table 2.

### *5.3 Financial model*

To calculate the saved costs by deploying flexibility, a financial model is developed. For a realistic cost estimation, historical data from the EPEX day-ahead market, where BAM is also likely to purchase their electricity from, is used to calculate the electricity costs per time step. The prices of the winter of 2019-2020 are used as this is the most recent heating season before the impacts of the COVID-19 crisis. However, there is a discrepancy between the weather profile of EnergyPlus for Groningen influencing the simulations and the actual weather that can have influenced the prices of 2019-2020. Therefore, days from 2019-2020 with similar weather profiles for the outdoor temperature, wind speed and Global Horizontal Irradiance to the EnergyPlus Groningen weather file are selected to create a new time series for electricity costs [14].

Furthermore, it is expected that the weather will increasingly influence the electricity prices besides all other market changes. Predictions for future prices can be used to give a better estimation of the future costs saving potential. CE Delft developed four scenarios for the day-ahead market prices in 2030 that differ in two factors with each two options: high or low renewable energy supply (RES) and high or low coal, gas & CO2 prices (prices). More details about these options can be found in their report [15]. The four scenarios are indicated with *2030A*, having low coal, gas & CO2 prices and low RES, *2030B*, having low prices but high RES, *2030C*, with high prices and but a low RES, and *2030D*, having both high prices and high RES. Based on descriptive data from CE Delft, that has a negative skewness, new price scenarios are created by using a Pearson system. For each scenario 5 data sets are created to anticipate on random generator errors. The data sets are placed in logical order based on the price profile of 2019-2020. This results in five time series for the four 2030-scenarios for the three different weeks of which one is shown in Fig. **6**.

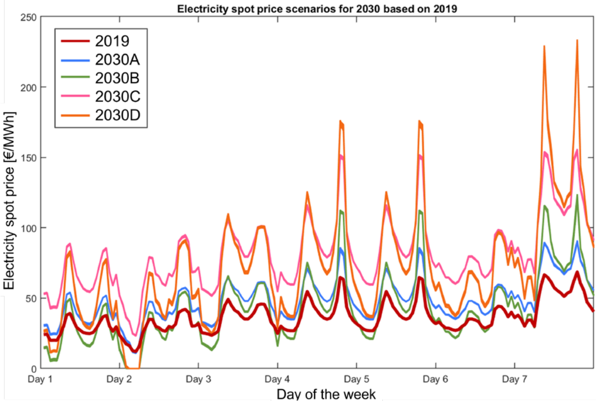


**Fig. 4** - Time series of the 2030 electricity spot price scenarios for week A.

# 6 Flexibility deployment

With the model in place, different operation settings can be simulated to test whether the electricity use of the heat pump can be shifted over time. To do so, flexibility events are defined in two steps: first, it is investigated during which moments it is desirable to decrease the electricity use, the so-called peak hours. The peak hours are here defined as the moments where the electricity price is high, mostly caused by a large electricity demand or low renewable electricity production. The peak hours function as signal or penalty for the electricity demand, as referred to in Section 3.1. To find realistic timings for these peak hours, the moments where simultaneously the Dutch electricity spot prices and the electricity use of the heat pump of Stoker & Brander are high, are considered [16]. It appears that the prices and consumption are high between 07.00 and 10.00 and between 16.00 and 20.00, which are therefore defined as the peak hours. Second, taking these peak hours into account, the temperature setpoint profiles described in the previous section are adjusted in such a way that the set-back temperature falls within the peak hours. Therefore, the timing of the setpoints is advanced to before peak hours, see the yellow profile in Fig. **7**.

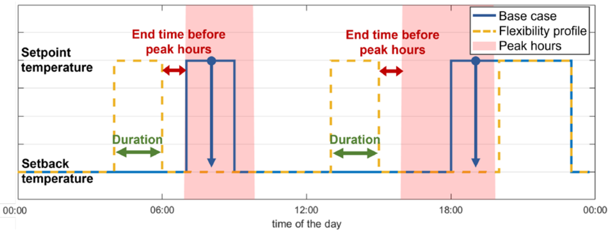


**Fig. 6** - Schematic graph of the conversion of the base case to the flexibility schedules

To investigate for how long and at which time the system should preheat to remain comfortable, several schedules are designed to test the differences. The different durations test how much thermal energy should be added to the building to remain comfortable. The different end times before the start of the peak hours are varied to create 'smarter' schedules in comparison to the base case temperature schedules, that ensure to have achieved a comfortable room temperature at the start of the peak hours. Combining the different characteristics leads to 9 different schedules, see Tab. **1**.

**Tab. 1** - The new temperature setpoint schedule characteristics that aim to deploy energy flexibility

| | Duration | End time before peak hours | Name |
|---|---|---|---|
| Schedule 0 | - | - | No flex |
| Schedule 1 | 2 hours | 0 min | 2h-0min |
| Schedule 2 | 2 hours | 30 min | 2h-30min |
| Schedule 3 | 2 hours | 1 hour | 2h-1hour |
| Schedule 4 | 1 hour | 0 min | 1h-0min |
| Schedule 5 | 1 hour | 30 min | 1h-30min |
| Schedule 6 | 1 hour | 1 hour | 1h-1hour |
| Schedule 7 | 30 min | 0 min | 30m-0min |
| Schedule 8 | 30 min | 30 min | 30m-30min |
| Schedule 9 | 30 min | 1 hour | 30m-1hour |

## 7 Results

The apartments are all simulated for the different flexibility schedules and this section will discuss the results. The results on building level are analyzed for one of the two buildings during one heating season, using the extrapolation method explained in Section 5.2. The following observations can be made when analysing the data presented in Fig. ***9***:

- More than 50% of the total load is shifted in time.
- The differences between the flexibility schedules are very small for the shifted load and the heat demand. This is because during the peak hours the temperature setpoints in all flexibility schedules are set to the lower setpoint, preventing the heating system to switch on. Consequently, the only heating demand that can occur during the peak hours comes from the bedrooms, which is for every schedule almost the same. This would imply that based on these two KPIs it would not matter which schedule to be used.

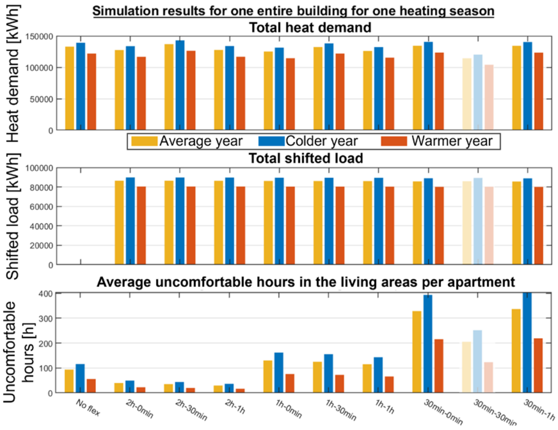


**Fig. 5** - Results for 3 of the 4 KPIs for one building, presented for an average, colder and warmer year.

- Though, when analyzing the uncomfortable hours, the schedules show that the shorter the preheating duration, the more uncomfortable hours. The end time before the peak moment does not seem to have an influence on the comfort. The schedules with a preheat duration of 30 minutes show a very high number of uncomfortable hours, which is not desirable. Though, it should be noted that most of these hours are a result of the simulations during the cold weeks. Therefore, it is too early to conclude that all schedules with a preheat duration of 30 minutes should not be used.

When looking into differences between the apartment types, the most important findings are the amount of shifted load per m$^2$ is higher for the larger apartments, however the range of the number of uncomfortable hours is also larger for larger apartments. Between the household types, the largest difference can be seen at the senior household types. As they have a higher heat demand, they also show a larger shiftable load, however without any uncomfortable hours. This can be explained by the fact that the adaptive comfort model is not specifically targeted to seniors, however, on average they do prefer a higher indoor temperature. Therefore, these results do not indicate that the seniors are always feeling comfortable.

The 30min-30min schedule shows a lower heat demand for all household types and all apartment types than the other two 30-minute schedules, and especially a lower number of uncomfortable hours. When comparing the times series of this schedule to the other schedules to track the cause, it shows that the total consumption is consistently lower while the indoor temperatures are higher. The deviating results are hard to explain as the only change to the model per schedule are the setpoint schedules. For these reasons, this schedule is not trusted, and will therefore be excluded from all results to come.

Looking at the remaining KPI, the amount of saved costs, the savings relative to the total costs are considered. Fig. ***10*** shows the savings as a share of the total electricity costs and the electricity purchase costs of Stoker & Brander. The grey bars refer to the current total electricity costs which include taxes, sustainable energy fees, transport costs, connection costs, measurement costs and the rent for the

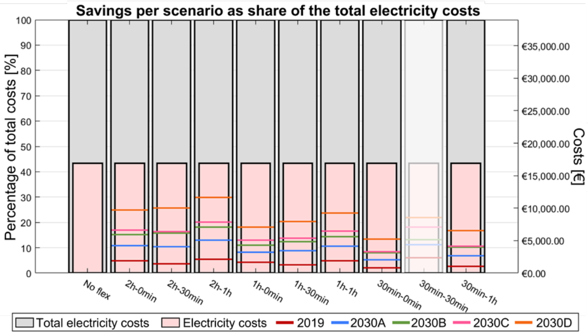


**Fig. 7** - Results for the saved costs with 2019 prices and for the 2030 price scenarios for the assumed household combination presented as percentage of the total costs (left axis) and as absolute costs (right axis).

transformer. The pink bar explicitly shows what part of the total electricity costs is spent at the actual purchasing of electricity. The graph only includes the results for the average year as it is found that the different years do not impact the results significantly. The graph shows that currently, around 5% of the total electricity costs can be saved per year, while in 2030 this could be around 25 to 30% of the total electricity costs. Though, it is remarkable that the amount of savings is influenced by the different flexibility schedules while the total demand or the shifted load do not vary significantly between these schedules. The schedules with a 2-hour preheat duration can achieve double the amount of savings, probably as heating only occurs at the set moments with low electricity pricing. In the contrary, for the schedules with a 30-minutes preheat duration the heating system also needs to operate during other, more expensive moments as comfort limits are not reached due to insufficient preheating, leading to higher costs. In addition, the heating peak of the 2-hour schedule occurs further away from the peak hours, profiting from lower prices. Besides the influence of the schedules, the price scenarios have a significant influence on the potential savings. The scenarios for 2030 all show an increase of at least double the amount of cost savings compared to the prices of 2019. Especially scenario 2030D (high prices and high RES), shows larger savings due to the increased fluctuations in electricity prices.

## 8 Discussion

This section will further discuss the interpretations, implications, accuracy and limitations of the model and its results, together with a translation of this research into practice.

It can be questioned if the three chosen weeks are representative enough for an entire heating season since no other week in the year can be completely equal to the simulated weeks, and no day is the same. Simulating day by day would give more accurate results, although it requires more computational load and adds additional complexity and uncertainty to the analysis. However, more accurate modeling is not assumed to be necessary for this research as the objective is to investigate the flexibility *potential* of the buildings in contrast to a detailed quantification.

Currently, it is not investigated if combining different schedules throughout the year would give better results. It would be interesting to perform an optimization study to find valuable combinations, for example by using model predictive control instead of rule-based control. To determine which temperature schedule to be used, the weather or the electricity price profiles can be leading. This requires accurate weather and price forecasting models to base the heating strategy on.

At the moment, the financial investigation is only based on cost savings due to variable electricity prices. However, potential flexibility incentives from distribution system operators (DSO) are not taken into account. This additional incentive can be valuable for BAM with respect to their Stoker & Brander ESCo and can increase their cost savings.

To bring the theory of this entire research into practice, it is important to place the findings in a practical context and to acknowledge possible limitations from practice. To begin with, it is looked at what should be changed to the installation to apply energy flexibility in the way that is investigated in this study. Generally speaking, this only means that the temperature setpoints of the occupants' thermostats need to be set to the temperature schedules as defined in this study. Preferably, this is done from a distance without any interference from the occupants, both to prevent errors and to unburden the occupants. This will require close communication with the occupants and agreements on the privacy of their data.

Yet, the operation and responsibility of BAM on the system in Stoker & Brander reaches until the delivery sets, but not beyond. However, the heat pump can also be controlled in another way. By lowering the temperature of the outflow of the heat pump, less thermal energy, and thus less electricity, is required by the heat pump. This will also mean that the incoming flow at the delivery set has a lower temperature, meaning that less heat is provided to the occupants. If an occupant experiences discomfort, the occupant can overrule this by increasing their thermostat temperature. Though, this way of flexibility deployment is not investigated in the model and therefore it is unsure if the same flexibility potential can be reached. It could be investigated if, for new ESCo projects, it would be interesting to also operate and deploy the underfloor heating system and the thermostat.

It should not be forgotten that before having the possibility to save costs as a result of load shifting, BAM should become an active participant in the electricity market. This means that they will purchase their electricity directly from the market without any electricity supplier in between (e.g. Eneco). This means that accurate forecasting of the demand of the ESCo is required to prevent large imbalance costs, also for the cooling season, when load shifting will probably not play a role.

Lastly, it is advised to closely collaborate with the local distribution system operator (DSO) to determine when load could be shifted. The DSO could provide information about potential local grid congestion and the local renewable energy rate. This could also be done by using the GOPACS platform.

## 9 Conclusion

In general, shifting the electricity load from the residential buildings Stoker & Brander with the heat pump is possible without exceeding the comfort limits when sufficiently preheating the apartment. Little differences are shown between an average, a colder and a warmer year, indicating that over the years, similar results can be expected. With this load shifting, a significant part of the electricity costs can be saved, especially when considering future electricity price scenarios. This shows that the potential for flexibility deployment can gain momentum during the coming decade. Moreover, the buildings can play a role in smart consumption of the generated renewable energy and preventing grid congestion as this investigation shows that under certain conditions the buildings can potentially shift more than 50% of the electricity demand of its heat pump. The analysis on the differences between schedules shows that the schedules with a 2-hour preheating duration have better results in terms of cost savings and comfort than the schedules with the 1-hour and 30-minutes preheating durations. Note that longer preheating does not necessarily lead to a higher heat demand as the schedules with a shorter preheating duration have to compensate with additional heat demand during other moments, resulting in a similar heat demand for all schedules. The end time of the preheating before the start of the peak hours shows to have less effect on the comfort, however, it does appear that the 1-hour before end time schedules can save more costs as their timing is further away from the peak hours and, therefore, they profit from lower prices. Regarding the cost savings, when comparing the simulated saved costs to the electricity purchase costs for Stoker & Brander, a maximum of around 10% of the purchase costs can be saved based on electricity prices for 2019. However, when calculating the saved costs with the electricity price scenarios for 2030, the potentially saved costs can go up to two-third of the purchase costs. The uncertainty about the future prices makes it difficult to conclude whether it is worth it or not to proceed with investing in flexibility deployment. Nevertheless, at least 20% of the purchase costs can be saved in 2030 and these reoccurring, annual savings are interesting for BAM as their ESCo contracts run for around 25 to 30 years. During a pilot, field tests should show if the comfort of the occupants is truly not affected and if no additional complaints arise when flexibility is deployed. Note that this paper is a shortened version of a full thesis where more details about the study can be found [17]. The datasets generated during and/or analyzed during the current study are not publicly available because the data is privately owned by BAM but are available on request by email.

## 10 References

[1] RVO. Energiecijfersdatabank - energiemix, 2019.

[2] Thibault Q. Péan, Jaume Salom, and Ramon Costa-Castelló. Review of control strategies for improving the energy flexibility provided by heat pump systems in buildings. Journal of Process Control, 74:35–49, 2 2019.

[3] IEA-EBC. EBC Annex 67 Energy Flexible Buildings. (December):32–36, 2014.

[4] Xue Li, Wenming Li, Rufeng Zhang, Tao Jiang, Houhe Chen, and Guoqing Li. Collaborative scheduling and flexibility assessment of integrated electricity and district heating systems utilizing thermal inertia of district heating network and aggregated buildings. Applied Energy, 258:114021, 1 2020.

[5] Hicham Johra, Per Heiselberg, and Jérôme Le Dréau. Influence of envelope, structural thermal mass and indoor content on the building heating energy flexibility. Energy and Buildings, 183: 325–339, 1 2019.

[6] Royal BAM Group. Eerste bewoners trekken in appartemententoren Stoker (Euroborg, Groningen), 2009.

[7] Christina Papachristou. Designing a decision support tool for high performance office buildings focusing on energy flexibility: supporting decisions on thermal comfort control strategies and building design parameters. PhD thesis, Eindhoven University of Technology, 2019.

[9] Sara Elhadad, Chro Hama Radha, István Kistelegdi, Bálint Baranyai, and János Gyergyák. Model simplification on energy and comfort simulation analysis for residential building design in hot and arid climate. Energies, 13(8):1876, 4 2020.

[10] Sultan Çetin-Öztürk. Net-Zero Energy Renovations of High-Rise Apartments in The Netherlands. Technical report, Eindhoven University of Technology, 2018.

[11] Dutch Ministry of the Interior and Kingdom Relations (BZK). WoON - WoonOnderzoek Nederland, 2012.

[12] O. Guerra-Santin and S. Silvester. Development of Dutch occupancy and heating profiles for building simulation. Building Research and Information, 45(4):396–413, 5 2017.

[13] EnergyPlus. Weather Data by Region, 2020.

[14] Pieter-Jan Hoes. Computational performance prediction of the potential of hybrid adaptable thermal storage concepts for lightweight low-energy houses. PhD thesis, Eindhoven University of Technology, 2014.

[15] Maarten Afman, Sebastiaan Hers, and Thijs Scholten. Energy and electricity price scenarios 2020-2023-2030: Input to Power to Ammonia value chains and business cases. Technical report, CE Delft, 2017.

[16] Nord Pool. Historical Market Data, 2019.

[17] Beatrix Bos. Flexibility deployment of a heating system with a heat pump in residential towers. MSc thesis, Eindhoven University of Technology, 2021.