# Heuristic Optimization of Clusters of Heat Pumps: A Simulation and Case Study of Residential Frequency Reserve

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## Abstract

The technological challenges of adapting energy systems to the addition of more renewables are intricately interrelated with the ways in which markets incentivize their development and deployment. Households with own onsite distributed generation augmented by electrical and thermal storage capacities (prosumers), can adjust energy use based on the current needs of the electricity grid. Heat pumps, as an established technology for enhancing energy efficiency, are increasingly seen as having potential for shifting electricity use and contributing to Demand Response (DR).

Using a model developed and validated with monitoring data of a household in a plus-energy neighborhood in southern Germany, the technical and financial viability of utilizing household heat pumps to provide power in the market for Frequency Restoration Reserve (FRR) are studied. The research aims to evaluate the flexible electrical load offered by a cluster of buildings whose heat pumps are activated depending on selected rule-based participation strategies.

Given the prevailing prices for FRR in Germany, the modelled cluster was unable to reduce overall electricity costs and thus was unable to show that DR participation as a cluster with the heat pumps is financially viable. Five strategies that differed in the respective contractual requirements that would need to be agreed upon between the cluster manager and the aggregator were studied. The relatively high degree of flexibility necessary for the heat pumps to participate in FRR activations could be provided to varying extents in all strategies, but the minimum running time of the heat pumps turned out to be the primary limiting physical (and financial) factor. The frequency, price and duration of the activation calls from the FRR are also vital to compensate the increase of the heat pumps' energy use. With respect to thermal comfort and self-sufficiency constraints, the buildings were only able to accept up to 34 % of the activation calls while remaining within set comfort parameters. This, however, also depends on the characteristics of the buildings. Finally, a sensitivity analysis showed that if the FRR market changed and the energy prices were more advantageous, the proposed approaches could become financially viable. This work suggests the need for further study of the role of heat pumps in flexibility markets and research questions concerning the aggregation of local clusters of such flexible technologies.

*Keywords:* frequency restoration reserve; power flexibility; demand response; heat pumps; plus-energy dwellings.

## 1 Introduction

As countries continue to implement support mechanisms for volatile renewable energy production, the systems and processes needed to maintain balance in power grids continue to increase in importance, and are consequential for the success of energy transitions. Methods for accommodating this volatile generation in the grid are being supported by new technologies (e.g., battery storage), regulatory measures such as strategic stability reserve plants, and innovation in the private sector with tariffs incentivizing flexible demand for electricity users [1,2]. The demand side has been acknowledged as an important part of ensuring this future stability in power grids more dependent on the fluctuations of renewables [3]. Especially, heating applications coupled with heat storage have shown promise in providing a significant contribution to power grid stability. Heat pumps, especially when they are ground coupled, offer the potential to both increase efficiency in building heating applications while being able to use available excess power from distributed renewables [4].

In this contribution, we assess the ability of the private sector to offer end users the option of allowing direct control of their heat pumps systems in order to sell the flexible power on the market for Frequency Restoration Reserve power (FRR). Our analysis focuses on a case study in Germany with a net zero energy district equipped with photovoltaics, heat pumps and storage, while also seeking to provide insight into the general potential of a cluster of buildings with heat pumps to contribute to Demand Response (DR).

### 1.1 Reserve market opportunities

The growing share of renewable energies and the use of the potential of DR require power networks that intelligently link producers and consumers with the status and demands of energy transmission and distribution systems. Many studies related to the use of heating and cooling strategies for DR focus on dynamic pricing and time-of-use tariffs. Another option, however, is the participation in ancillary services markets. Integrating DR into ancillary services for electricity networks has received interest internationally and has to varying extents been integrated into national markets [5]. For Germany alone, depending on the technology, 18 to 27 GW of flexibly controllable load and 35 GW of negative controllable load could become available [6], which is comparable to the ramp-down or start-up of approximately 20 large-scale power plants [7]. In addition, Continental Europe has a need for 3 GW of Frequency Containment Reserve (FCR) to stabilize the grid frequency automatically within seconds.

The provision of ancillary services to grid operators is organized differently across national power markets. [5] reviews and provides a comparison of national ancillary services markets in the context of DR in Europe. Participation in providing these grid services is contingent on various requirements on bidding generation plants and DR providers. Among other factors, this also includes a minimum power requirement needed to bid for participation in most countries. For example, in Germany, this requirement is a +/1 MW symmetric flexibility band for frequency containment reserve (FCR) and 1 MW (asymmetric positive or negative) for automatic Frequency Restoration Reserve (aFRR). In addition to such country specific requirements, the European Network for Transmission System Operators for Electricity (ENTSO-E) establishes standards and common structures for the European market as a whole and aids the European Commission (EC) in establishing guidelines in the form of common regulations [8]. Thus, before participating in ancillary services, generators and DR assets must document and prove their suitability and fulfillment of the requirements. This is a challenge for small DR assets and in particular for assets such as household heat pumps whose suitability to providing these grid services is dependent on aggregating many small assets that individually would not otherwise, alone, qualify for participation. In our studied case of the integration of flexible heat pumps into these markets, the challenge involves predicting the individual units' flexibilities and scheduling their operation.

Several model-based approaches are proposed in the literature. In [9] commercial building frequency regulation capability is estimated. [10] exploits HVAC and internal thermal storage systems to show the provision of DR by buildings, and concluded that the intraday market allowed for successfully meeting objectives of maintaining comfort while providing dependable DR capacity. An aggregated model of a fridge-freezer population is developed in [11], examining a price control strategy to quantify DR savings. In the study current ancillary service payments are analyzed and it is shown that they are insufficient to ensure widespread uptake by small consumers, and that new mechanisms need therefore to be put in place to make providing DR with consumer appliances such as refrigerators an attractive option. The challenges in distributed provision of FCR can even lead to undesirable rebound effects in system frequency if distributed algorithms for the control of small load shedding DR assets (such as refrigerators, HVAC systems or heat pumps) are not properly synchronized [12]. A case study for a battery energy storage system under the German regulatory framework is investigated with different operation strategies in [13].

Providing ancillary services in the context of microgrids is also the focus of some studies. For example, [14] proposed an optimal scheduling model for a microgrid which coordinates the aggregated prosumers net load in its connected distribution feeder. Furthermore, [15] developed an algorithm for the aggregation of flexible loads for DR applications at the substation level, while [16] developed a framework focusing on domestic storage heating DR capability in balancing markets.

More recently, other studies that deal with the provision of FRR have been published. For example, [17] includes a very accurate description of the German Frequency Restoration Reserve market and presents an operating strategy for battery energy storage systems providing FCR. In [18] the benefits of combining PV-battery systems and the provision of FRR are assessed, concluding that prioritizing the provision of FRR over self-consumption enhancement results in even higher revenues, but significantly reduces self-consumption. Also, [19] proposes a distributed price-based optimization scheme for involving a population of consumers in day-ahead procurement of electricity and frequency containment reserves, while [20] introduces plug-in electrical vehicles as a way to store energy, taking part in both day-ahead and reserve markets. Last of all, a similar study to that proposed in the present work is given in [21], which focuses on the integration between the heating and the power system by analyzing a heat pump supplying a district heating island system.

Simulation studies of building flexibility and, as particularly shown in the literature referenced above, studies about integrating heat pumps into flexibility markets and grid services have clearly received attention in the literature. Several demonstration projects of such systems have been set up in recent years, for example [22] demonstrated flexible DR provision with 54 residential heat pumps. The system presented in our work contributes to the study of flexible heat pump integration into ancillary services markets based on real demonstrations. Our case study is that of a plus energy neighborhood of single family dwellings with distributed heat pumps and PV systems in the community of Wüstenrot in Southern Germany.

## 1.2 The importance of the interactions between buildings

In [23] the importance of coordinating flexible DR assets to avoid undesirable side effects of DR at the distribution network level is shown, and the performance of conventional DR at the level of a group of buildings is evaluated. Control strategies that coordinate at the cluster level are important and especially so for ancillary services such as FRC and FRR. [24] estimates the amount of energy storage and revenue that thermostatically controlled loads can provide in residences participating in ancillary service markets. The study presented in [25] developed a methodology to quantify the flexibility in buildings, which returns the amount of energy that can be shifted and the associated costs. The results are presented in cost curves, which allow the comparison between buildings and the aggregation of flexibility, and reveal large variations depending on time, weather, utility rates, building use and comfort requirements. Also, an aggregator controlling a cluster of residential heat pumps to offer direct control flexibility services is evaluated in [26]. In that study, heat pumps are required to supply hot water and space heating at certain times and are activated flexibly in order to do so. The results show a larger potential for upward modulations than for downward modulations.

Another example of such a study is [27], which considers HVAC and domestic electric water heaters for potential DR applications and an interaction between the system operator and consumers to facilitate managing cyclic operation of consumer heating loads. In this case, the system operator and consumers signed a contract allowing the operator to control the operating cycle of EWC and HVAC loads without overriding the user preferences. In the algorithm proposed in [27], house modules submit operating proposals to a system-wide module, which judges the received proposals and accepts those in line with the objective, resulting in significant benefits.

### 1.3 Aim of the investigation

The present work is carried out in the framework of the EU Horizon2020 project Sim4Blocks, and the application is based in particular on the project's demonstration site in Germany, a newly built plus-energy settlement called "Vordere Viehweide" in the rural municipality of Wüstenrot in Southern Germany. This neighborhood incorporates a cold-water district heating system (also known as low temperature district heating) utilizing a variation of a geothermal collector. All buildings are equipped with PV systems, heat pumps, electricity storage and thermal buffer storages. More details about the case study are given in Section 3.

In this study, a cluster manager makes the decision whether the buildings that are managed (six types in total with different parameters) should activate their heat pumps or not when an activation call from the FRR is received. Our goal is to analyze the potential cost savings of different cluster manager strategies for negative reserve power, considering various price scenarios for the electricity used while providing the load flexibility. The present work focuses not only on the potential cost savings, but also on other important factors such as the thermal comfort of residents, the heat pump consumption (considering partial load factors) and the influence on the PV self-consumption ratio of the household.

The price scenarios are: 1) negative (the heat pump owner is paid to use electricity), 2) zero cost and 3) positive cost. We still consider and apply taxes and regulatory surcharges in each of these cases. These price scenarios also vary in their number of activation calls and their duration. We model this demand for activation of DR assets using published historical data on the bids of participants in the German FRR market (publicly available at www.regelleistung.net). We test the flexibility of the buildings by comparing heating and flexibility strategies with different temperature thresholds.

This paper is structured as follows. In Section 2, the frequency restoration reserve is presented. The description of the case study, the TRNSYS model and its validation is then shown in Section 3, as well as the proposed strategies. The analysis of results of the DR potential of a cluster of buildings is then discussed in Section 4. Finally, we conclude with a brief summary and future outlook in Section 5.

## 2 Market integration: frequency restoration reserve

Historical data for actual demand and for utilization price bids for positive and negative FRR in Germany were first examined at a resolution of 4 s (see Figure 1 and Figure 2), and then converted into 30 minute time steps with average activation duration for a given price bid in each 30 minute interval. The utilization payment is our focus in the analysis here. Capacity prices for FRR in the German market have drastically declined in recent years. Average weekly capacity prices for off peak negative FRR fell from 1430 EUR/MW/week on average in 2012 to 86 EUR/MW/week in 2016 (publicly available market data: www.regelleistung.net).

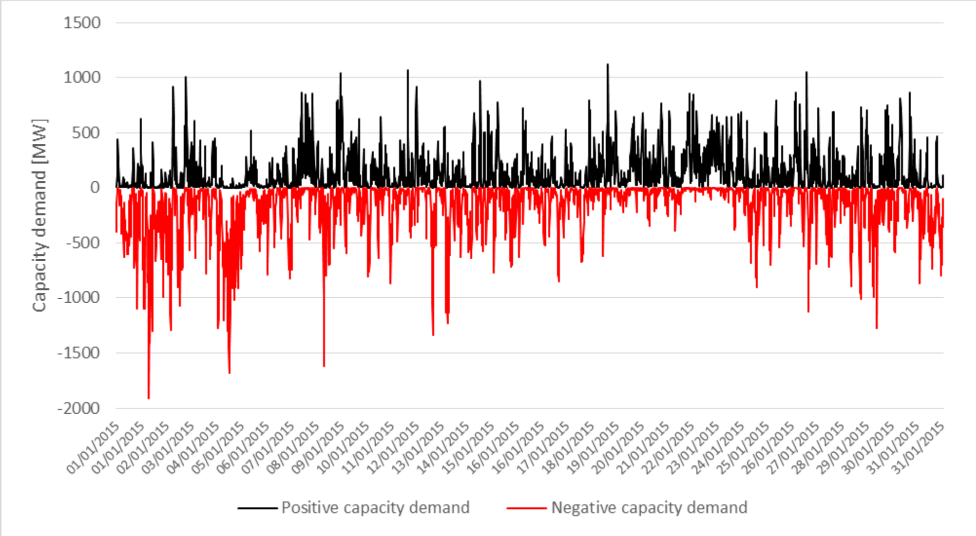


*Figure 1: Example of positive and negative FRR activation calls for the month of January 2015 in the international grid control cooperation (IGCC) covering Germany, Denmark, the Netherlands, Switzerland, the Czech Republic and Belgium. Both Austria and France have also joined IGCC* [28].

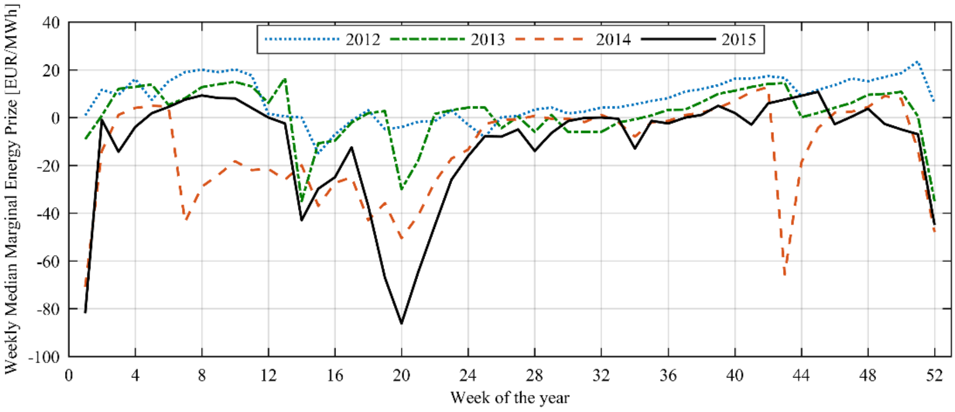


*Figure 2: Weekly FRR off peak negative reserve utilization payment price development in recent years in Germany. Own analysis of published TSO data (www.regelleistung.net).*

The bids for energy utilization are sorted and according to merit order activated by the TSO. The cheapest bids are almost constantly activated. Providers with increasing costs are then activated until the demand for balancing energy in the grid is fulfilled. In the German market, separated products for peak (HT) and off peak (NT) times are available for market participants to offer. Negative utilization payments, which imply a cash flow from the electricity network operator to the customer, lead to short activation periods of typically less than two minutes. This is a problem for heat pump operation, since such short cycles have a negative impact on lifespans. Activations of participants bidding positive prices last significantly longer (see Figure 3). Examples of control strategies for distributed devices providing direct frequency regulation include [29,30]. Figure 3 shows that FRR activations are typically very short (on the order of minutes) and that they decrease rapidly with decreasing (also negative) utilization price bids on the part of participants.

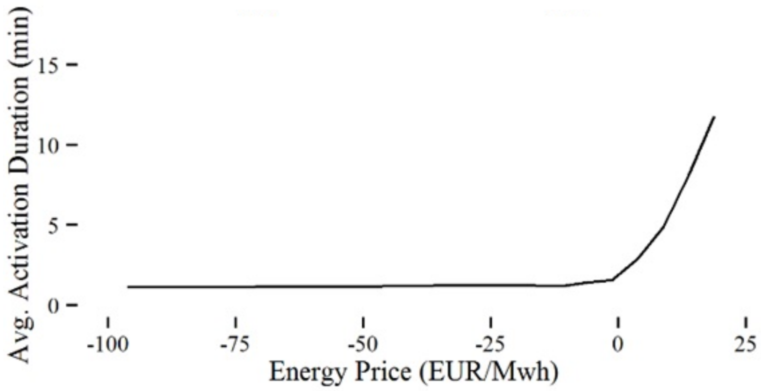


*Figure 3: Example of the duration of the activation calls vs. energy price bid. Own analysis of data for calendar year 2015. Data published by TSOs and publically available at www.regelleistung.net.*

The benefit that can be achieved in this process consists on the avoided supply of electricity purchased through the standard heat pump tariff (assumed based on local market conditions to be 22 cEUR/kWh, a flat tariff) and in the additional income from participation in the FRR market. The regulatory surcharges and taxes shown in Table 1 must additionally be subtracted. Apart from that, an additional fee for participation and services from an aggregator must also be set aside. This was assumed, based on informal interviews with multiple utilities and aggregators in Germany, to be 10 % of the FRR earnings for the purposes of this study.

| | |
|---|---|
| EEG reallocation charge | 81.87 EUR/MWh |
| CHP surcharge | 5.21 EUR/MWh |
| §19 StromNEV-reallocation (Regulation on charges for access to electricity supply networks) | 4.02 EUR/MWh |
| Offshore apportionment of liability | -0.33 EUR/MWh |
| Reallocation charge for switchable loads | 0.07 EUR/MWh |
| Electricity grid usage charge | 43.30 EUR/MWh |
| Concession charge | 15.71 EUR/MWh |
| Electricity tax | 24.40 EUR/MWh |
| Total | 174.24 EUR/MWh |

*Table 1: Gross surcharges and taxes in the studied community on energy purchased through FRR provision (2017).*

## 3 Case study: Modelling and Simulation

### 3.1 Description of the case study

The case study is based on a group of dwellings located in a district of real inhabited houses in Wüstenrot (Germany). This district consists of 25 Plus-energy houses recently built with high insulation standard (KfW 55, a benchmark used to classify a building's energy performance), of which six are being monitored. All of them have photovoltaic modules and an electrical storage system of 5 kWh located in each home.

Heat is distributed inside the dwellings through underfloor heating and all of them are connected to a cold district heating network utilizing a low depth (2m) agrothermal collector. This geothermal collector field is used as an environmental heat source for the decentral heat pumps. In each building, thermal energy storage capacity is available through a space heating tank, a Domestic Hot Water (DHW) storage tank and the buildings own thermal mass.

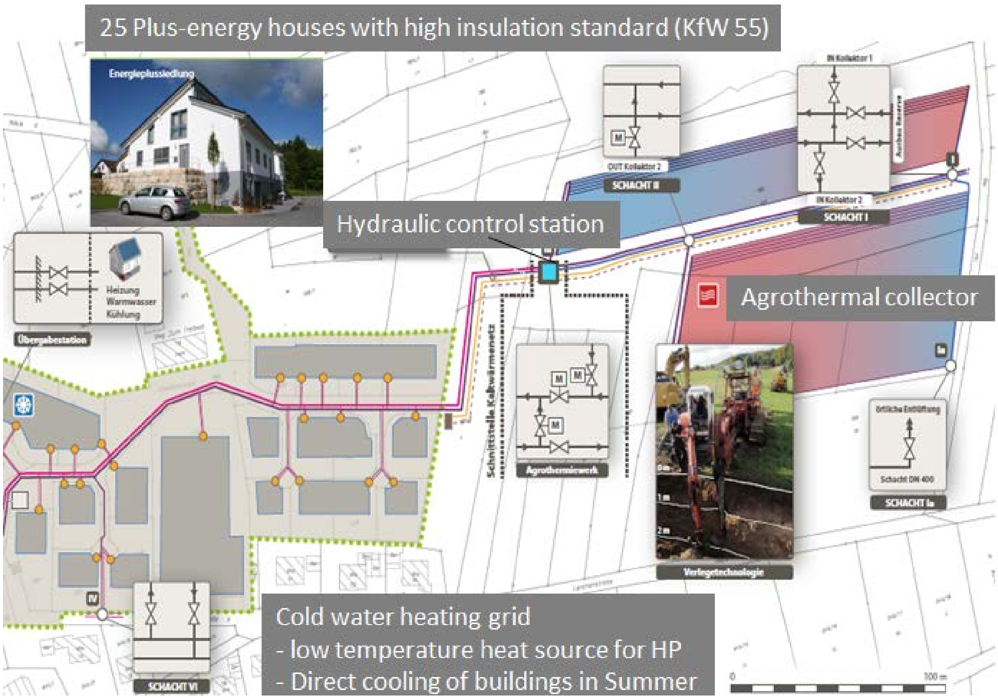


*Figure 4: Visualization of the cold district heating network and the neighborhood.*

To analyze the impact of the heating demand load curve on FRR, six different building typologies (shown in Table 2) were chosen for the study with the same geometry (two floors of around 125 $m^2$) and ventilation schedule but with different internal gains (people, equipment and lighting) as well as different infiltration rates and size of the heating tanks. Building 1 exists in the reality, and the rest are fictitious. In this way the sample is quite heterogeneous, which allows to draw conclusions for different building types. Also, since the DHW and electrical appliance consumption of the dwellings are not available, typical consumption profiles of a German household have been used.

There is one peculiarity in the considered real building: the heat pump is connected directly to the radiant floor of the building, and the heating tank is located on the return flow. This somehow uncommon configuration offers however an advantage: the focus will be on the storage capacity of the buildings, not on the storage tanks. Since these dwellings have a significant thermal mass, the thermal mass storage capacity of the buildings themselves is used. It is this capacity that allows to store the heat inside the dwellings during a certain amount of time, improving the thermal comfort of the occupants.

| Building | People | Internal Gains [W/m$^2$] | Infiltrations [1/h] | Heating tank [l] |
|---|---|---|---|---|
| 1 | 5 | 3 | 0.10 | 1000 |
| 2 | 3 | 5 | 0.10 | 400 |
| 3 | 4 | 8 | 0.10 | 500 |
| 4 | 6 | 5 | 0.30 | 1000 |
| 5 | 5 | 8 | 0.30 | 800 |
| 6 | 4 | 5 | 0.80 | 1000 |

*Table 2: Characteristics of the buildings under study.*

The parts of the energy supply system which will be included for each building are listed below:

-Photovoltaic collectors: 48 modules (58.4 m$^2$) with a south orientation, and 40 modules (49.5 m$^2$) with a north orientation. Both have a tilt angle of 15° (that of the roof). The installation has 13.64 kWp in total. PV manufacturer and model: Solar frontier Type SF155-L.

-Heat pump: ground-source heat pump (geothermal energy recovery, Watterkotte DS 5023.5Ai), connected to the cold district heating network. Used to produce hot water with a thermal capacity of 23.1 kW and a rated power of 3.7 kW. It has a performance factor of 6.14 according to DIN EN 14511.

-Water heat storage for space heating/cooling: varying sizes as shown in Table 2.

-Water heat storage for DHW: 400 liters.

-Electricity storage: 5 kWh. Lithium ion polymer technology, efficiency (system level) greater than 95 %, used for the optimization of PV self-consumption and already present in the real dwelling.

## 3.2 Selection of the time interval

Although in reality the minimum running time of the heat pumps is usually between 10 and 15 minutes, in this study a minimum running time of 30 minutes will be considered. One of the reasons, is that to preserve the life cycle of the heat pumps this timeframe should be increased, since the heat pumps will be activated much more frequently in this FRR framework than during a normal operation. In addition, our study looks into the ability of buildings to provide energy flexibility with their heating systems and focuses thereby on the limits of their participation in terms of energy restrictions. The decision to analyze 30 minute time steps of heat pump operation allows for abstracting away from the nontrivial issues of hardware failure and maintenance costs that are also associated with fast on-off reactive heat pump activations. We thus allow heat pumps to participate in the market in our simulation while assuming that the cluster manager and aggregator will compensate this minimum runtime restriction with internal balancing within their portfolios (compensating positive capacity reactions, battery capacity, etc.).

Additionally, although our study involves the use of heat pumps for frequency restauration reserve markets with activation times in the minute range, they can also be used in an aggregator´s asset portfolio for primary reserve applications. Primary or frequency containment reserve can for example be provided symmetrically by large MW batteries. However, as one requirement of the German TSO is that the batteries provide total FCR activation of at least 30 minutes in each direction, aggregators now suggest to actively manage the state of charge of a battery using other assets. Heat pumps could thus be used to cheaply reduce a battery´s state of charge, when necessary.

## 3.3 Model description: TRNSYS

Both the building model and the supply model have been developed by using TRNSYS 17 [31], trying to reflect the reality as closely as possible. The models will be the same for each building typology, but varying the parameters mentioned in the previous section. A representation of the TRNSYS model can be seen in Figure 5.

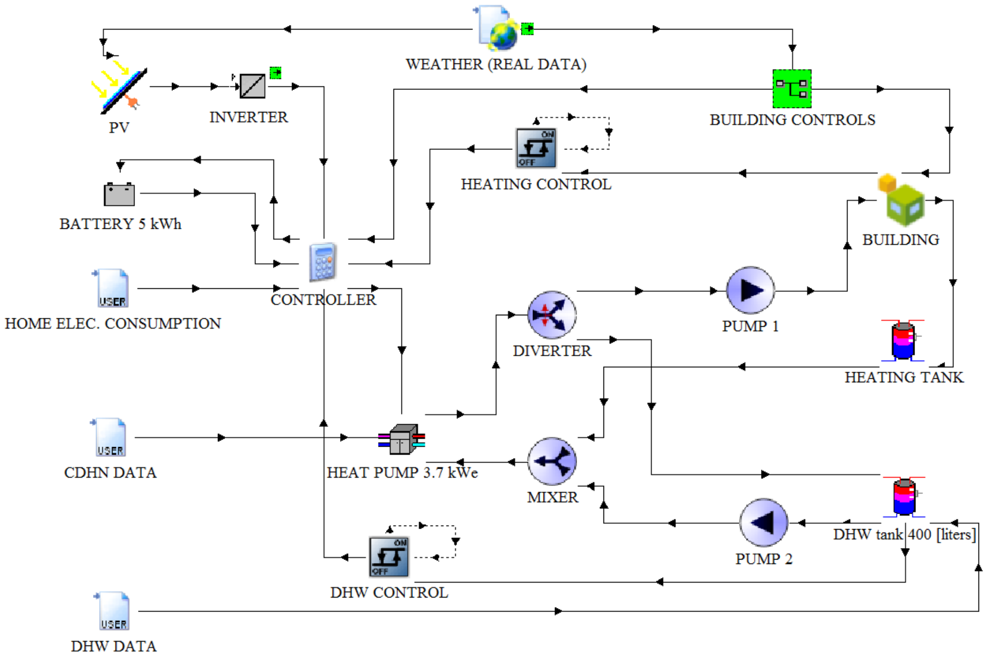


*Figure 5: Simplified representation of the TRNSYS model.*

A time step of 30 minutes has been chosen for the simulations, which is also a good compromise between accuracy and time consumption due to the great amount of simulations that will be carried out. In addition, as mentioned before the minimum running time of the heat pump and other issues regarding FRR were considered when choosing the correct time step.

## 3.4 Experimental Validation

A validation of the model of building 1 has been carried out so as to ensure that the results of the simulations would be representative of the reality. Experimental data available through the monitoring of indoor temperatures as well as heat pump consumption and PV production of the household have been used. In addition, measurements of global radiation and outdoor temperature in the location of the dwelling are available and will be used for the simulations and for the validation of the model.

Due to the intricacies of obtaining experimental data for all the required variables with no perturbations due to intervals of no occupancy for example, the period concerning the first 3 weeks of February 2017 has been chosen for the validation. As a result of the uncertainty regarding the real electricity and DHW consumption profiles as well as the use of 30 minute time steps, only aggregated daily values have been used for the heat pump validation. Figure 6, Figure 7 and Figure 8 show the comparison between simulation and measurements of heat pump consumption, PV production and hourly indoor temperatures respectively.

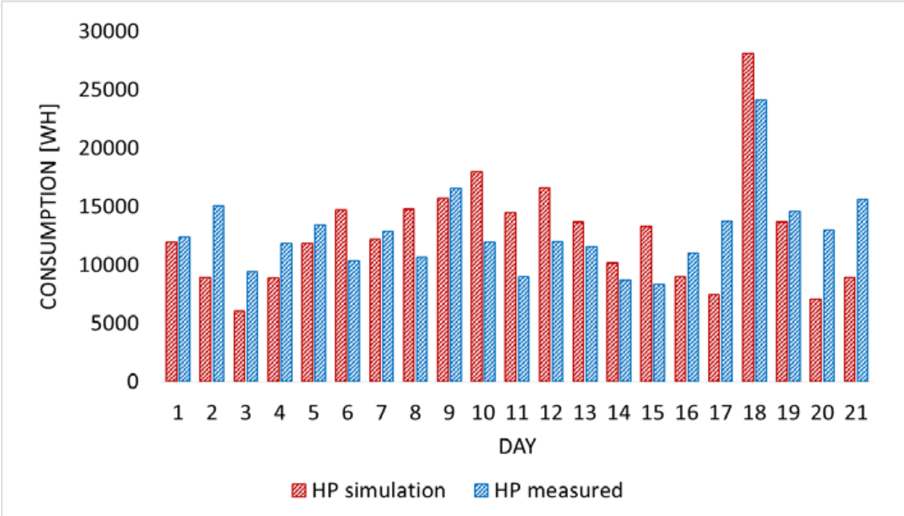


*Figure 6: Heat pump consumption validation, February 2017.*

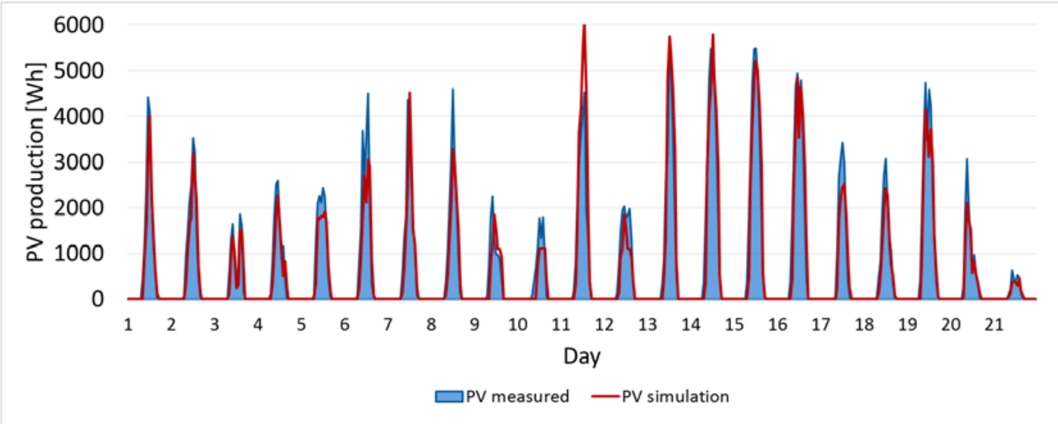


*Figure 7: Hourly PV production validation, February 2017.*

In the case of the PV production, an overall difference of 4.94 % has been obtained. As for the heat pump consumption, the difference is 0.20 %. In addition, the comparison of the hourly temperatures of the building in Figure 8 is satisfactory, although some discrepancies may be observed during the weekend due to the uncertainty regarding the behavior of the users. The average COP of the modeled heat pump was also calculated in the TRNSYS simulation, obtaining an average value of 5.3, which is adequate according to the data provided by the manufacturer.

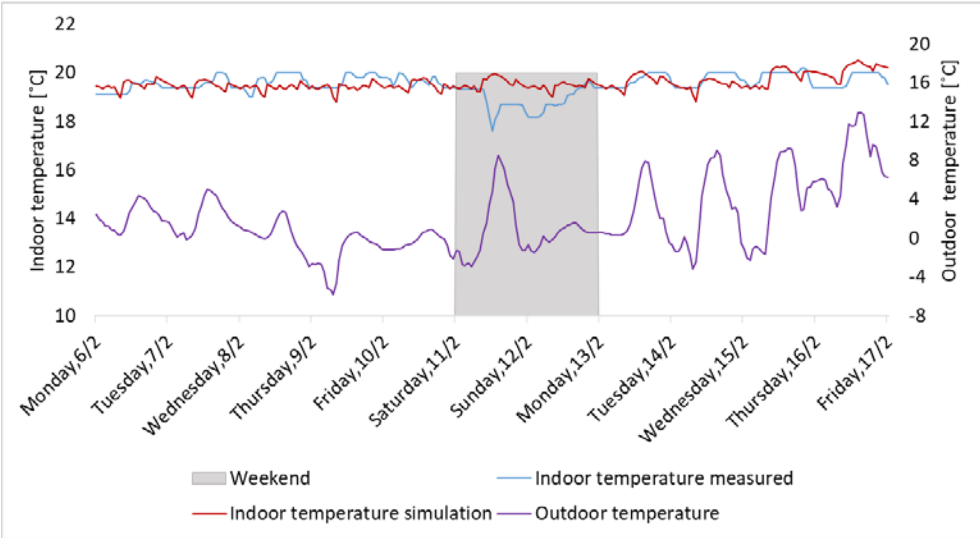


*Figure 8: Hourly indoor temperatures, February 2017.*

## 3.5 Cluster manager: analyzed strategies

The aim of the present work is to study the potential cost savings achieved considering different strategies when a cluster manager controls the heat pumps of many buildings, by participating in the FRR market. For doing so, the cluster manager needs to know what would happen regarding the status of each building if the heat pump had to be activated, and decide whether a building is suitable to be used or not. The focus of the study has been on the month of February. Data from the FRR for that month in 2015 has been used.

The cluster manager will deal with 6 buildings. Figure 9 depicts the cluster manager framework in our study. First, there is an interaction between the Transmission System Operator (TSO), which releases the activation calls, and the aggregator, who has a portfolio of customers willing to provide power to participate in the FRR. Then, there is an open option between the aggregator and the cluster manager, since they can agree to sign a private contract with different requirements.

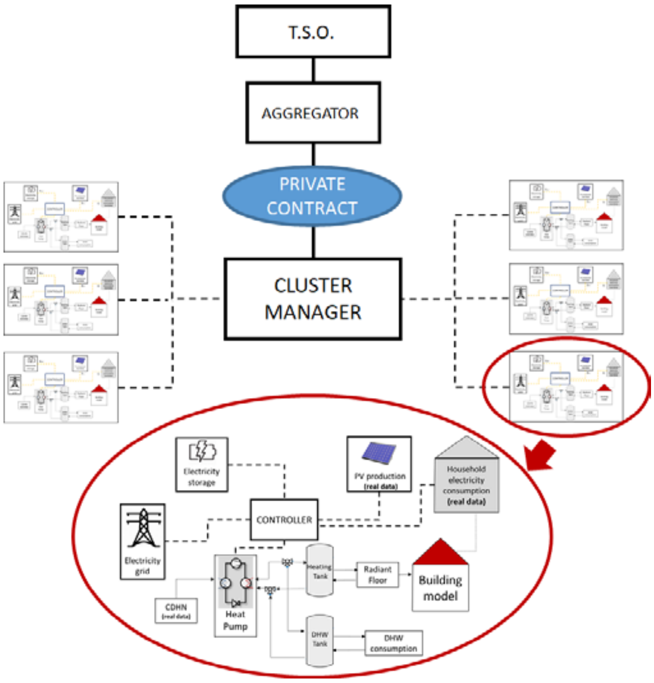


*Figure 9: Overview of the cluster manager framework.*

Our analysis studies two different configurations of such private contracts. The first one is an agreement which allows the cluster manager to provide the aggregator with as much flexible power as it has available by activating the flexibility of its portfolio of buildings. In this case, any building that fulfills several set conditions will activate their heat pumps at full power if the aggregator sends the cluster an activation request. Settlement between the cluster and the aggregator is then based on the total energy used by the heat pumps during the activation time period, irrespective of how much additional energy this turns out to be compared to the original baseline expected consumption of the heat pumps (up to the maximum possible power consumption of the devices). In the second type of contract studied, the agreement is such that the cluster manager always has to provide the aggregator with a specified (and constant) amount of power. In this case, the cluster must decide which subset of buildings to activate, in order to comply with the activation of only a fixed, limited amount of power.

These two variations on bilateral contracts represent existing participation schemes in the area of DR in real-world market contexts [32]. Firstly, the contract allowing the cluster manager to provide as much regulating power as is available implies a situation in which simple protocols are defined at the building level, and activated manually or automatically according to fixed switching rules. This could, for example, be a power savings mode of operating a single dwelling or a high-rise building with reduced levels of air conditioning and other power-intensive systems. Multiple such buildings could be called upon by the cluster manager to be activated and each building is allotted payment for participation at their maximum capacity irrespective of actual grid demand. The other "defined-amount" power provision type of DR contract studied in the simulation is a case more suited to controllable power systems, such as power to heat systems among others, which exhibit a high degree of automation and accuracy and for which the quality of DR power delivered must be relatively high. The assumption that our work tests is whether heat pumps, with dynamic and complex physical constraints but with nonetheless high degrees of flexibility, could benefit and/or be appropriate for participation in both types of market contractual arrangements. We report on simulation tests of both types of operation (and heuristic optimization) in the following.

Table 3 displays the considered bidding strategies for the cluster manager. We analyze bids of three different FRR prices including the case of a negative value (the customer is paid for consuming the energy), although in all cases, regulatory taxes and surcharges are still applied to the overall incurred costs of the dwellings. Strategies 2, 3 and 4 are simulations studying the variable power contract between the cluster manager and the aggregator (the cluster provides maximal flexible power, and the aggregator pays for all of it, irrespective of amount or variability). In this case, any building would activate its heat pump (HP) if the following conditions are met: an activation call is received, the building is electrically self-sufficient during the time step and the indoor temperature of the building is below a certain threshold.

The self-sufficiency requirement is included as a result of the financial incentive to apply net-metering to the building and its energy systems, in order to profit from local own-use of PV generation. In addition, limiting activations to time periods during which the building is self-sufficient allow for a simplified calculation of the HP's operating baseline while retaining the (financially) necessary condition that own-use generation can benefit the household. The self-sufficiency requirement is fulfilled at a certain time step if either the PV production is enough to cover the household consumption and the surplus energy can be stored in the battery, or if the PV production plus energy taken from the battery are able to cover the household consumption. In both ways, the volatility in the household energy use and in the onsite PV generation has no influence, and the heat pump consumption (which has a more or less known constant power available) can be considered separately, thus avoiding forecast errors when participating in the FRR market.

On the other hand, strategy 5 involves the contract which guarantees a constant power. In this strategy, the three buildings with the lowest indoor temperatures will always be chosen by the cluster manager to be activated. In this case, there are no self-sufficiency or temperature thresholds.

| FRR | FRR(-50) Price: -50 EUR/MWh | FRR(0) Price: 0 EUR/MWh | FRR(+10) Price: +10 EUR/MWh |
|---|---|---|---|
| Strategy 1 | Normal control, no activation calls. | | |
| Strategy 2 | Activate HP if electrically self-sufficient and $T_{air}$ below 21 °C. | | |
| Strategy 3 | Activate HP if electrically self-sufficient and $T_{air}$ below 22 °C. | | |
| Strategy 4 | Activate HP if electrically self-sufficient and $T_{air}$ below 23 °C. | | |
| Strategy 5 | Choose the 3 buildings with the lowest temperature. | | |

*Table 3: Strategies and FRR price scenarios considered.*

The acceptance level of the activation calls depends on the price: the more the customer is willing to pay, the more often he gets activated. Depending on the FRR bids (-50, 0, or +10 EUR/MWh), which were explained in Section 2, a different number and frequency of activations occur. The higher the FRR price, the longer the duration of the activations and the more often they occur. This is shown in Figure 10 and in Table 4. These three very different scenarios have been chosen to consider different alternatives when participating in the German FRR market and to be able to check their influence in the obtained results.

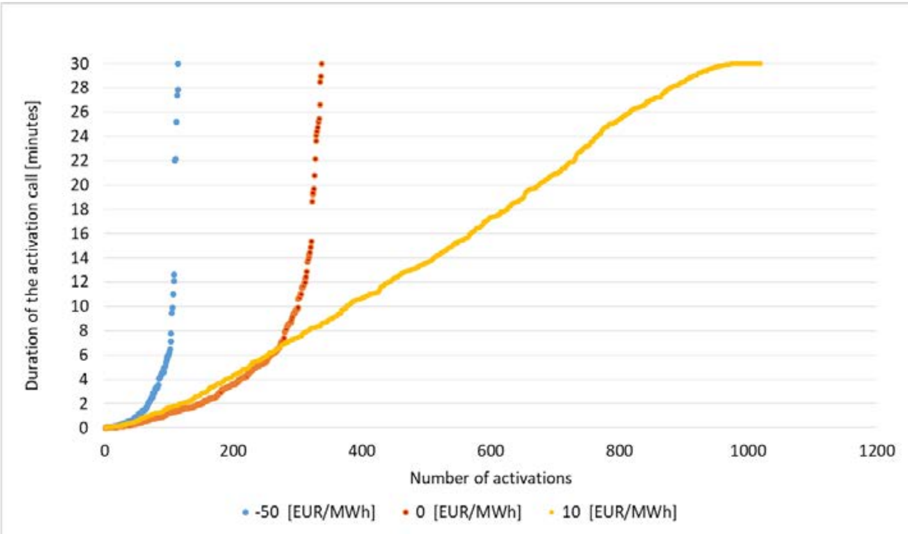


*Figure 10: Comparison of the number of activation calls for the three scenarios depending on the duration. Real FRR data from February 2015.*

| FRR Bid Price [EUR/MWh] | Average activation time [min] | Number of activations |
|---|---|---|
| FRR(-50) | 3.55 | 114 |
| FRR(0) | 4.50 | 336 |
| FRR(+10) | 14.81 | 1019 |

*Table 4: Average activation time and number of activations of each scenario.*

## 3.6 Control strategy of the simulations

Whenever an activation call is received, a prediction of what would happen regarding the indoor temperature of the building if the heat pump is activated is necessary, since otherwise the activation of the heat pump could result in temperatures outside the comfort limits. However, predicting the state of each building after an activation call is a problem that incorporates many dynamic interactions, including solar and internal gains, climate, and the temperature of the thermal storage tanks. To overcome this, simulations with the control strategy shown in Figure 11 were developed for this work.

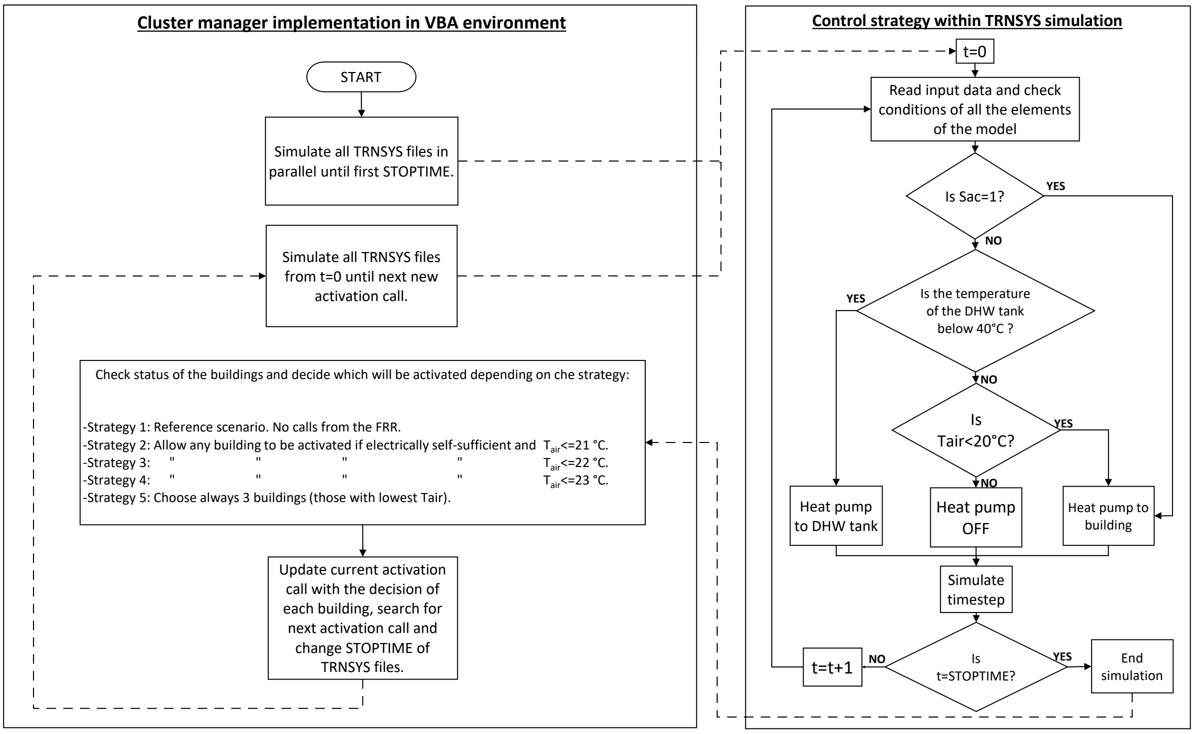


*Figure 11: Flowchart of the simulations.*

All of the buildings are simulated in parallel. At the start of the simulation, the TRNSYS models of the six buildings are simulated in parallel through a batch file until the first FRR activation call is received. The control strategy during the simulation of each time step in TRNSYS can be seen on the right part of Figure 11, giving priority to activating the HP for the building if an activation call (Sac) is received, then to the DHW tank if there is no activation call but its temperature is below 40 °C (so that the provision of hot water is always guaranteed, which is the behavior in the real system), and last of all to the building to try to maintain a consistent temperature of 20 °C. It should be taken into account that the simulation in 30 minute intervals means that the HP will be either on or off during the whole time step.

Once the six buildings have been simulated until the first activation call (including it), the information flow is returned to the cluster manager, which checks the status of every building, and then makes a decision about the activation of each building depending on the strategy that is being followed. Then, the distribution of the activation calls among the buildings and the logging of the respective data are updated based on the decision. Then the simulations start again from the beginning, this time bypassing those activation calls where a decision has already been made.

On the other hand, the costs of running the heat pump during the 30 minutes interval are calculated in the following way. If no activation call was received but the heat pump is running:

$$Cost_{HP} = E_{HP} * C_{EL}$$

If the heat pump is running due to an activation call (participation on the FRR):

$$C_{AGG} = (C_{EL} - (C_{FRR} + C_{TAXES})) * 0.1$$

$$Cost_{HP} = E_{HP} * \left(\frac{(C_{AGG} + C_{FRR} + C_{TAXES}) * t_{FRR} + C_{EL} * (30 - t_{FRR})}{30}\right)$$

where $Cost_{HP}$ is the cost of running the HP in EUR, $E_{HP}$ is the energy consumed by the HP in kWh, $C_{EL}$ is the normal electricity price of 22 cEUR/kWh, $C_{TAXES}$ is the total amount of taxes shown in Table 1 of 17.424 cEUR/kWh, $C_{AGG}$ is the extra which has to be paid to the aggregator in EUR/kWh, $C_{FRR}$ is the tariff of the FRR in EUR/kWh and $t_{FRR}$ is the duration of the activation call in minutes. Note that a short duration of an activation call implies using the heat pump at the retail price of 22 cEUR/kWh for a long time, until completing the 30 minutes of its minimum running time.

Some DR markets and participating aggregators have begun offering fixed payment schemes instead of reimbursement based on actual market prices. Such products can contribute to higher levels of acceptance for demand response by consumers and in turn higher levels of penetration in the market. This has the effect of reducing risk for the consumer, while shifting risk to the cluster manager or aggregator. While such fixed price tariffs could lead to increased security and acceptance from consumers, aggregators and cluster managers will be less willing to take on the fixed costs of investment. Further discussion of this dilemma is necessary and relevant, but we abstract from it, focusing our analysis instead on the available (energy price based) financial incentives to dwellings coordinated by a cluster manager.

# 4 Results: DR potential of a cluster of dwellings

## 4.1 Overview of the strategies

In order to illustrate the way in which the different strategies work, Figure 12 shows an example of activation call decisions for the price scenario FRR (+10). In the graph, if an activation call is received and accepted its value is a 1. If it was received but discarded, it is shown as a 0.5. There were an observably large number of activation calls on this day for this price scenario. At the beginning of the day, none of the strategies accepts any activations. This is because the self-sufficiency constraints were not fulfilled for strategies 2, 3 and 4, and the building was not among the three with the lowest temperature in strategy 5. Later, some of the self-sufficiency constraints were fulfilled and the simulated building accepted some of the activations in the different scenarios, reaching higher temperatures in those with higher temperature thresholds. Note that ventilation and solar gains also influence the temperature patterns in the simulation.

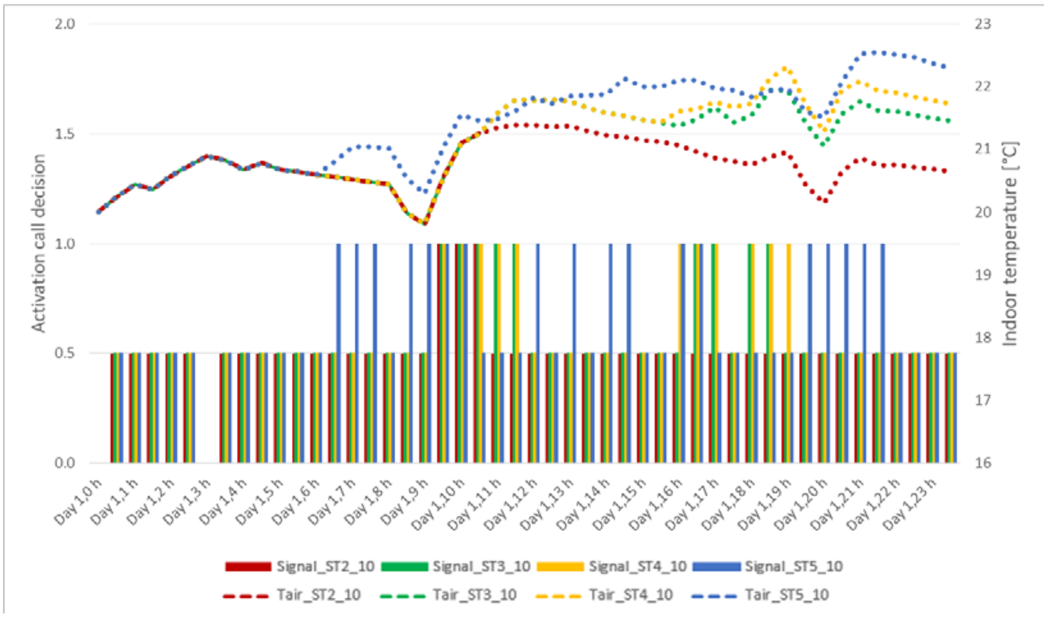


*Figure 12: Example of activation call decisions and indoor temperatures.*

As stated in the previous section, strategies 2, 3 and 4 involve a variable contract between the cluster manager and the aggregator, which means that every building is independent and will be activated if the constraints are fulfilled. Conversely, in strategy 5 the building will be chosen regardless of its current conditions if it is among the three with the lowest indoor temperature. Figure 13 shows for one day the variation in the number of buildings that participated in each activation call. The requirements of strategy 5 impose a constant amount of 3 buildings which are always able to offer approximately the same amount of power to the aggregator during each activation call. The rest of the strategies vary the number of activated buildings.

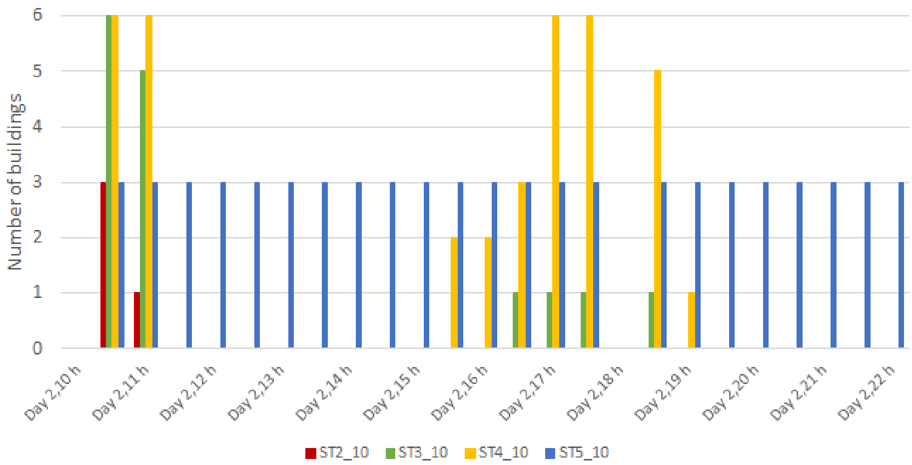


*Figure 13: Comparison of the number of activations.*

## 4.2 Acceptance of the activation calls

We studied the amount of times that each building accepted the activation calls for each strategy and for each price scenario. This is shown in Figure 14 as a percentage of activations. The nature of the data and experiment is such that there were a different number of activation calls in each price scenario, as higher price bids received more activations. In Figure 15 we also report the absolute value of the number of activations.

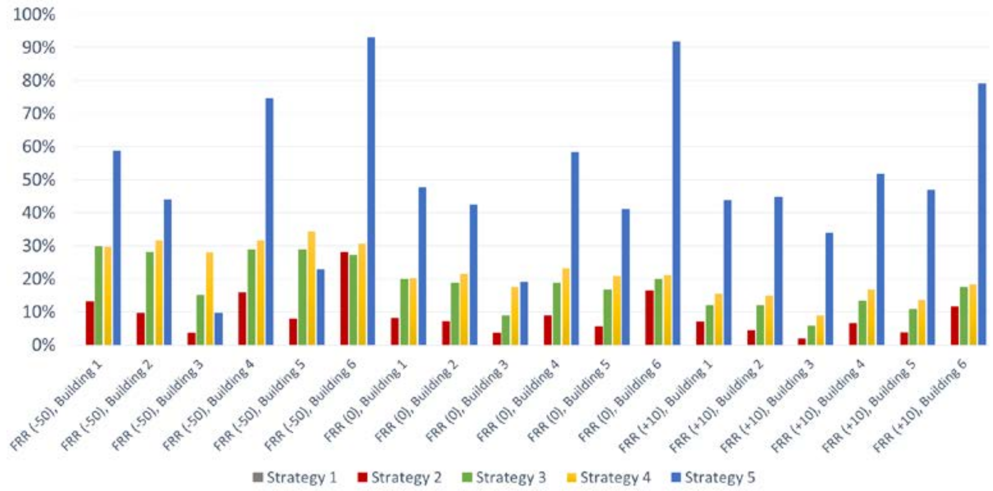


*Figure 14: Percentage of accepted activations.*

From the data we see, first, that strategy 5 results in the highest number of accepted activations. The reason is that there are no temperature constraints, and that three buildings are always chosen. Second, the higher the temperature threshold is, the higher the number of activations, which is logical consequence of the building being allowed to be more overheated. However, the differences between strategies 3 and 4 are much smaller than between strategies 2 and 3. Third, the number of accepted activation calls is rather low due to the self-sufficiency constraint, which could be partially solved by having supplementing the heating systems with electric batteries with higher capacities. Fourth, these results allow for confirming that the number of activations generally increases in the price scenarios which have a higher number of activation calls. It is interesting to see that depending on the characteristics of the buildings, one participating in the price scenario FRR (+10) could be called less times than another one in the scenario FRR (-50). That is the case for example of FRR (+10), Building 3 compared to FRR (-50), Building 6, even if the number of potential activation calls goes from around 100 to 1000. The reason is that building 6 has much higher energy losses, and so it would be able to accept the activation calls more often than building 3 which retains more thermal energy. The differences between the building typologies are further discussed in section 4.8.

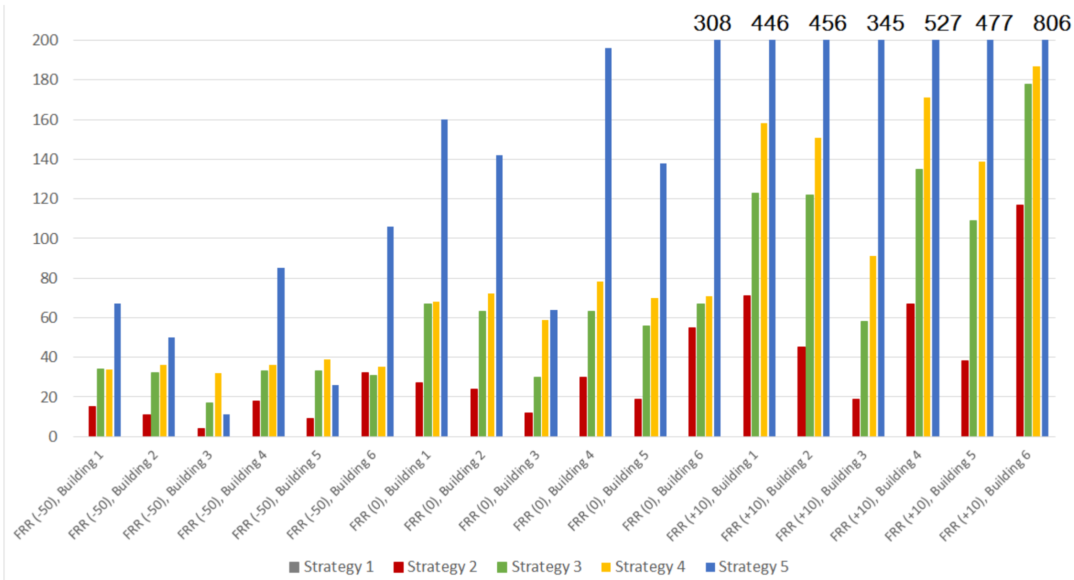


*Figure 15: Number of accepted activations.*

## 4.3 Thermal comfort

An important indication of residents' levels of comfort despite control of their heating systems are the temperatures reached in the buildings during the different strategies' simulations. Figure 16 shows the total excess degree hours above 20 °C reached in the scenarios. By definition, this amount always increases with increasing temperature thresholds. However, we observe that the behaviour of strategy 5 is very different depending on the price scenario. In FRR (-50), the number of activation calls is low, so the amount of overheating is similar to that of the other strategies. In FRR (0) the excess degree-hours is already higher than in the other strategies and in FRR (+10) it is hugely increased. To illustrate this, Table 5 shows an example of the maximum temperatures reached by some strategies. We also observe that there is not a noticeable difference when going from strategy 3 to strategy 4 in the case of building 6 for the price scenario FRR (+10). This is explained by the combination of there being a large number of activation calls, relatively high energy losses in the building and that the self-sufficiency requirement does not allow the building to reach the upper temperature limit of 23 °C.

All these observations allow us to conclude the following: if there is a contract requiring a constant power to be delivered by cluster manager to the aggregator, and the number of activation calls is rather high, then either temperature constraints should be imposed, or the amount of power offered should be decreased so that it is not necessary to activate large numbers of buildings. Otherwise, the overheating would result in unacceptable comfort levels for the residents.

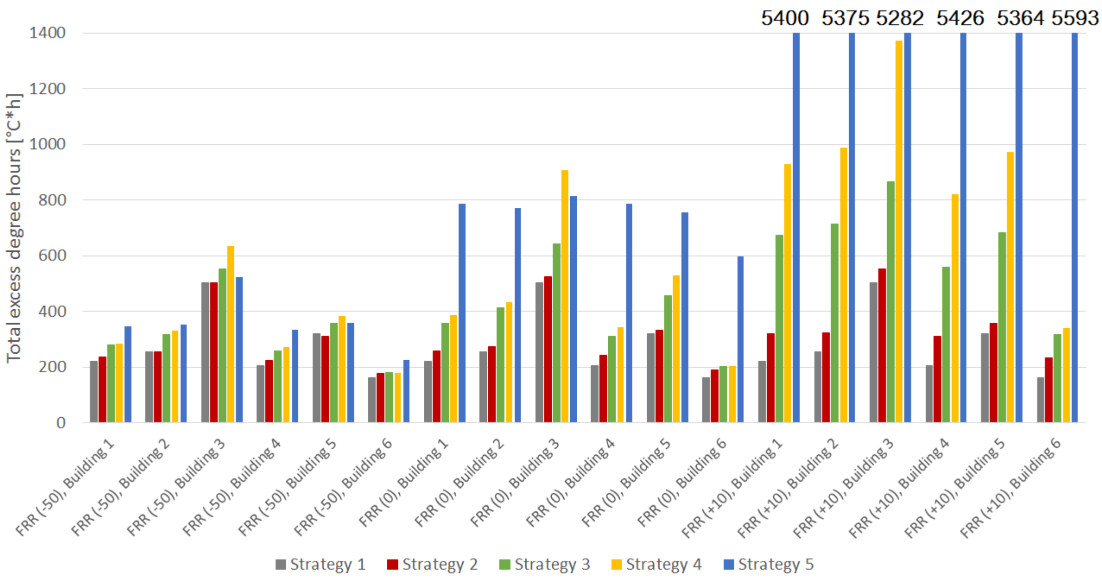


*Figure 16: Total excess degree hours (> 20°C).*

| Maximum temperature [°C] | FRR (10), Building 1 | FRR (10), Building 2 | FRR (10), Building 3 | FRR (10), Building 4 | FRR (10), Building 5 | FRR (10), Building 6 |
|---|---|---|---|---|---|---|
| FRR (10) Strategy 1 | 21.0 | 21.1 | 21.6 | 21.1 | 21.3 | 21.1 |
| FRR (10) Strategy 2 | 21.4 | 21.5 | 21.6 | 21.3 | 21.5 | 21.6 |
| FRR (10) Strategy 3 | 22.3 | 22.1 | 22.5 | 22.3 | 22.0 | 22.3 |
| FRR (10) Strategy 4 | 23.1 | 23.1 | 23.1 | 22.9 | 23.2 | 22.1 |
| FRR (10) Strategy 5 | 31.0 | 31.0 | 31.0 | 31.2 | 31.0 | 31.5 |
| FRR (-50) Strategy 5 | 22.02 | 21.98 | 21.86 | 22.21 | 21.87 | 21.80 |
| FRR (0) Strategy 5 | 23.82 | 23.98 | 23.64 | 24.01 | 23.74 | 24.38 |

*Table 5: Examples of maximum temperatures.*

It should be mentioned that the possibility of increasing the thermal inertia of the dwellings (to increase system flexibility) could be analyzed in more detail, due to the fact that the reduction of the thermal losses of the buildings allows to store the energy inside them for longer periods. The dwellings presented in this work are very efficient, but this issue should be carefully considered in case of dealing with buildings which are less efficient.

## 4.4 Heat pump consumption

Both increasing FRR price bids as well as increasing temperature thresholds increase the consumption of the HPs, which is as expected. In Figure 17 the HP consumptions for every building and strategy are presented.

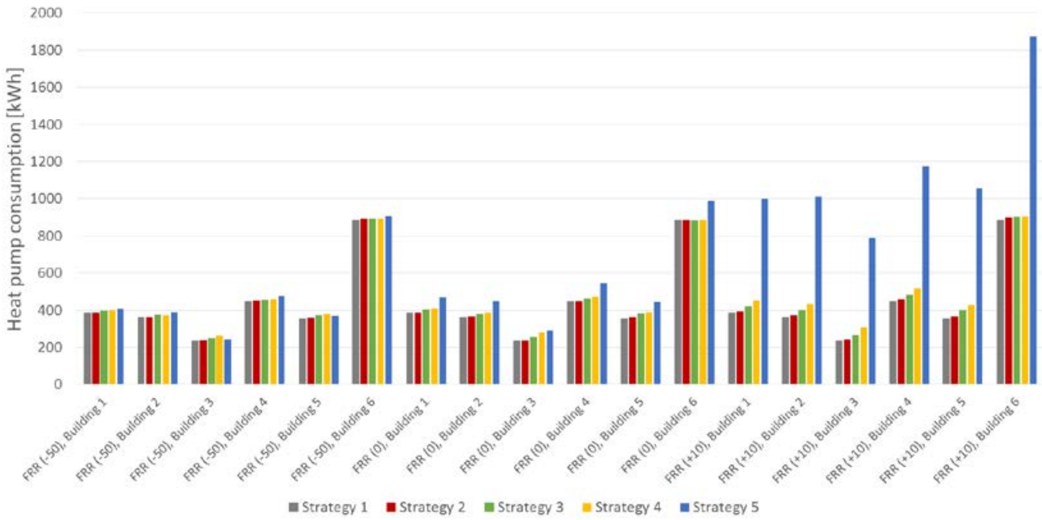


*Figure 17: Heat pump consumption.*

## 4.5 Cost savings

The cost savings that can be achieved by the cluster manager when participating in FRR is one of the most important outcomes of the present work. Apart from taking into account when the HP accepts an activation of the FRR, we calculate the costs that would have been incurred had the heat pump been operated according to its original plan. The costs incurred by the HP follow the same tendencies shown for the consumption in Figure 17. If the temperature threshold is increased, the costs are increased, so the cost savings are decreased. However, there is an advantage: if the temperature limit is higher, then the power offered to the FRR market increases, as we show in section 4.7. The cost savings are calculated in each case by comparing each building with its own baseline case (strategy 1, no FRR participation). Figure 18 shows the results. As it can be seen, almost none of the proposed strategies are profitable, and those that are, produce practically negligible benefits.

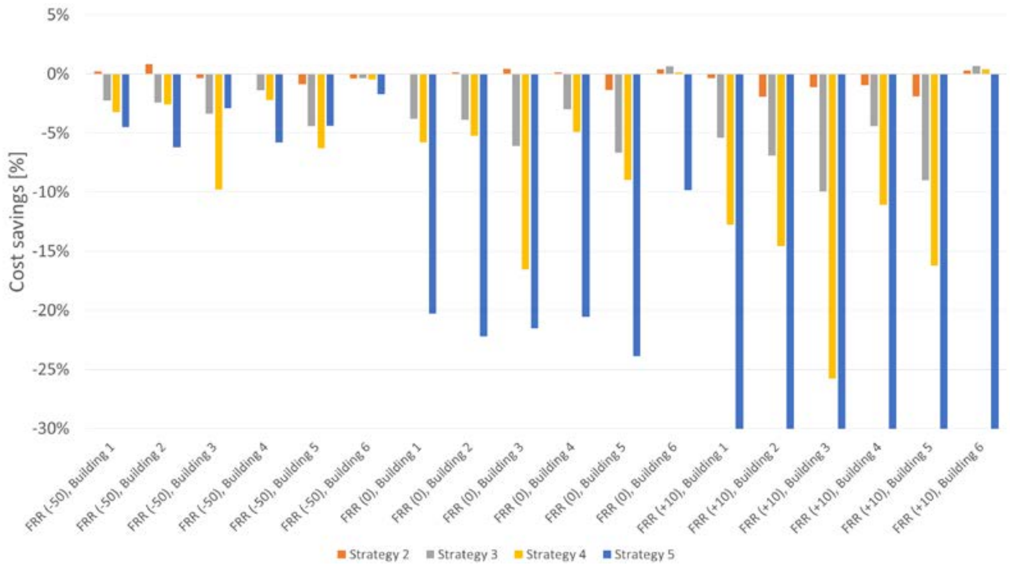


*Figure 18: Cost savings [%] of the proposed strategies (negative values mean higher costs than their base case).*

The main reason for such poor profit results is the following: as stated before, the assumption of the present work is that the heat pumps cannot be activated for less than 30 minutes to prevent a reduction of lifetime with many activation calls among other reasons. However, participating on the FRR market means that the heat pumps will be activated more often than in the original scenario, thus increasing their consumption and costs. Profits could still be made if the revenues from the FRR market were considerably higher, but in the present context, these revenues (or cheaper electricity costs) do not compensate for the higher HP power use. Although the heat pumps benefit from lower prices during the activation calls, their duration may be short, and during the rest of the time that they are running until completing 30 minutes, the normal price will be charged. There therefore needs to be a large difference between the retail price and the energy price available on the FRR market if actors such as heat pump owners are to be motivated to participate in FRR. We discuss this further in Subsection 4.9.

## 4.6 Self-consumption ratio

Figure 19 shows the variation of the ratio of PV self-consumption for all the strategies. As it can be seen, the variations for a particular building are very small, independent of the strategy considered. When focusing on the same building it becomes clear that changing the price scenarios does not significantly affect the ratios of self-consumption. Within this study, whenever an activation call is accepted, the negative power provided as FRR is that of the heat pump, and the rest of the system is isolated from this exchange. Since in the analysed strategies the heat pump consumption would in that case be assumed by the FRR, the ratio of self-consumption of the household is increased.

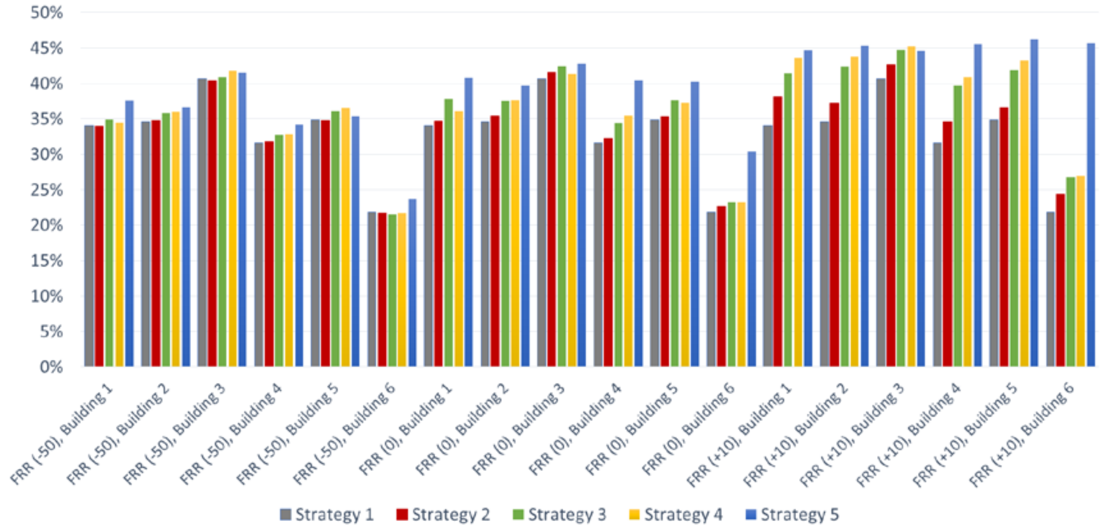


*Figure 19: Ratio of PV self-consumption.*

## 4.7 Power to the FRR

Depending on the strategy considered, a different amount of energy will be exchanged. Figure 20 shows the energy that each building takes from the FRR market for each strategy. The higher the HP consumption or the temperature threshold, the higher the exchange of energy between the cluster manager and the aggregator, therefore being able to provide more power as FRR.

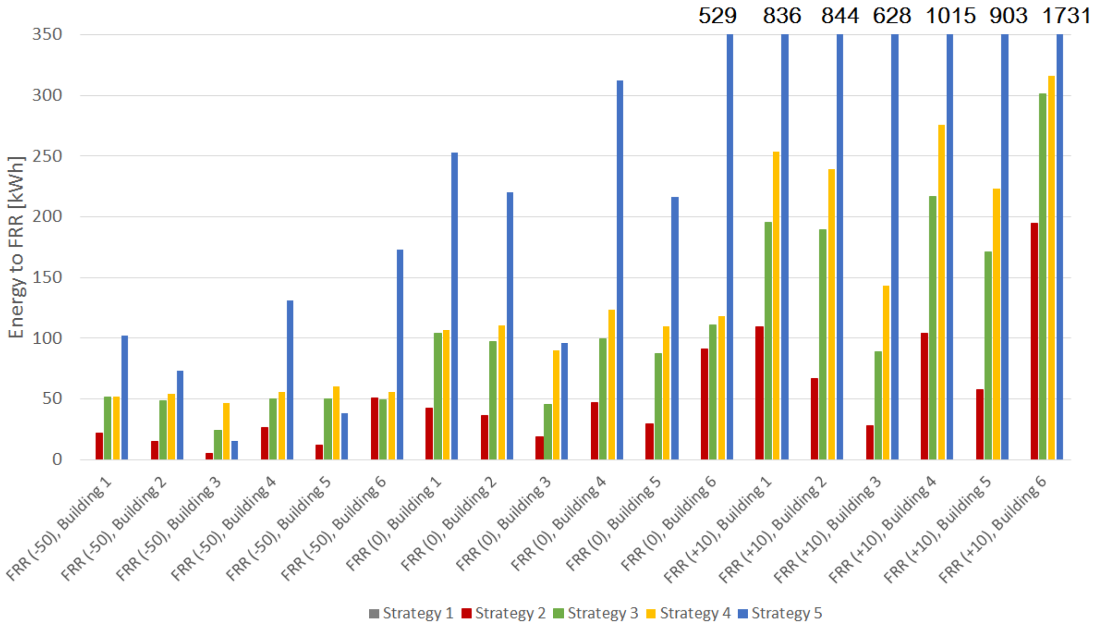


*Figure 20: Energy to FRR.*

For the purpose of estimating the amount of energy obtained from the FRR market, we assume that there are 100 buildings of each of the 6 building typologies. In this case, the power exchange between the cluster manager and the aggregator follows the activation calls as shown in Figure 13, since the power of the heat pumps is always approximately the same. In this case, when looking at the cluster results for FRR(0) the amount of power exchanged during the month can be seen in Figure 21. Strategies 2, 3 and 4 vary in the provided power, which can reach up to 2 MW in some cases but the activation calls are not always accepted. On the other hand, strategy 5 activates always the heat pumps of 300 buildings, providing in this way a more or less constant power of almost 1 MW, however with the thermal comfort issues stated in section 4.3.

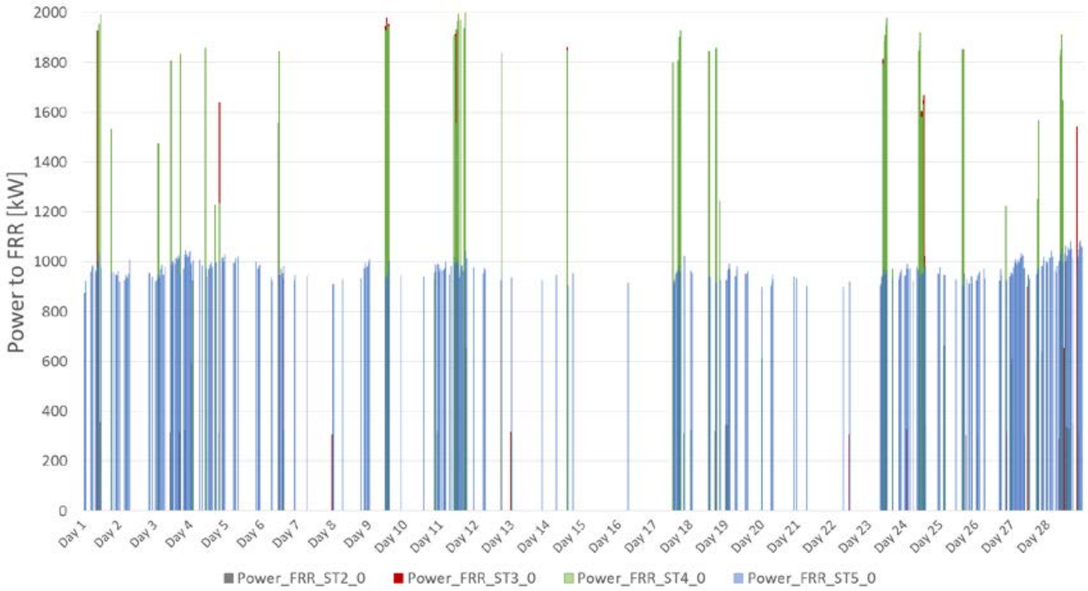


*Figure 21: Power provided for price scenario FRR (0).*

## 4.8 Comparison between building types

As shown in the previous sections, there are significant differences among the different building typologies. Regarding the number of activations, the buildings with higher energy losses, for example building 6, participate much more often on the FRR than those with fewer losses. The HP costs and consumption are obviously also higher, as well as the power exchanged with the FRR. The self-consumption ratio is also lower. The main conclusion is therefore that buildings with higher energy losses are more suited for participation in FRR than highly insulated buildings. These buildings can accept more activation calls, thus making their participation using these strategies more viable (although the thermal losses should also be carefully assessed).

## 4.9 Possible future price scenarios

Since the present study demonstrates that almost none of the proposed strategies are economically feasible with the current prices and taxes applicable to the DR participation in FRR in the studied German case, a sensitivity study based on different prices has been done to analyse the potential of these strategies if the market were to change. These prices would already include the taxes, so they are the final costs that the cluster manager would pay for the energy whenever an activation call is received. The rest of the time, the constant price of 22 cEUR/kWh is kept. Figure 22 shows the results, which consider different prices, but the previous price scenarios keep the same number of activation calls as well as duration.

As is apparent, there is a high influence of the number of activation times and their duration. The higher the number of activations and duration, the higher the profits. Strategy 5 is not profitable unless a very negative price is achieved, which seems unrealistic. The strategy 5 of FRR(+10) was discarded due to extreme overheating of the buildings. On the other hand, the profits of using the activation calls of price scenarios FRR(-50) and FRR(0) are mostly negative or negligible. In the case of using the activation calls of price scenario FRR(+10), the strategies start to be profitable when a final price around 10 cEUR/kWh is applied. Once that limit is reached, the lower the price, the higher the profits. Last of all, it can also be seen that the profits are higher for the number of activations and duration of the FRR(+10) price scenario when compared to FRR(-50) and FRR(0), even if the price for FRR(+10) is higher. All these outcomes highlight the importance of the number of activation times and their duration for heat pumps to participate in secondary reserve markets, as well as the need to reduce the taxes in order for them to be economically feasible.

| Savings Cluster [%] | Price [€/kWh] | ST2_-50 | ST3_-50 | ST4_-50 | ST5_-50 | ST2_0 | ST3_0 | ST4_0 | ST5_0 | ST2_10 | ST3_10 | ST4_10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Price 1 | 0.20 | -0.5% | -2.6% | -3.8% | -4.6% | -0.2% | -3.2% | -5.5% | -18.6% | -1.4% | -5.5% | -11.5% |
| Price 2 | 0.15 | -0.2% | -2.1% | -3.2% | -4.1% | 0.3% | -2.2% | -4.3% | -16.5% | 1.2% | -0.5% | -5.1% |
| Price 3 | 0.10 | 0.0% | -1.6% | -2.7% | -3.5% | 0.8% | -1.3% | -3.2% | -14.4% | 3.7% | 4.5% | 1.3% |
| Price 4 | 0.05 | 0.3% | -1.1% | -2.1% | -3.0% | 1.2% | -0.4% | -2.1% | -12.3% | 6.3% | 9.5% | 7.7% |
| Price 5 | 0.01 | 0.4% | -0.7% | -1.6% | -2.5% | 1.6% | 0.4% | -1.2% | -10.6% | 8.3% | 13.6% | 12.8% |
| Price 6 | 0.00 | 0.5% | -0.6% | -1.5% | -2.4% | 1.7% | 0.6% | -1.0% | -10.2% | 8.8% | 14.6% | 14.1% |
| Price 7 | -0.01 | 0.5% | -0.5% | -1.4% | -2.3% | 1.8% | 0.8% | -0.8% | -9.8% | 9.4% | 15.6% | 15.4% |
| Price 8 | -0.05 | 0.7% | -0.1% | -0.9% | -1.9% | 2.2% | 1.5% | 0.1% | -8.1% | 11.4% | 19.6% | 20.5% |
| Price 9 | -0.10 | 1.0% | 0.4% | -0.4% | -1.3% | 2.7% | 2.5% | 1.3% | -6.0% | 14.0% | 24.6% | 26.9% |
| Price 10 | -0.20 | 1.5% | 1.4% | 0.8% | -0.2% | 3.6% | 4.3% | 3.5% | -1.8% | 19.1% | 34.7% | 39.7% |
| Price 11 | -0.5 | 2.9% | 4.4% | 4.3% | 3.0% | 6.5% | 10.0% | 10.2% | 10.7% | 34.4% | 64.8% | 78.2% |

*Figure 22: Cluster cost savings depending on different price scenarios.*

## 5 Conclusions and outlook

This work analyzes the role of heat pumps controlled by a cluster manager and equipped with both electrical and thermal storage systems for flexibility when providing FRR to the grid. Simulations with a time resolution of 30 minutes for a case study based on a plus-energy district built in southern Germany showed that the DR potential is significant, but for profits to be achieved, particular attention needs to be given to the number of activation times, and most importantly to their duration. Otherwise, it is very difficult for such a framework to be economically viable. As shown by an analysis of possible future scenarios, even if the prices paid by the grid operator were higher, the influence of the duration would be more important, since lower durations would entail a longer runtime billed at the normal price of electricity due to the minimum running time of the heat pumps.

Reducing the size of the time steps in the simulations is also a step that will be taken in further studies. Interpreting this will also involve more detailed analysis and consideration of the physical limits of heat pumps to participate in quick on-off activations and will provide a platform for testing positive and negative capacity reactions in more complex arrangements within the cluster and between the cluster manager and aggregator.

For the reasons given in the previous discussions, many changes are necessary before these approaches that activate the heat pumps of a portfolio of buildings can be put into practice. If it is foreseen that households will participate in DR business models, then further control system algorithms at the cluster and aggregator levels need to be studied and applied to effectively manage and coordinate the availability of individual systems in and across households.


## Acknowledgements

This work was carried out with the support of the European Commission within the project Sim4Blocks, grant number 695965. The authors also thank the University of Seville for its financial support through the US Research Plan V (VPPI-US), which enabled the cooperation between the teams in Seville and Stuttgart.

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