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Erasmus Mundus Masters in Decentralized Smart Energy Systems (DENSYS)

Analysis of Heat Pumps Potential in Demand Response Programs for Residential Buildings in Belgium and their Impact on Grid Flexibility with Thermal Comfort consideration

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Abstract

This study investigates the potential of heat pumps in demand response (DR) programs, to provide flexibility to power grids with a focus on residential buildings in Belgium. The research highlights the interplay between grid flexibility, energy efficiency, and thermal comfort, presenting a multi-dimensional analysis of sustainable practices within the residential sector through analytical simulations and analysis of (3) case studies of demonstration projects in this research domain. Through strategic heat pump management, the study explores pathways for enhancing energy efficiency without significantly sacrificing occupants' thermal comfort.

The core strategy of this work relies on the utilization of two distinct building types, with varying insulation levels defined by Belgian building standards as K15 and K45, each with a 180m^2 floor area, as the backdrop for the investigation. These buildings are equipped with aero-thermal heat pumps that supply either radiators or a floor heating system and the building insulation serve as a proxy for thermal mass storage. The uniqueness of the study is embedded in the deployment of a genetic algorithm that optimizes the heat pump operations according to day-ahead pricing signals.

In a winter scenario set for February 2022, the findings reveal a 13% difference in heating energy demand between the two building types, attributable to their different insulation levels. The genetic algorithm's application brought about notable cost savings, reducing peak demand by 28.56% for the K45 building and 14.52% for the K15 building. Flexibility is quantified in terms of heat pump consumption shifted away from peak demand periods. These numbers highlight the benefits of strategic heat pump operation and reflect the potential of DR programs to shift substantial energy demand from peak to off-peak periods.

Table of Content

List of Symbols

α_{ab}	Absorptance	[-]
α	Thermal diffusivity	[m²/s]
A	Areas of the elements of the building	[m²]
A_t	Turbidity factor for radiation calculation	[-]
c_p	Specific heat	[J/kg.K]
C_{es}	Correction of Earth-Sun distance	[-]
C_T	Temperature coefficient	[-]
f_{sh}	Shading factor on the building	[-]
h	Convective heat transfer coefficient	[W/m².K]
H	Height of the building	[m]
k	Thermal conductivity	[W/m.K]
l	Lengths of the elements of the building	[m]
L	Thickness of the materials of the building	[m]
$\dot{m}$	Mass flow	[kg/s]
n_a	Number of air changes rate for natural ventilation calculation	[-]
n_p	Assumed number of people in the building	[-]
n_{light}	Assumed number of lamps in the building	[-]
P	Power	[W]
Q	Thermal energy	[W]
ρ	Density	[kg/m³]

τ	Energy transmittance for radiation calculation	[-]
θ_Z	Zenith angle	[°]
T_{amb}	Ambient temperature	[°C]
T_{com}	Comfort temperature	[°C]
T_r	Temperature of the room	[°C]
U	Global heat transfer coefficient	[$W/m^2.K$]
V	Volume of the building	[m^3]

List of Abbreviations

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

DR: Demand Response

DSM: Demand side management

EMSs: Energy management systems

ESSs: Energy storage systems

GA: Genetic Algorithm

GSR: Global Solar Radiation

HVAC: Heating, Ventilation and Air Conditioning

IEA: International Energy Agency

RERs: Renewable energy resources

RES: Renewable energy sources

RTP: Real-time pricing

SET: Standard elective temperature

SGs: Smart grids

TC: Thermal comfort

TES: Thermal energy storage

List of figures

List of tables

1. Introduction

To achieve the ambitious climate objectives specified in the European Green Deal, concerted efforts across all sectors of society are necessitated, with the energy sector taking precedence due to its responsibility for approximately 82% of total European GHG emissions[1].

Considering future energy forecasts, electricity is poised to emerge as the predominant energy carrier, with the European electricity grid forming the cornerstone for decarbonizing other energy sectors. Given the superior efficiency of electricity in electrical end uses, and the predicted maturation of renewable electricity technologies, it is of paramount importance to leverage the full potential of electricity for decarbonization by enlarging its share in the energy sector. This process, commonly referred to as direct electrification of energy consumption, can also contribute to reducing primary energy needs. The EU's long-term strategy predicts an increase in consumption electrification from 23% in 2019 to more than 50% by 2050 [2]. Coupled with a projected rise in renewables in the energy mix (expected to constitute over 85% of the generation mix by 2050 according to Eurostat's RES share calculation), over half of the energy consumption by 2050 can be completely decarbonized.

In the EU, the Heating, Ventilation, and Air Conditioning (HVAC) sector accounts for half of the energy consumption and is primarily fuelled by fossil fuels (80%). The Figure 1-1 from a 2023 ENTSO-E study on Power and Heat sectors [3] illustrates the sectors' primary consumption for HVAC in Europe:

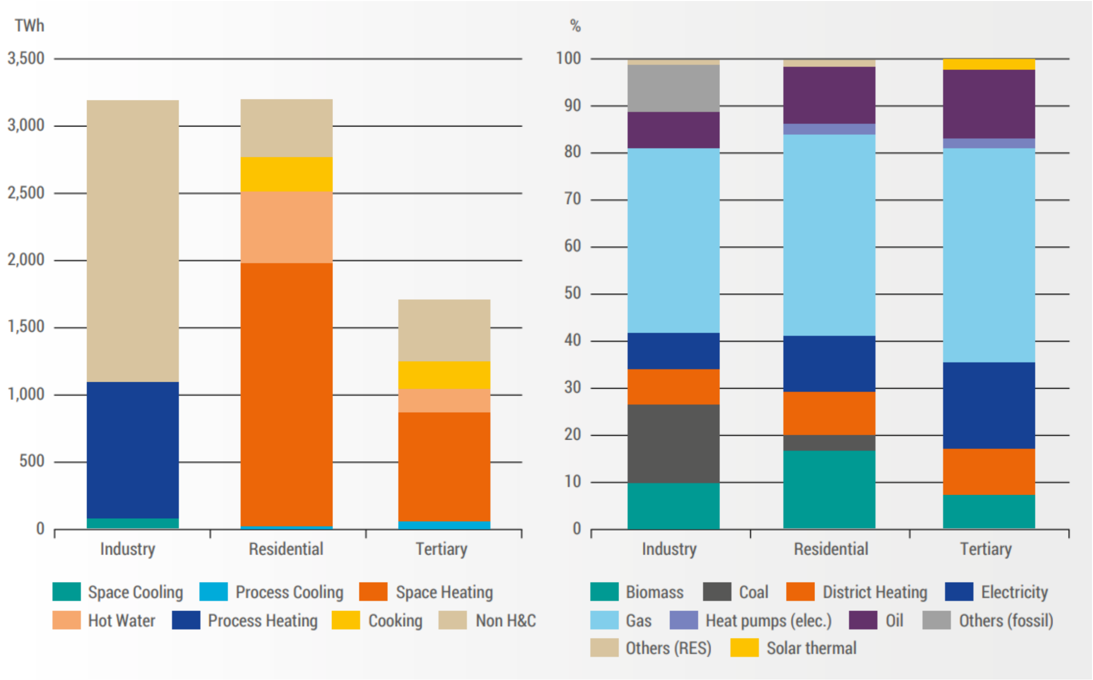


Figure 1-1: (a) H&C FEC and (b) various sectors primary sources decomposition for H&C, in EU-28. Data Source: JRC IDEES Database (JRC 2018)

European Union buildings consume 40% of the total energy, primarily for space heating and hot water [4]. In 2021, households constituted 27% of the EU's final energy consumption, largely supplied by natural gas (33.5%) and electricity (24.6%) [5]. Specifically, in Belgium, yearly household energy consumption for heating demand in terms of space heating forms the largest part, consuming almost three-quarters of the yearly household energy based on 2020 data [5]. This is marginally more than the EU average of 63.6% for space heating due to the cooler climate and lower insulation level of the buildings. In 2018, approximately 12% of this heating demand was met by electricity[6].

1.1. Motivation

1.1.1. Heat Pumps

In the residential heating domain, heat pumps distinguish themselves through their effective utilization of electricity. By converting electricity into thermal energy with exceptional efficiency, they revolutionize energy usage in residential contexts. The operational principle, like refrigerators or air conditioners, extracts heat from a source (like the ambient air or geothermal energy) and transfers it where needed, resulting in an energy output that surpasses their consumption. Therefore, heat pumps don't directly generate heat from electricity; instead, they move thermal energy from one place to another, 'pumping' heat from an external source into the residence. The energy output, in the form of heat, typically outmatches the electrical power required to operate the heat pump. Heat pumps can also be hybridized with other heating systems, typically gas. An efficiency comparison of heat pumps and other heat generation sources is provided in Figure 1-2

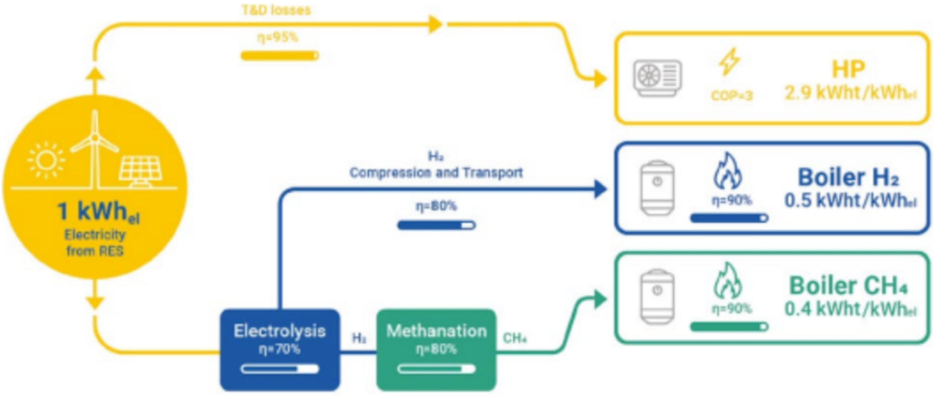


Figure 1-2 : Comparison of Efficiency: Heat Pumps vs H2 Boiler vs Synthetic Methane Boiler

In recent times, several major advancements have been observed that have the potential to influence the role of heat pumps within the energy system. Primarily, ongoing advancements in heat pump technology have led to increases in their Coefficient of Performance (COP). An analysis of over 800 heat pumps under nominal conditions, as cited in [7], reveals that COP values for commercially available heat pump units range between 3.2 to 4.5 for air-source heat pumps (ASHPs) and between 4.2 to 5.2 for ground-source heat pumps (GSHPs) under testing conditions conforming to EN 14511.1:(T_air = 2C, T_water = 35C; T_brine = 0C, T_water = 35C).

Also, recent EU policies aimed at enhancing energy efficiency provide a substantial boost for heat pump adoption. According to the Heat Roadmap Europe baseline scenario, heat pump penetration is projected to surge until 2050, accounting for 7% of the total electricity demand[8]. Furthermore, the recent Repower EU plan signals a transition towards a sustainable energy future, positioning heat pumps in residential buildings at the forefront. The EU's commitment is reflected in the ambitious target of doubling the current roll-out rate of heat pumps, aspiring to install 20 million units by 2027 and escalating to 60 million by 2030 [9]. The projected rise in heat pump installation signifies their vital role in the EU's energy transformation. Their recognized efficiency in converting electricity to heat and potential to enhance grid flexibility makes heat pumps a promising and sustainable solution for the future.

1.1.2. Power Grid Flexibility

Grid flexibility, in the context of power systems, is described as the system's capacity to adapt to the variability and unpredictability of electricity demand, supply (inclusive of renewable generation), and grid availability over all relevant time scales [10]. This spans a broad spectrum, from sub-hourly requirements that encompass seconds or minutes to larger units such as daily or weekly, even extending to seasonal or inter-annual needs [2].

Flexibility plays an integral role in power systems for several reasons. Firstly, it ensures system stability. Secondly, it assists in the deployment of intermittent renewable energy sources (RES) by adjusting to their fluctuating nature. Lastly, it strives to minimize system costs. It represents the ability of various power system participants to respond to market price signals, which indicate shifts in electricity demand, supply, and grid availability [11].

The fundamental rule of power system operation requires supply and demand to be always balanced. Therefore, both the unpredictable and variable nature of power generation and consumption drives system flexibility. As an example, electricity demand is influenced by various factors, including temperature, behavioural patterns, daylight, and unpredictable events, all of which affect the temporal dynamics of electricity demand [11]. The electrification of end-use sectors like buildings, industry, and transport will enhance the total demand for electricity, modify demand patterns, and potentially increase peak demand. Increased penetration of variable RES, such as solar and wind power, necessitates flexibility sources to maintain supply-demand balance due to their inherent variability and uncertainty. Further, potential disruptions to the energy system, such as extreme weather events or international conflicts, can affect generation or grid availability[11]. Lastly, the phasing out of dispatchable generation, like coal-fuelled power or nuclear power, may reduce available solutions to manage increasing flexibility needs, placing additional stress on the system. In this evolving energy landscape, technologies like heat pumps, with their inherent flexibility, can play a critical role in demand response programs, helping to maintain system balance and stability.

1.1.3. Heat Pumps in Demand Response Programs for Flexibility

In the context of a smart grid, heat pumps can play a role in the demand side to contribute flexibility to the Grid. The ability of heat pumps, when paired with thermal storage or when utilizing the thermal inertia of buildings, to decouple electricity consumption from heat demand, underlines their flexibility potential [12]. This flexibility has the capacity to address an escalating problem: the growing intensity of hourly and seasonal variations in electricity demand, particularly during peak winter periods.

In the absence of Demand Response, grid operators must rely on costly, fossil-fuelled power stations during peak electricity consumption times. Within the framework of a building, DR mechanisms facilitate the migration of a portion of the electricity requirements for HVAC from high-demand, high-cost periods to intervals of lower demand [13]. Such shifts not only minimize the energy expenditures of the building but also enhance the grid-wide load factor of the electrical power system. The International Energy Agency (IEA) predicts an important role for heat pumps, with their projection estimating them to contribute to a more than threefold increase in EU demand-side flexibility between 2021 and 2030. Their share of total flexibility resources is projected to escalate from 9% in 2021 to around 12% by 2030 [14].

However, this potential faces some challenges as the realization of heat pumps as a major contributor to system flexibility necessitates the incorporation of digital technologies. Automation stands as a crucial factor, facilitating the remote operation of these devices to optimize the on and off cycles. Consequently, a critical element of modern heat pumps is the integration of communication and control features that would permit such functionality [14].

Furthermore, there is a pressing need for modifications in heating systems and enhancements in building insulation to maximize the power system flexibility of heat pumps without affecting end users' thermal comfort. In buildings with well-insulated structures, heat pumps can be switched off for several hours without significantly impacting indoor temperatures. However, many buildings even in advanced economies, still are poorly insulated, thereby limiting the potential role of heat pumps in demand-side flexibility [14]. As such, the pathway to fully harnessing heat pumps as a substantial solution for demand response programs may require a series of infrastructural adjustments and policy shifts, to transform heat pumps from a niche solution to a mainstream contributor to demand-side flexibility[14].

1.2. Objectives of the work

The central aim of this study is to investigate the potential contribution of heat pumps to grid flexibility via active participation in demand response programs. This primary objective emerges from the nexus of increased integration of renewable energy sources into the power system and the rising need for flexibility to ensure grid stability and efficiency.

To achieve this general objective, the following specific tasks will be carried out:

Objective 1: Dynamic Modelling and Simulation of Heat Pump Energy Consumption

The first task involves the dynamic modelling and simulation of a heat pump's energy consumption in a typical residential house, capturing the temporal evolution of the building's thermal state. Two buildings with different types of insulation levels are considered to model the thermal mass storage effect according to the Belgian building standards. This process serves as a foundation for understanding the heating patterns, energy consumption and the inherent potential for flexibility within a residential setting.

Objective 2: Optimization of Energy Consumption via Demand Response

The subsequent objective is the creation of a strategy that utilizes electricity price signals to incentivize optimized energy consumption behaviour in heat pumps. The aim here is to determine an approach that minimizes cost and avoids energy use during peak periods while still maintaining the thermal comfort of occupants as defined.

Objective 3: Analysis of Thermal Comfort Considerations

The third objective is to assess the impact of energy optimization strategies on thermal comfort. The intent is to strike a balance between energy optimization, cost savings, and maintaining acceptable comfort levels.

Objective 4: Case Study Analysis

The final task involves the examination of three case studies reflecting different stages of heat pump integration in demand response programs. Ranging from early-stage proof of concepts to commercial-scale cases, the goal is to draw out best practices, identify areas for improvement, and ultimately recommend strategies for effective heat pump integration in demand response programs for grid flexibility.

This work explicitly focuses on the intrinsic thermal storage capacity and flexibility of the building itself, rather than exploring the use of external storage tanks. In doing so, this thesis seeks to uncover a compromise between cost savings, increased energy consumption, occupant comfort, and the reduction of the grid's peak load. By examining these objectives, this work aims to contribute to the field of energy system optimization and the role of heat pumps in creating a more flexible and resilient power grid.

1.3. Scope of work

This research, focused on the potential of heat pumps for enhancing grid flexibility in residential buildings in Belgium, maintains precise boundaries to ensure a comprehensive examination of the subject. While the selected dimensions, including spatial, temporal, environmental, and technological, help to effectively delineate the scope of this work, there are certain inherent limitations that need to be acknowledged.

Spatial and Temporal Scope: The geographical area of this research is strictly confined to Belgium, chosen for its matured market of demand response programs within Europe. This study analyses residential buildings throughout Belgium, emphasizing the current state of demand response programs and heat pump utilization in the country. However, the weather data utilized for the dynamic thermal modelling is based on the winter period of February and is sourced from The Royal Meteorological Institute of Belgium (RMI). Therefore, the outcomes might vary for other climatic conditions, given that heat demand would be different. The Figure 1-3 below shows an illustrative map to contextualize Belgium's position in the broader European demand response progress.

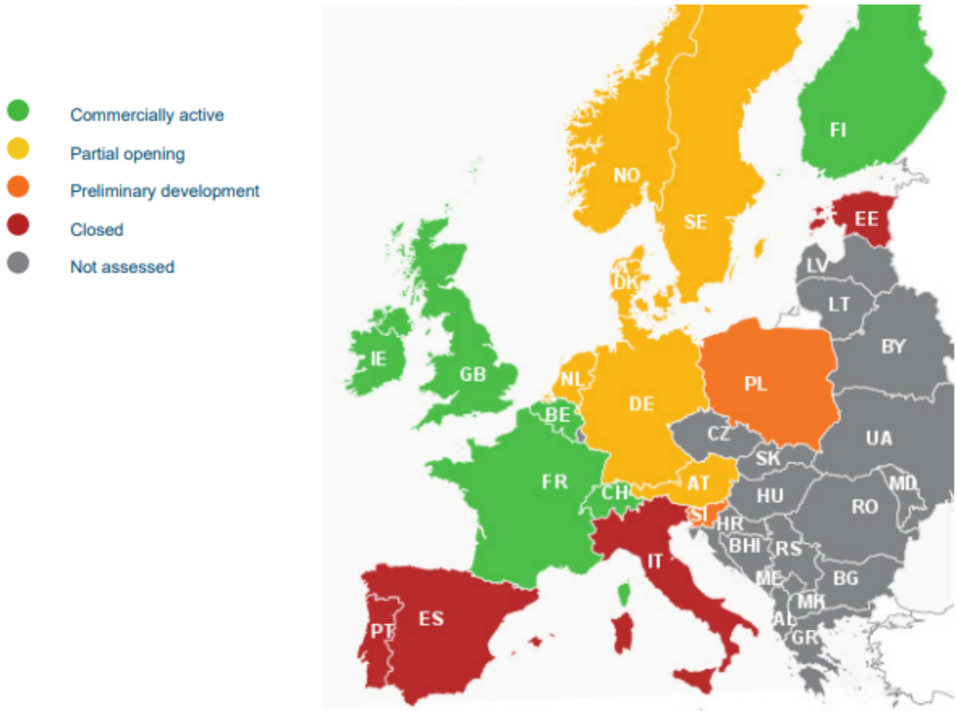


Figure 1-3: Map of Explicit Demand Response development in Europe 2017 [15]

Environmental and Technological Scope: This research focuses on grid flexibility and efficiency, exploring the role of advanced heat pump technology and dynamic modelling within the residential sector of Belgium. A key consideration here is that the electricity price data used is derived from the February 2022 ENTSO-E day-ahead database[16]. As the price of electricity fluctuates year on year, this could potentially influence the results.

Building Type: In terms of the type of buildings under study, the focus is on detached houses. This restriction indicates that the results may not fully apply to other types of residential structures.

2. Literature Review & Case Study Analysis

With the European Union at the forefront for energy transition efforts, there has been a new emerging market focused on taking advantage of the potential of heat pumps and thermal storage to provide grid flexibility. In this section, 3 case studies are analyzed ranging from a research concept to demonstration and finally commercial projects of matured technology readiness levels.

2.1. Proof-of-Concept in Research

2.1.1. Heat Pumps in Demand response: using dynamic day-ahead price signals and variable temperature setpoints.

A 2018 study by [17] dissects the operation of heat pumps within plus-energy dwellings that engage in dynamic pricing markets, thus serving as participants in Demand Response (DR) programs. The study done for a building in a southern Germany district utilized the TRNSYS 17 software to simulate the building and its associated supply systems. Aiming to highlight the advantages of dynamic over fixed pricing, the study undertook an in-depth exploration of 16 different strategies based on temperature setpoints for comfort and electricity price thresholds. With these strategies and by emphasizing the thermal storage capacity of buildings, the study showed that strategic dynamic pricing can generate cost savings up to 25%, elevate self-consumption ratios, and contribute to significant peak reductions on the grid.

2.1.2. Methodology to achieve Thermal comfort.

The paper utilized dynamic pricing strategies, with fine tuning of thermal comfort setpoints to reflect daily variations, avoiding the underutilization of the heat pump, and consequently avoiding comfort losses. Moreover, the study sheds light on the implications of overheating a building beyond its normal setpoint temperature, which could lead to increased energy consumption and offset the intended savings.

It can be noted that the balance between energy savings and thermal comfort depends on the occupants' comfort tolerance levels[17]. Once determined, the study's approach suggested ways to inform estimations of potential savings without considerably impacting thermal comfort. Finally, while the case presents promising insights, the uniqueness of the energy market and local renewable energy generation in Southern Germany is unique and requires further considerations to extrapolate these findings to other contexts.

2.2. Mitsubishi Electric DR Demonstration experiments with Heat Pumps.

The (REACT) project[18], co-funded by the European Union Horizon 2020 program, is an exploration of the potential for energy independence in remote island environments. The focus of the project is on the Irish Aran Islands and San Pietro Island in Italy, harnessing the capabilities of renewable energy sources such as photovoltaic (PV) panels and wind turbines. The unique geographical and structural challenges faced by remote islands, including high dependence on fossil fuels and mainland energy supplies, provide a compelling backdrop for this pioneering initiative.

At the heart of the REACT project is an innovative, community-centric approach to energy management, leveraging distributed renewable energy generation and storage technologies in combination with demand response strategies[19]. This approach is designed to maintain a delicate balance between power supply and demand. Ambitious targets underscore the project's commitment to energy efficiency and environmental responsibility: a 10% energy savings target, a 60% greenhouse gas reduction goal, and an aim to increase renewable energy use by 50% compared to the baseline operation case before the implementation of the REACT solution.

2.2.1. Maintaining Thermal Comfort: The Central Role of Heat Pumps in the REACT Project

A crucial component of the REACT project is the careful consideration of thermal comfort, achieved through an advanced heat pump control system. Mitsubishi Electric's heat pump systems, linked with the REACT demand-response platform via the MEL Cloud service, provide a seamless integration of technology and user comfort[18], [19]. These heat pump systems constantly send operating status information, such as temperatures and energy consumption data, to the REACT platform. This data then informs the optimal demand-response control actions that are executed by each heat pump.

The project incorporates a diverse range of buildings for its demonstrations, including three residential buildings and two public facilities in the Irish Aran Islands, and six residential buildings and two public facilities in Italy's San Pietro Island. This range allows the project to verify the effectiveness of the demand-response control in different types of buildings, contributing to the broader goal of energy efficiency and thermal comfort.

In total, the project utilizes 6 heat pumps for domestic hot water and space heating on the Aran Islands and 18 heat pumps for air conditioning and domestic hot water heating on San Pietro Island. By analyzing the data from these various types of buildings and heat pumps, Mitsubishi Electric aims to refine its understanding of demand-response controls, leading to innovations that can further the cause of carbon neutrality.

2.3. Commercial Case: Swisscom Energy Solutions' project, TIKO

The TIKO project has been operational since 2014, and at its base it establishes a robust instance of a fully operational virtual energy storage network. This project includes over 10,000 electric heating devices with a 100MW connected capacity throughout Switzerland as at 2017[20], thus creating a strong web of both residential and industrial applications, a significant portion of which are heat pumps. The backend of this system is centrally managed, employing mobile communication and power line carrier technology to constantly oversee and regulate all connected loads[21]. Remarkably, the network capitalizes on the flexibility of these aggregated loads, providing primary and secondary control for Swiss grid, the Swiss power transmission system operator. In essence, the TIKO system exploits the potential of the inherent capacity of private loads like the heat pumps systems, orchestrating them to partake in real-time power grid frequency control, thus presenting a successful blueprint of demand response implementation.

2.3.1. Methodology to achieve Thermal Comfort

Beyond the project's technical and commercial achievement, it places a notably priority user experience and comfort. The system implements a room temperature programming solution with the aim to measure temperature and humidity every 5 minutes with a 0.1°C resolution[21]. This innovative network puts a strong emphasis on preventing any compromise to consumer comfort while harnessing flexibility from the connected devices. Crucially, any potential issues are detected by the system in real-time, with alerts being dispatched to users promptly, preventing any loss of comfort. This programming solution reportedly brings up to 20% reduction in the user's energy bills as well as up to 1600kg of CO_2 savings over a period of 5 years[21]. Finally, users are able interact with the system via webpage and smartphone applications, gaining access to instant and historical power consumption data, the system's comparative functionality enables users to juxtapose their energy usage against others within the network[20].

3. Methodology

The methodology of this study is divided into subsections, each providing the analytic foundation for the exploration of heat pumps' potential to enhance grid flexibility in residential houses.

The first subsection details the specifications of the residential building under investigation, crucial for understanding the heating requirements. This is followed by an energy balance analysis, simulating temperature evolution and heat pump energy consumption within the residence. Subsequently, thermal comfort is assessed, considering how it influences and is influenced by the occupancy behavior. The final critical subsection focuses on demand response, including a discussion on price-based demand response programs, specifically day-ahead hourly electricity prices, the role of optimization algorithms in heat pump operation schedules, and the associated constraints. This systematic breakdown provides a roadmap for the research project and establishes the groundwork for subsequent results and discussions.

3.1. Building description and energy system

A traditional urban building block of single-family house as illustrated in Figure 3-1, is considered in this study. The main properties and dimensions of the studied building are presented in the Table 1. The building has a floor area of 180 m2 and contains some separated rooms. The room height of the building is 2.6m and the building type is determined with a massive structure and a passive level of thermal insulation according to Belgium guidelines for passive houses (PHL 2011) [22]. Additionally, it was assumed that a family of 4 lives in the house.

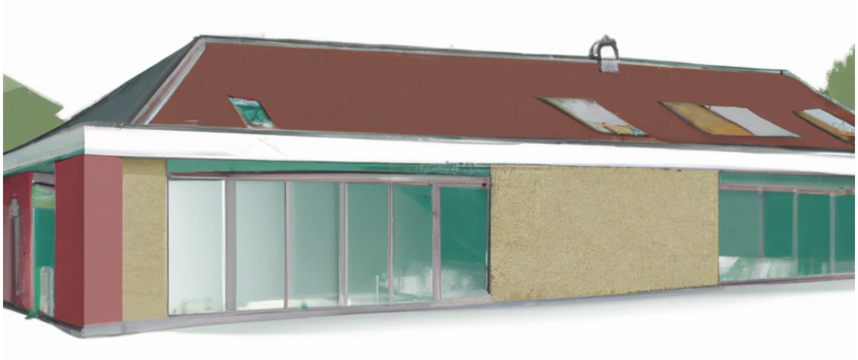


Figure 3-1: Sketchup model of typical Belgian residential building. (A.I generated image)

Symbol	Dimension	Value
l_1	Length of walls 1 and 3	12 [m]
l_2	Length of walls 2 and 4	15 [m]
H_b	Height of the building	2.6 [m]
A_1	Area of walls 1 and 3	31.2 [m²]
A_2	Area of walls 2 and 4	39 [m²]
A_{floor}	Area of floor	180 [m²]
A_{roof}	Area of roof	180 [m²]
V	Volume of the building	468 [m³]

Table 1: Building Dimensions

Two levels of insulation and air tightness for buildings are considered for analysis in this study as defined by Belgian building codes[23]:

1) Buildings with n_{50} value with insulation K45 corresponding to an average U-value of 0.458 W/m2K and a given air change rate (ACR) equal to 1.8.
2) Buildings with n_{50} value with insulation K15 corresponding to an average U-value of 0.152 W/m2K and a given air change rate (ACR) equal to 0.6.

The building with K45 insulation level was the standard for new buildings before 2014, and the K15 is for buildings afterwards. The K45 building type is the most common type and represents about 75% of the building stock available in the Belgian region[24]. The building materials and dimensions can be found in Appendix I.

3.2. Building Energy Balance

The energy balance includes analysis of a range of factors contributing to the overall thermal energy load of the building, crucial for the optimal design of its HVAC system. This section provides an overview of the methodology employed to conduct this analysis.

The process begins with identifying key contributors to the building's heat gains and losses. These include heat gained or lost through conduction, direct beam and diffusive solar irradiation, lights and home electrical equipment, air infiltration, and heat generated by occupants.

The interplay of these factors culminates in the thermal energy load that the Heat Pump must cater to, influenced by weather conditions set in the winter period, building geometry, orientation, location, occupancy, and utilization of electrical appliances. Each of these element's factors into our energy balance calculations, yielding the necessary heating load required.

A few assumptions are considered for simplicity, such as homogeneous walls without doors affecting thermal transmittance, uniform interior temperature across all rooms, and the assumption that all interior walls and rooms are at the same temperature. To account for the various heat transfer modes, we solve a suite of equations numerically, covering diffuse radiation, direct radiation, infrared radiation, conduction, and natural convection.

The thermal comfort metric, is derived from the Adaptive Comfort Method, further informs the load calculations. This metric gauges indoor comfort temperature as a function of the ambient temperature and two standard indices for non-mechanically cooled buildings in free-running mode. For this study, we adopt the European standards for these indices (a=0.33 and b=18.8) [25]. The objective is to estimate the thermal load needed to be covered during the winter period as a function of the pre-defined thermal comfort metric and the indoor temperature of the room. The detailed calculations and equations for the heat gains/losses are expanded in the following subsections.

3.2.1. Weather Data Collection

Three weather parameters were sourced from online databases to conduct this study. The Royal Meteorological Institute of Belgium (RMI) provided the data on ambient temperature, while solar irradiance (G_{sun}) was procured from a tool made available by the European Commission. This tool offers comprehensive weather data from various global locations in a choice of monthly, daily, or hourly timesteps[26]. For this study, data was specifically gathered on an hourly basis for the month of February, thereby representing the winter period when the demand for heating thermal energy is at its peak.

To complete the data set, the zenith angle (θ_Z), essential for radiation calculation, was retrieved from the online tool Solar Topo[27]. This data was gathered at 15-minute intervals, also focusing on the month of February.

3.2.2. Conduction and Natural Convection Analysis

The calculation for conduction and natural convection was divided in 4 parts (according to each element of the building) and is shown in Equation 3-1. $Q_{c,wall1}$ is the thermal energy portion for walls 1 and 3, $Q_{c.wall2}$ is the portion for walls 2 and 4, $Q_{cond,roof}$ is the portion for the roof and $Q_{cond,floor}$ is the portion for the floor.

$$Q_c = 2.Q_{c,wall1} + 2.Q_{c.wall2} + Q_{cond,roof} + Q_{cond,floor}$$

Equation 3-1

For the calculation of external and internal natural convections (walls and roof), the methodology applied consists in obtaining common values for the coefficient of convection *h* found in standards published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)[28].

For the walls 1 and 3, the thermal energy can be calculated by Equation 3-2 to Equation 3-5. U_{wall1} represents the global heat transfer coefficient, $R_{wall,1}$ represents the thermal resistance of the wall, $R_{cond,1}$ represents the thermal resistance due to conduction, $h_{ext,1}$ represents the external convective heat transfer coefficient and $h_{int,1}$ represents the internal convective heat transfer coefficient.

$$Q_{c,wall1} = U_{wall1}.A_1.(T_r - T_{amb})$$

Equation 3-2

$$U_{wall1} = 1/R_{wall,1}$$

Equation 3-3

$$R_{wall,1} = \frac{1}{h_{ext,1}} + R_{cond,1} + \frac{1}{h_{int,1}}$$

Equation 3-4

$$R_{cond,1} = \frac{L_{extglass}}{k_{extglass}} + \frac{L_{intglass,1}}{k_{intglass}} + \frac{L_{intglass,2}}{k_{intglass}}$$

Equation 3-5

The parameter *k* represents the thermal conductivity of each material in the building, the values used were obtained from the literature[29], [30].

The same methodology is applied to calculate the thermal loads for walls 2/4, floor and roof. Finally, for the floor it was assumed that the internal and external convective coefficients have the same value.

3.2.3. Radiation

Heat gain/losses due to radiation were calculated by Equation 3-6, separated in 4 terms. $Q_{rad,wall1}$ represents the portion for walls 1 and 3, $Q_{rad.wall2}$ is the portion for wall 2, $Q_{rad,wall4}$ is the portion for wall 4 and $Q_{rad,roof}$ is the portion for the roof. Due to the orientation of the building related to the position of the sun, it was assumed that the effects of radiation for the walls 1 and 3 were the same.

$$Q_r = 2.\, Q_{rad,wall1} + Q_{rad.wall2} + Q_{rad,wall4} + Q_{rad,roof}$$

Equation 3-6

a) Walls

The methodology to calculate the radiation for the walls and the values for the constant parameters involved were obtained from literature. Equation 3-7 shows the calculation of the radiative heat transfer for the walls 1/3.

$$Q_{rad,wall1} = \tau.\, A_1.\, G_{sun}.\, C_{es}.\, A_{t,1}.\exp\left(-\frac{A_{t,2}}{\cos\theta_Z}\right).\cos\theta_Z\, .\, f_{sh}$$

Equation 3-7

τ is a constant value and represents the energy transmittance[31], C_{es} is the correction of the Earth-sun distance[32] and $A_{t,1}$ and $A_{t,2}$ represent the turbidity factor. The parameter f_{sh} represents the shading factor and its values were assumed according to the positions and orientations of the walls and the roof.

The same equation was used to obtain the radiative heat transfer for walls 2 and 4.

b) Roof

An alternative model was used to calculate the radiative heat transfer through the roof. Equation 3-8 describes a more precise methodology to represent the effects of radiation through a roof [33]. Parameter α represents the absorptance of steel and h_r represents the radiative heat transfer coefficient between the roof surface and the sky; the values for these two parameters were obtained through tables found in the literature roof [33]. $h_{ext,roof}$ is the convective heat transfer coefficient obtained through ASHRAE standards[28] and U_{roof} is the global heat transfer coefficient calculated through Equation 3-8.

$$Q_{rad,roof} = \frac{\alpha . A_{roof} . U_{roof} . G_{sun} . C_{es} . A_{t,1} . \exp\left(- A_{t,2}/\cos\theta_Z\right)}{\left(h_{ext,roof} + h_r\right) . f_{sh,roof}}$$

Equation 3-8

3.2.4. Ventilation Losses Estimation

To account for ventilation the process is divided into two distinct methods: one focused on deriving the interior temperature profile of the building, and the other to estimating the thermal load demand for the Heat Pump. To develop an accurate temperature profile within the building, a model is employed to compute natural ventilation, which is defined by Equation 3-9. This model takes into consideration natural ventilation resulting from air leakage via doors and windows in the absence of an HVAC system. The air change rate within the building, denoted as n_{50}, is modulated by the time of year and wind speed. The chosen value, gleaned from literature-based plots and Belgian building code(Annex I), are n_{50}= 0.6 and 1.8 for building K15 and K45 respectively for winter.

$$Q_v = c_p \rho V n_a (T_r - T_{amb})$$

Equation 3-9

The second approach aims at quantifying the thermal load that the Heat Pump system is required to handle. This methodology utilises Equation 3-10 and Equation 3-11 to provide the heat loss/gain values and Equation 3-12 to calculate the requisite mass flow of fresh air for the building. The variable n_p denotes the number of occupants within the building, assumed to be four (4) in this instance. The parameters A and B represent the minimum ventilation rates for residential buildings, as determined by the ASHRAE standards[28]. For this study, the values adopted are A = 0.00069 m³/s and B = 0.000083 m/s [19].

$$Q\_v = U\_vent. (T\_r - T\_amb)$$

Equation 3-10

$$U_{vent} = \dot{m}_{vent} . \rho . c_p .$$

Equation 3-11

$$\dot{m}_{vent} = A . n_p + B . A_{floor}$$

Equation 3-12

3.2.5. Internal Heat Gains

The methodology considers three significant factors of internal heat gains in residential structures, comprised of metabolic heat from occupants, dissipated heat from home appliances, and heat emitted from lighting. These are denoted as Q_{ip}, Q_{equp}, and Q_{light}in the model, with the total internal heat contribution calculated using Equation 3-13.

$$Q_i = Q_{ip} + Q_{equp} + Q_{light}$$

Equation 3-13

The calculations use constant parameters sourced from the ASHRAE standards[34]. It should be noted that these internal heat gains, inherent to the operational use of the building, have strong correlations with occupancy levels and this is set between the hours of 5:00 till 23:00 for this study. Furthermore, the sensible and latent heat produced by individual occupants can vary, influenced by factors such as their activity levels, age, and gender. Consequently, these sensible heat gains from occupants induce changes in the indoor temperature, thereby significantly impacting the overall thermal behaviour of the dwelling. A latent heat value of 100W per person is assigned and an installed power of 6 W/m^2 is considered for the lighting.

3.2.6. Time step Discretization

The energy balance equations in this study were solved using Python programming, a flexible language capable to solve for a transient regime. External data, comprising ambient temperature and irradiance, were collected at one-hour intervals. In contrast, the zenith angle was obtained at intervals of 15 minutes.

To accurately represent the heat transfer within the building, an appropriate timestep was determined based on the thermal diffusivity of the materials, a factor that measures the conductive heat transfer rate. The thermal diffusivities were sourced from existing literature[35], [36] and used to calculate the timestep for each structural component of the building - walls, floor, and roof. The smallest value among these calculated timesteps was selected for enhanced accuracy. Consequently, the collected hourly data for ambient temperature and irradiance were interpolated to align with the selected 15-minute timestep.

The Figure 3-2 and Figure 3-3 shows the Indoor temperature evolution because of the energy balance done to the two case buildings.

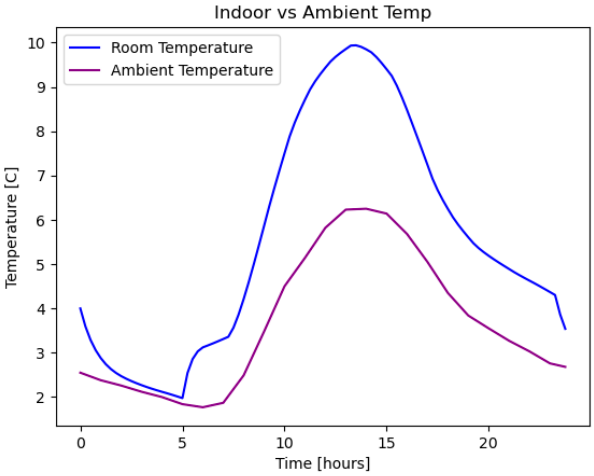


Figure 3-2: Indoor Temperature evolution: (Building K45)

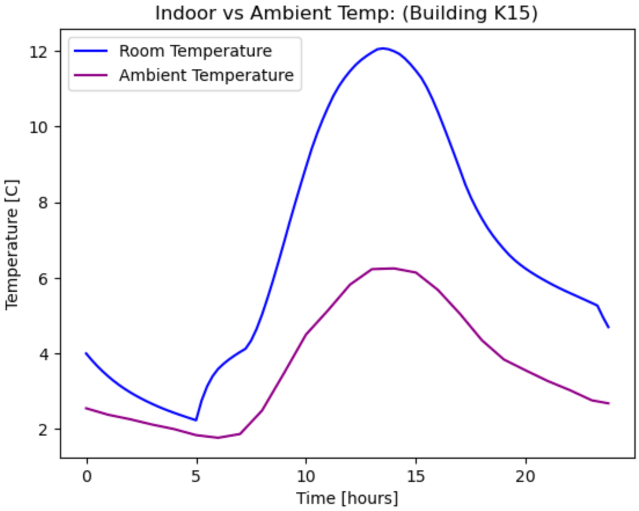


Figure 3-3: Indoor temperature Evolution: (Building K15)

3.3. Thermal Comfort Determination and Occupancy Pattern

The thermal comfort metric used for the study and for the simulation of the energy load profile for the building is obtained from the Adaptive Comfort Method[37]. It simplifies the comfortable temperature levels as a function of the ambient temperature only. This assumes that the occupants in the thermal environment have some degree of control over their personal thermal space. The European standard for the adaptive comfort method is used in this study. It expresses the indoor comfort temperature as function of three parameters: the ambient temperature and two standard indices (a and b) for non-mechanically cooled buildings in free running mode. For this application, those indices chosen from European standards (a=0.33 and b=18.8)[25], [38].

For this study, the occupancy pattern is defined for the analysis of thermal comfort and heating load calculations with the DR strategy. This pattern follows that indicative of a typical weekend period. The rationale for this choice rests on the premise that for a typical weekend with full occupancy throughout the day, the heat pump system remains continuously available and operational to satisfy the heating demand for maintaining comfortable levels. This assumption allows to analyse the study for an extreme case scenario with the heat pump under constant demand. While this may not mirror the unpredictable real-life pattern for occupancy, it allows for a simplified analysis.

Furthermore, the calculated thermal load is defined by the difference of the temperature inside the room (T_r) and the comfort temperature (T_{com}) that is calculated by Equation 3-14. T_amb is the ambient temperature for the location.

The objective is to use Equation 3-15 to estimate the natural indoor temperature evolution T_r and then calculate the thermal load (Q_HVAC) with the use of Equation 3-16.

$$T_{com} = a.T_{amb} + b = 0.33.T_{amb} + 18.8$$

Equation 3-14

$$\rho.c_p.V.\frac{\partial T}{\partial t} = Q_c + Q_r + Q_v + Q_i$$

Equation 3-15

$$Q_{HVAC} = \pm\,\rho.c_p.V.\frac{(T_r - T_{com})}{dt}$$

Equation 3-16

The Figure 3-5 and Figure 3-4 below shows the differences in the temperature evolution for the Comfort, indoor and ambient levels for the case buildings K45 and K15.

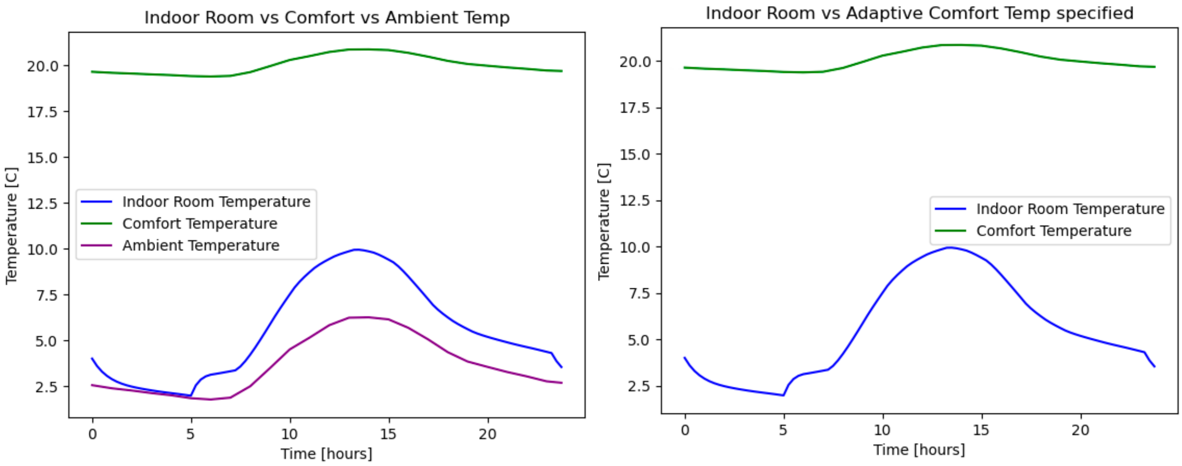


Figure 3-5: Buildings K45 (Average U-Values = 0.458 W/m2K)

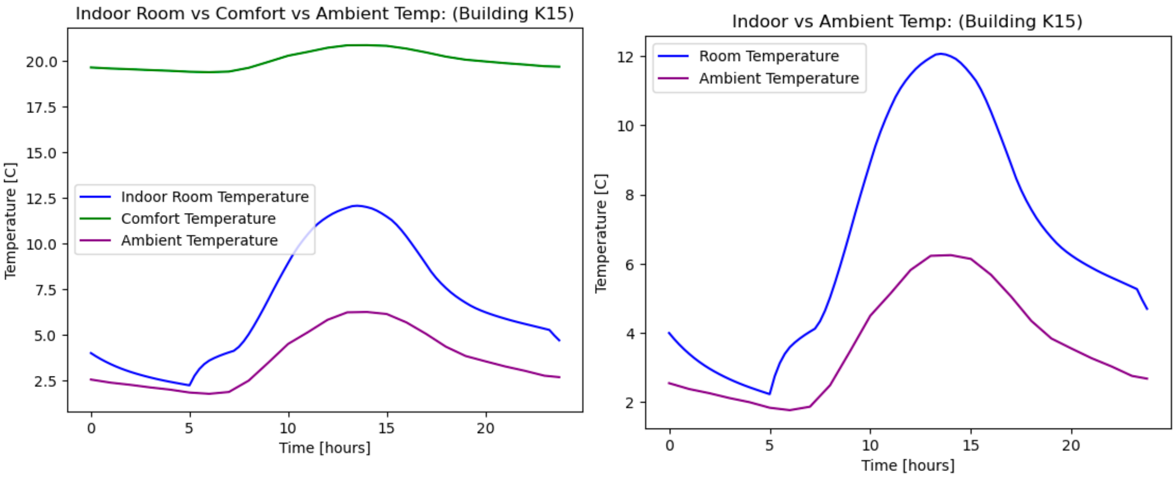


Figure 3-4: Building K15(Average U-Values = 0.152 W/m2K)

3.4. Heat Pump System

The building model analysed in this study is equipped with an aerothermal or air-source heat pump. This type of heat pump was selected to represent the prevailing technology in operation across Belgium, accounting for over 90% of installations between 2013 and 2020, according to data made available by the Statista Research Department for Belgian buildings [25] To align the study with contemporary building practices in Belgium, air-water heat pumps that supply either radiators or floor heating system is considered and also using the rate of ventilation in winter that fulfils the requirements of the Belgian building guidelines (PHL 2011)[22].

3.4.1. Air Source Heat Pumps

The coefficient of performance (COP) determines the heating power ratio and electrical power of the heat pump, given as follows:

$$COP = Q_{hp}/Power_{HP}$$

Equation 3-17

Where Q_{hp} and $Power_{hp}$represents the heating power in Watts and Electrical Power demand (Watts) for the heat pump respectively. The power demand of the heat pump includes the required electricity for the compressor and auxiliary devices of the heat pump. COP is commonly measured for both partial operation conditions and at nominal conditions. Different standardized test points (for example, 0 °C / 35 °C or 0 °C / 45 °C) are considered for describing the measured COP (SFS-EN 15316-3-1 2007). For the Air source heat pump selected, the maximum power is given as 4 kW with a manufacturer-provided COP of 3.83 under standard laboratory conditions (outdoor temperature of 7 °C and exhaust temperature of 35°C)[39] The product catalogue is detailed in annex II.

The Figure 3-6 and Figure 3-7 below shows the evolution for the heating load and heat pumps electrical consumption profile for both K45 and K15 buildings studies.

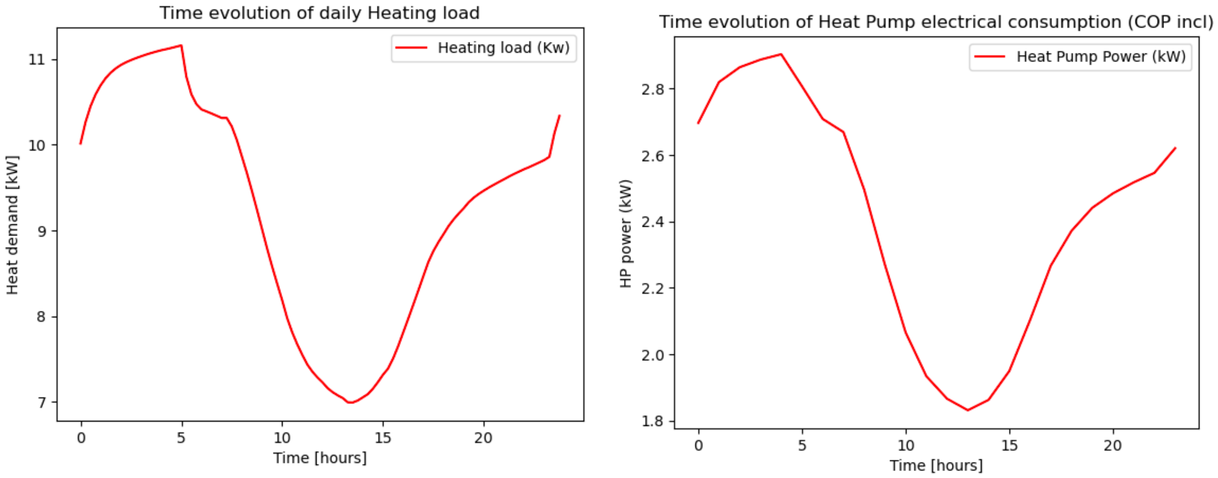


Figure 3-6: Time Evolution for Heating load and Heat pump energy consumption (Building K45)

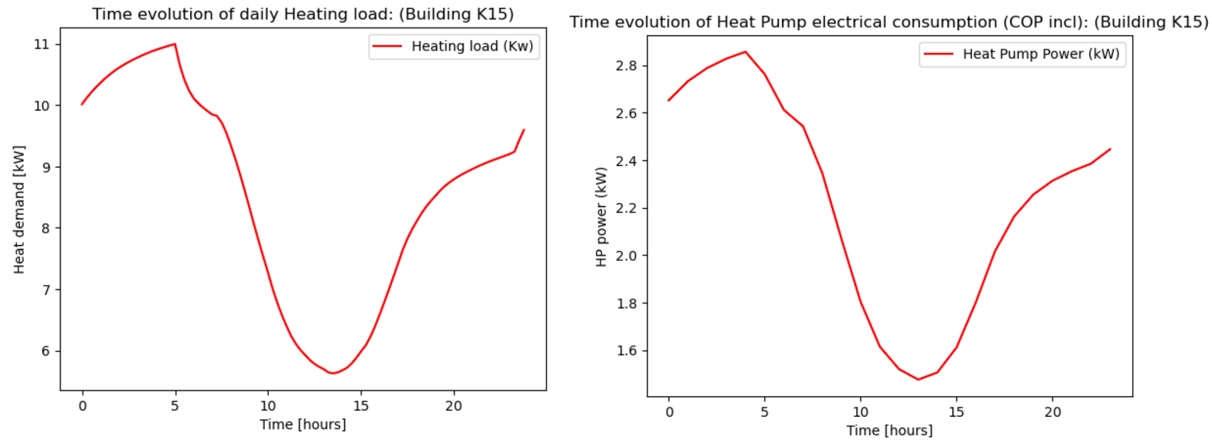


Figure 3-7: Time Evolution for Heating load and Heat pump energy consumption (Building K15)

The daily load demand and heat pump consumption for the building profiles simulated are quantified in Table 2.

Building Insulation type	Daily heating load (kWh)	Daily Heat Pump Consumption (COP incl.) (kWh)
K45	234.91	61.33
K15	204.67	53.44

Table 2: Results for heating load demand and Heat pump electrical energy consumption for buildings K45 and K15

3.4.2. Thermal Energy Storage: Building's Thermal Mass

For this study, the thermal mass of the building is investigated as storage option as a means for operating a cost-reduction potential. The potential for flexibility is investigated to find the optimal control of building thermal mass storage that will allow for significant energy costs reductions through energy loads shifts to lower price periods and peak shavings for overall consumption in a demand response implementation.

Following the building standards in Belgium, a typical geometry is used for the study with a concrete structure and vertical walls composed of concrete blocks, inclusive of variable thickness for rigid insulation panels. The ground floor is made of precast concrete providing a considerable amount of insulation for the thermal mass of the room. Two levels of insulation and air tightness are considered for analysis in this study as defined by Belgian building codes [22]:

- Buildings with n_{50} value with insulation K45 corresponding to an average U-value of

0.458 W/m2K and a given air change rate (ACR) equal to 1.8.

- Buildings with n_{50} value with insulation K15 corresponding to an average U-value of 0.152 W/m2K and a given air change rate (ACR) equal to 0.6.

The standard (K45) corresponds to Belgian standards for newly built houses before 2014 to represent low insulation house from the 80's and (K15) corresponds to the new regulations for high insulation passive house to be built after 2014. The new K15 standard corresponds to the passive house law (PHL)[22].

Overall, the building thermal mass, and evolution of the solar and internal gains of the building influence the available storage capacity over the course of the simulation and this was considered to investigate the flexibility potential.

3.5. Demand Response Program

In the rapidly evolving landscape of the power sector, the integration of heat pumps into a smart grid has provided a range of alternative applications for their usage, thus creating novel prerequisites for their control and design.

Over the past years, a myriad of research projects and scholarly publications have explored different smart grid applications and control strategies for heat pumps[40]. The conditions under which heat pumps operate and the specific application domains vary substantially across these studies. However, three principal domains emerge as common threads in these explorations:

- The provision of ancillary services to the power grid.
- The facilitation of renewable electricity integration at the building level, distribution grid and power system levels.
- The operation of heat pumps in response to variable electricity prices.

Though these three domains - grid-friendly operation, renewable electricity integration, and operation under variable electricity prices - often intertwine and overlap, research typically zeroes in on one aspect to explore its specific intricacies in detail. The three main domains are outline in the Figure 3-8:

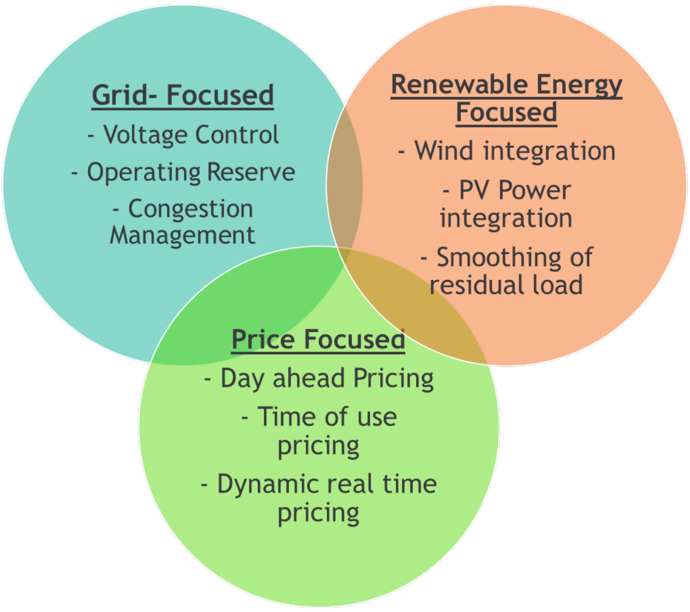


Figure 3-8: Main domains for heat pumps application for grid flexibility[40]

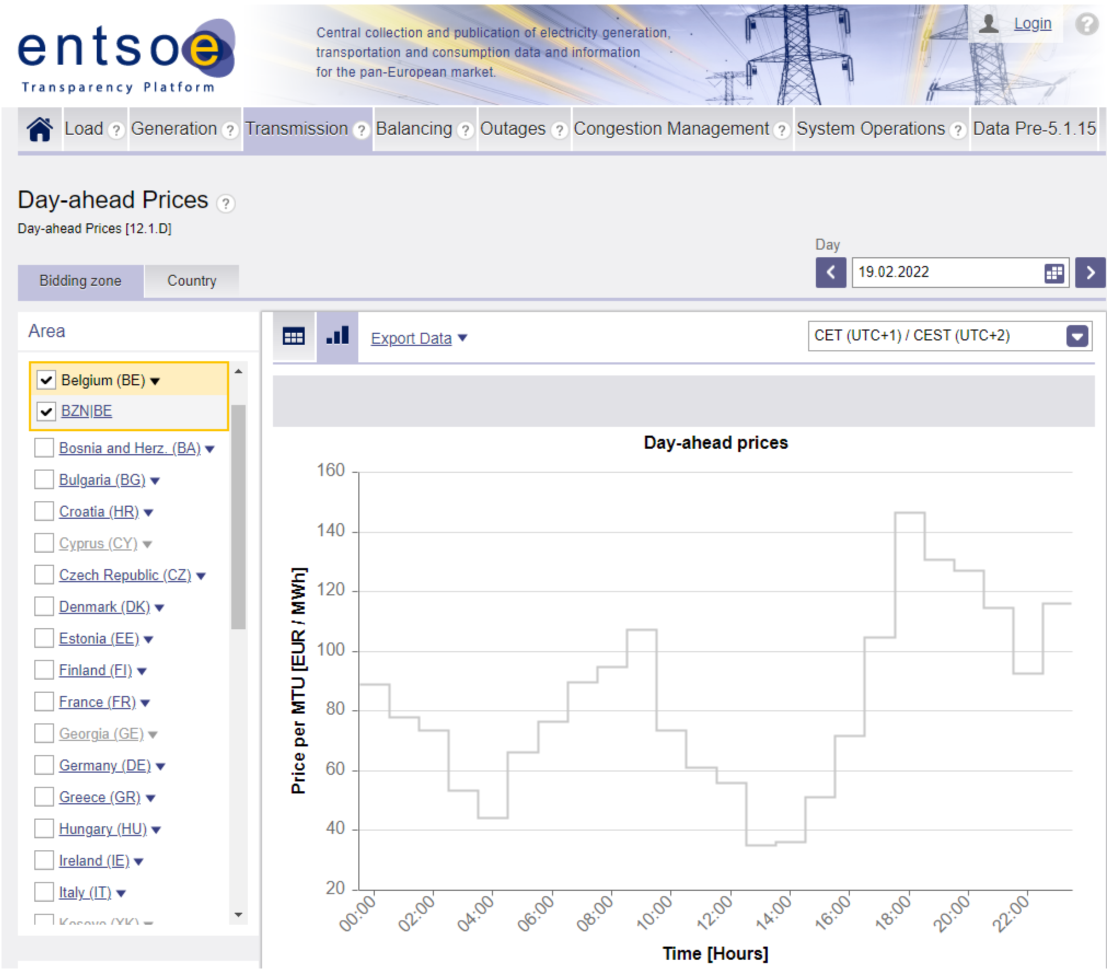
For this study, the focus is on the operation of heat pumps influenced by fluctuating electricity prices, as seen in the day-ahead market. This focus allows for a comprehensive analysis of how smart grids and heat pumps can collaboratively adapt to market changes, promoting grid flexibility through demand response and energy efficiency. Operating heat pumps in response to varying electricity prices opens new opportunities for better energy use and sustainability.

3.5.1. Data collection (Day Ahead Electricity Prices)

For this study, the day-ahead electricity prices were primarily gathered from the ENTSO-E Transparency Platform[16], a reliable platform for comprehensive on the electricity market for the Transmission System Operators (TSOs) and specifically for the Belgium market. The database includes electricity prices for different years and periods.

The study focused on the data from February 2022, as the aim was to simulate winter conditions and align these with the weather data that was collected for the same period. February was an ideal month for this study as it typically represents a high-demand period for heating systems and thus provides an opportunity to analyse the performance of the heat pump system under such conditions. The data used was specifically retrieved for a typical weekend period, which is consistent with the occupancy pattern defined earlier in this study. This ensured coherence between the occupancy patterns and the electricity price data, providing a more accurate simulation of the real-world scenario where both these variables interact.

Figure 3-9 illustrate the evolution of the day-ahead electricity prices for the chosen day, as well as the average prices over the course of February 2022. This not only provides a detailed insight into the price fluctuations during the studied period but also offers a broader view of the price trends throughout the month.



Day 19.02.2022

CET (UTC+1) / CEST (UTC+2)

☑ Belgium (BE)
☑ BZN|BE

Figure 3-9: ENTSO-E Transparency Platform: Day ahead prices Feb 19th, 2022

3.5.2. Demand Response Implementation and Problem Formulation

Electricity prices serve as an incentive mechanism, to shape consumption behaviour. In the context of a smart grid, variable electricity prices, closely linked to grid and renewable energy-focused applications communicate information about critical events, capacity thresholds, predictable load, and generation situations, as well as congestion, by reflecting real-time or day-ahead occurrences such as surplus renewable energy generation.

In this study, day-ahead electricity spot prices, is used as price signals. Optimal Heat Pump operation is planned in advanced by employing heuristic or optimal control methods. The overarching goal of developing energy-flexible buildings and integrating heat pumps into smart grid systems is to foster flexibility in demand response programs, thereby facilitating the incorporation of a greater share of intermittent Renewable Energy Sources (RES). The electricity spot price serves as a valuable indicator of RES availability in Belgium[41].

To create optimal bids, the estimates of the residential buildings heat pump consumption is obtained through the numerical and analytical simulation of the heating load as detailed in earlier sections. Furthermore, in this study, the thermal comfort is considered as a single room temperature, which is designed to be maintained at 20°C, within certain minimum and maximum limits for each hour of the day. For the purposes of this study, a single temperature is assumed to signify comfort levels for the entire building, conceptualized as a single room.

Therefore, the implementation of demand response is formulated as an optimization problem with the objective of reducing the overall consumption of the heat pumps and is done by avoiding peak price periods to provide flexibility, while simultaneously maintaining the indoor comfort temperature as closely aligned with the reference point as possible.

3.5.3. Optimization Algorithm (Including Constraints defined and optimum)

For the optimal control strategy, the resolution scheme and decision tree for the algorithm developed in this study is illustrated in this section. The Genetic Algorithm is used to search the optimal solution of the nonlinear programming problem. The python codebase for the building energy simulation and heat pump power optimization of both building types is detailed in appendix III and IV respectively.

The objectives for the optimization problem are:

1) The minimization of the cost of electricity, expressed mathematically as:

$$X_{cost} = \sum_{i=1}^{N=p} P_{price}(i) * W_{HP}(i)$$

Equation 3-18

Where p is the receding horizon, W_{HP} is the heat pump electrical power (decision variable) and P_{price} is the electricity price paid by the customer as defined from the day-ahead market.

2) The minimization of thermal discomfort during the occupancy period defined:

$$Y_{cost} = \sum_{i=1}^{N=p} f_{ocp} * \ \beta * |T_{ref} - T_{room}(i)|$$

Equation 3-19

Where f_{ocp} is factor to express presence of occupants, $T_{ref}\ and\ T_{room}$ are decision variables representing the reference comfort temperature set and the optimized room temperature respectively and β is the weight factor set to influence the balance between costs and discomfort, meaning a large factor will force the algorithm to keep the room at the reference temperature and otherwise the emphasis will be to achieve overall lowest cost.

The following constraints are set:

3) The comfort temperature set as the reference point should be between the upper and lower limits defined as (minimum of 18°C and Max of 22°C)

$$T\_\mathrm{min} \leq \boldsymbol{T\_room} \leq T\_\mathrm{max}$$

Equation 3-20

4) The heat pump electrical power should be between zero and the maximum electrical power specified as 4kW.
5) The final cost function P is defined as:

$$P = X_{cost} + Y_{cost}$$

Equation 3-21

Notation	Description
$\boldsymbol{X_{cost}}$	Heat pump electrical energy consumption costs (€uros)
$\boldsymbol{Y_{cost}}$	Discomfort costs (€uros/°C)
$\boldsymbol{T_{room}}$	Room Temperature (°C)
$\boldsymbol{P_{price}}$	Electricity day-ahead prices (€uros)
$\boldsymbol{f_{ocp}}$	Occupancy pattern (represented as 0 if unoccupied and 1 if occupied)
$\boldsymbol{W_{HP}}$	Electrical work of the Heat Pump (kWh)
$\boldsymbol{T_{ref}}$	Reference comfort temperature as specified by occupant

Table 3: Optimization Model parameters and description

3.5.4. Genetic Algorithm

The Genetic Algorithm (GA) is chosen approach for the optimization of heat pump power consumption in the simulated building environment. (GA)s are a subset of evolutionary algorithms, designed around the principle of Darwinian natural selection - survival of the fittest. They provide a stochastic method for solving optimization problems that might be challenging for traditional optimization algorithms due to factors such as the high dimensionality of the solution space, complex constraint interactions, or non-linear cost functions. The reasons for this algorithm choice are justified below:

- **Balance of Multiple Objectives:** This problem involves multiple conflicting objectives: maximizing occupant comfort while minimizing energy costs. (GA)s are particularly useful in these multi-objective optimization scenarios, as they can maintain and evolve a diverse set of solutions (Pareto front), providing a range of optimal trade-offs between the conflicting objectives.
- **Robustness:** (GA)s are generally more robust in comparison to traditional methods, being less prone to getting trapped in local minima, hence finding solutions that are globally optimal.
- **Adaptability to Dynamic Environments**: Given that conditions influencing heat pump efficiency, such as weather patterns and energy prices, indoor temperature change over time and with uncertain occupancy patterns. (GA)s can adapt to these dynamic conditions, thereby constantly adjusting the optimal power consumption pattern.
- **Scalability:** (GA)s can be easily scaled, which is beneficial in this case given the potentially large number of buildings that could be included, each with different configurations and requirements, that may be optimized using the algorithm.

The python-based code base for this methodology was built using the Distributed Evolutionary Algorithms in Python (DEAP) package [42], taking advantage of its inbuilt functionalities to implement and experiment with the genetic algorithm. The optimization process conducted by the algorithm is an iterative one, founded upon the principles of initial population creation, fitness evaluation, and application of genetic operations - particularly selection, crossover, and mutation.

4. Results and discussion

In this section, the results from the optimization algorithm applied to the two case-study buildings is detailed and evaluated. The algorithm is applied to the structure's representative of different levels of insulation for the building's thermal mass; (K45 and K15) which are the standards as defined by Belgian housing authority for new buildings constructed before and after 2014 respectively.

The discussion for the results obtained will be examined under five domains, The heat pump optimized power patterns, cost savings, Thermal comfort maintenance, Potential for flexibility in the context of demand response events and finally the impact of overconsumption of the heat pump.

4.1. Optimization of Heat Pump Power

With the aim set to minimize overall costs of electricity purchase by modulating the heat pump consumption. The Figure 4-1 below shows the predicted optimized power purchase for the **K45 building (Average U-value 0.458 W/m^{2}K and Air change rate = 1.8)**

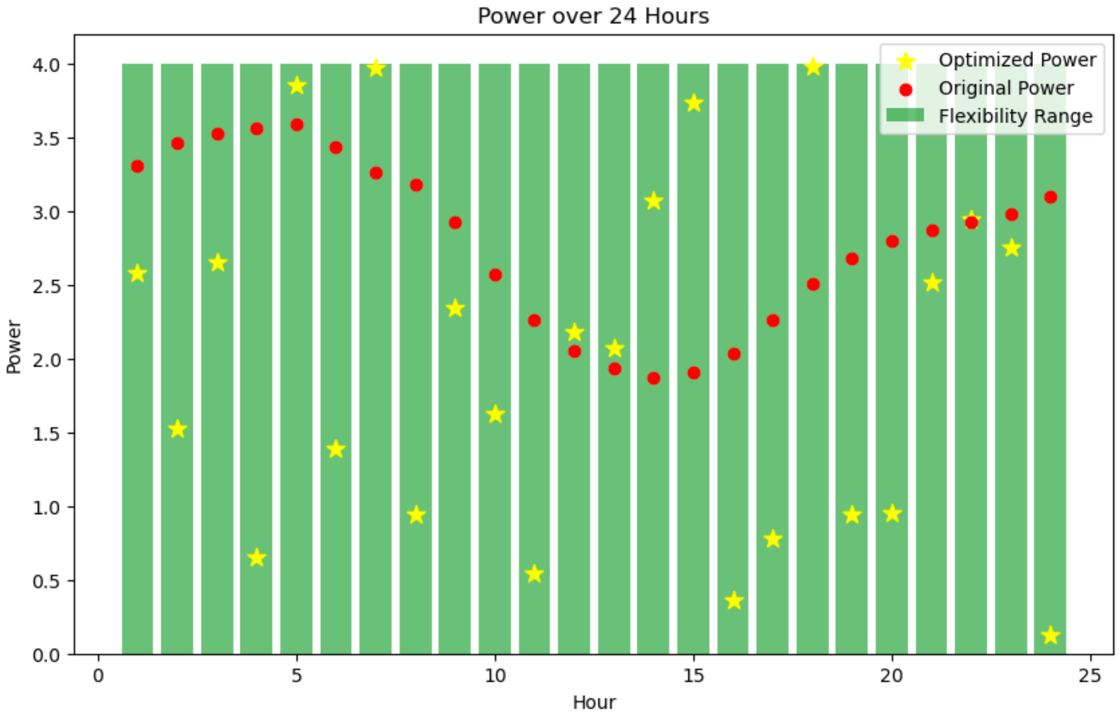


Figure 4-1: Optimized Power Purchase vs Baseline consumption for K45 building.

As observed from the plot above, the green bars represent total flexibility for every hour, the yellow marks show the optimized power purchase, and the red marks indicate the baseline heat pump consumption set to keep the room at 20°*C.* The difference between the yellow and red marks shows the profitability to shift power consumption to low prices period. For example, in hour 8, the optimal power consumption is approximately 1kW, against the baseline consumption set at approximately 3.2kW. The maximum possible consumption is 4kW which is the maximum capacity if the heat pump.

The Figure 4-2 shows the predicted optimized power purchase for the **K15 building (Average U-value 0.152 W/m^{2}K & Air change rate 0.6)**

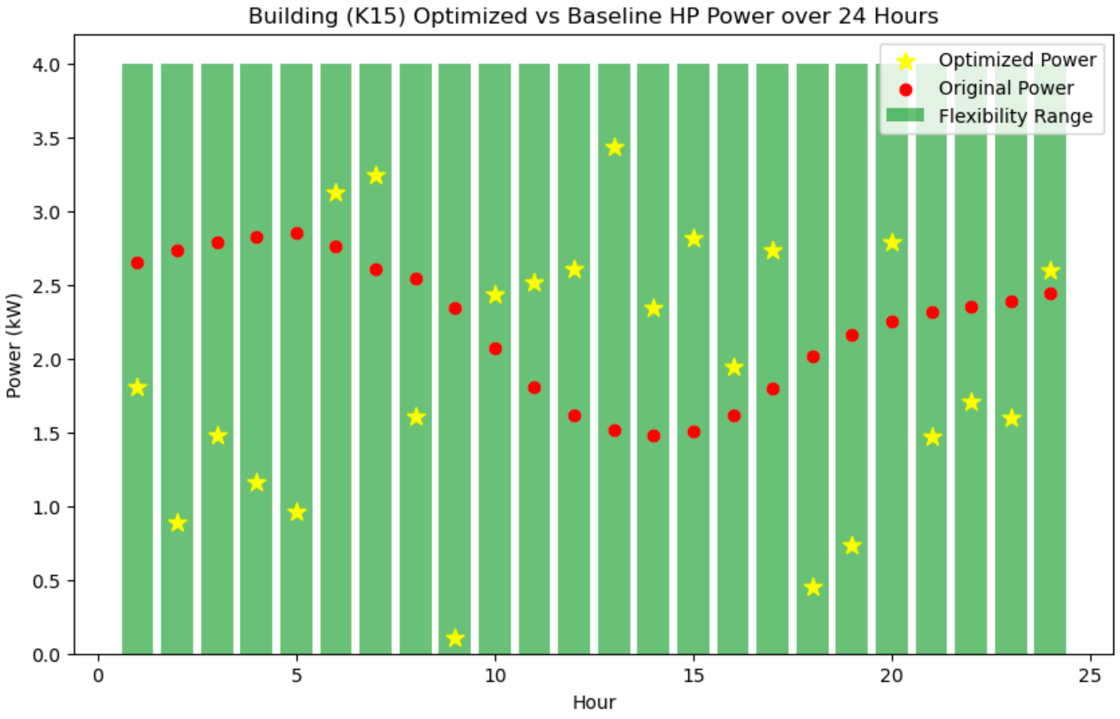


Figure 4-2: Building (K15) Optimized vs Baseline HP power over 24 hours.

A similar thread is observed in the simulation for K15 Buildings. E.g., at hour 8, the optimal heat pump consumption is approximately 1.8kW while the baseline for comparison is set at approximately 2.5kW. It is important to note that the use of possible flexibility in one hour influence the need and possible variation of energy use in neighbouring hours.

4.2. Cost Efficiency due to HP Power Optimization

The results for the optimization of the heat pump power at every hour demonstrated positive economic impact on the operation of the heat pump without sacrificing the thermal comfort when compared to the baseline scenario. The table delineates the detailed power costs comparisons for each building types to quantify the overall savings. While the total cost savings for both individual building types are not significant enough to impact grid operations, when scaled to a larger number of buildings - such as in a residential complex or a city scale - the overall savings can be substantial and can provide flexibility to the grid over different timescales.

This study's focus is on demonstrating the practical value of the genetic algorithm as a tool for energy and cost optimization in various types of built environments to offer flexibility. Figure 4-3 shows the relative difference for the two buildings costs savings compared to baseline consumption.

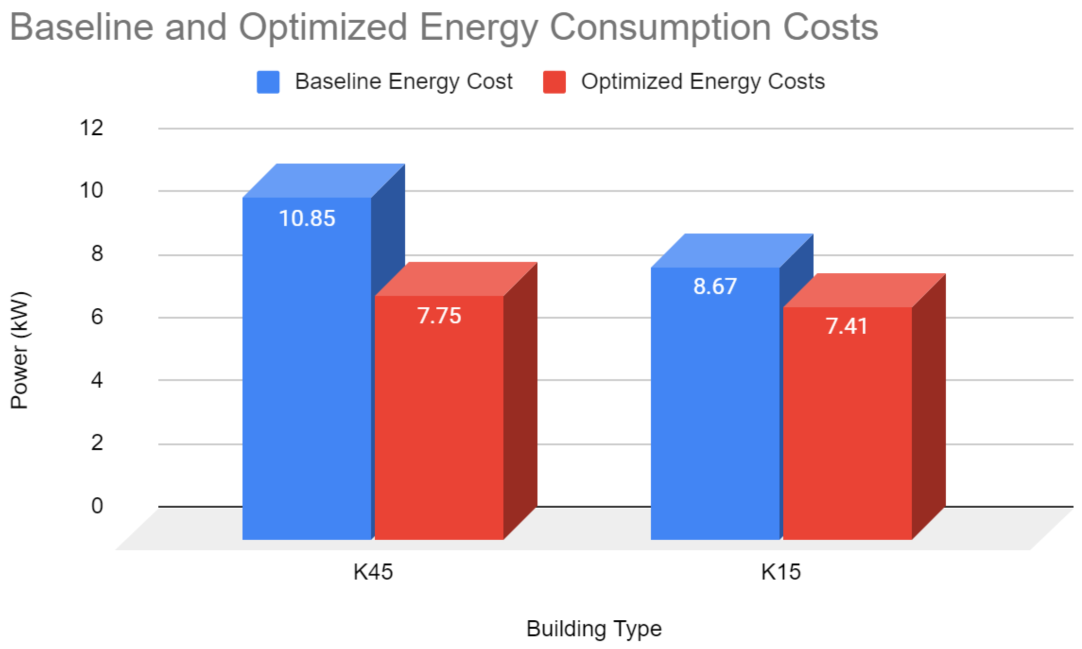


Figure 4-3: Energy costs (Baseline vs Optimized consumption)

Building Type	Total Energy saved (kWh)	Baseline Total Costs (€)	Optimized Energy costs (€)	Total Cost savings (€)	Savings compared to baseline (%)
K45	18.52	10.85	7.75	3.1	28.56 %
K15	6.88	8.67	7.41	1.26	14.52 %

Table 4: Energy and Costs savings for Typical day (24 hours)

As observed, the results show a higher savings for the K45 building insulation level compared to the K15 building studied.

4.3. Thermal Comfort Maintenance

The variations in room temperature in response to the optimized usage of the heat pump are in both building types are depicted in Figure 4-4 and Figure 4-5 for the Building K45 and K15 respectively.

Building K45

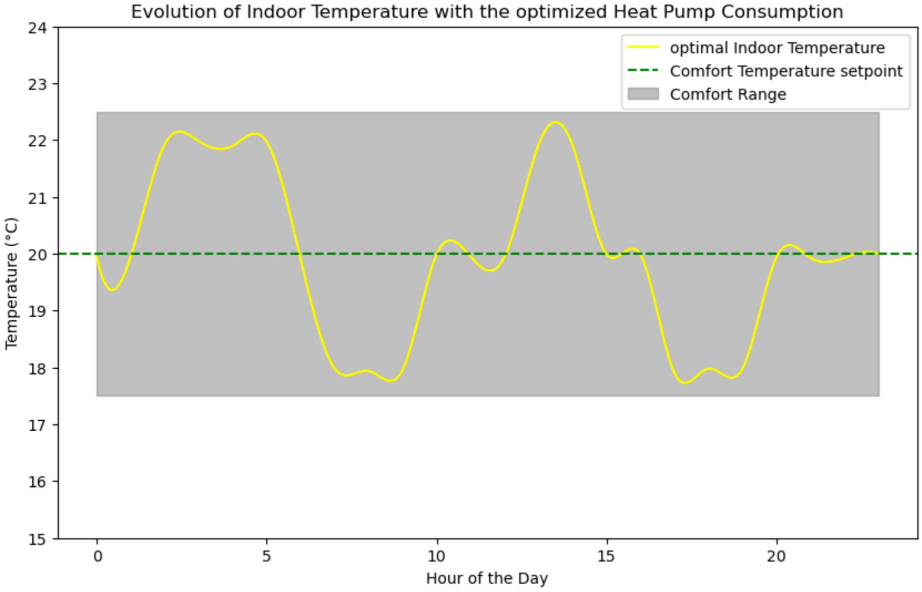


Figure 4-4: Building (K45) room temperature evolution over 24 hours based on optimized HP power.

The yellow lines represent the predicted fluctuations in the room's temperature over the course of the simulation. Upon examination, it becomes apparent that the predicted room temperature aligns with the comfort criteria predefined for the experiment, thereby affirming the effective optimization of the heat pump operation. This pattern of indoor thermal regulation always ensures a satisfactory level of comfort, validating the purpose of the algorithm in maintaining thermal comfort.

An elevation in room temperatures during morning and mid-day hours is observed. This phenomenon can be potentially attributed to the lower electricity rates prevalent during these periods. In comparing the temperature profiles of the two building types under investigation, a striking similarity is observed despite each having distinct hourly evolutions of optimized power. This could be due to the minor relative differences in the total heating load demand and heat pump consumption over the 24-hour simulation period. It is thus possible that the relatively short simulation period does not provide sufficient temporal scope to discern significant differences. To address this, further investigations is needed.

Building K15

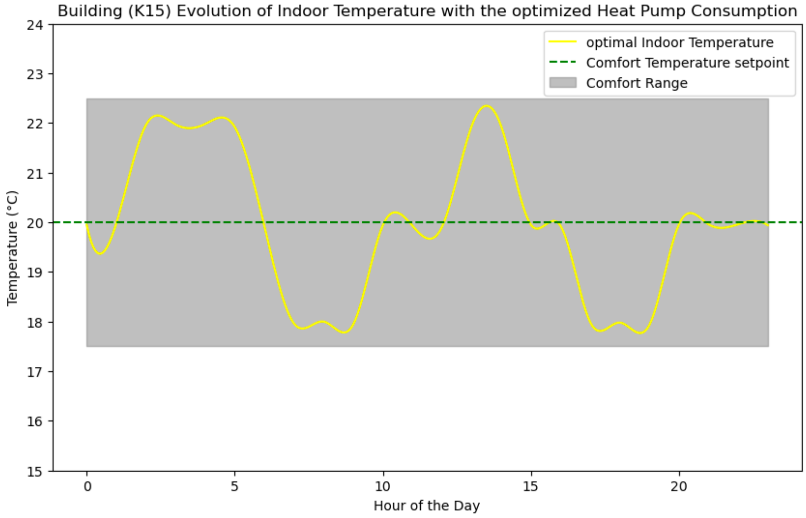


Figure 4-5: Building (K15) room temperature evolution over 24 hours based on optimized HP power.

4.4. Peak Shavings (Demand Response Event)

The main aim for demand response (DR) as stated in literature review is the potential to contribute to grid flexibility by reducing consumption in peak demand periods. The optimal schedule for the heat pump consumption was tailored to reduce consumption in those periods. Peak demand period in this study is categorized as periods where the electricity power prices as defined by the day-ahead market is above the 75th percentile for price of that day.

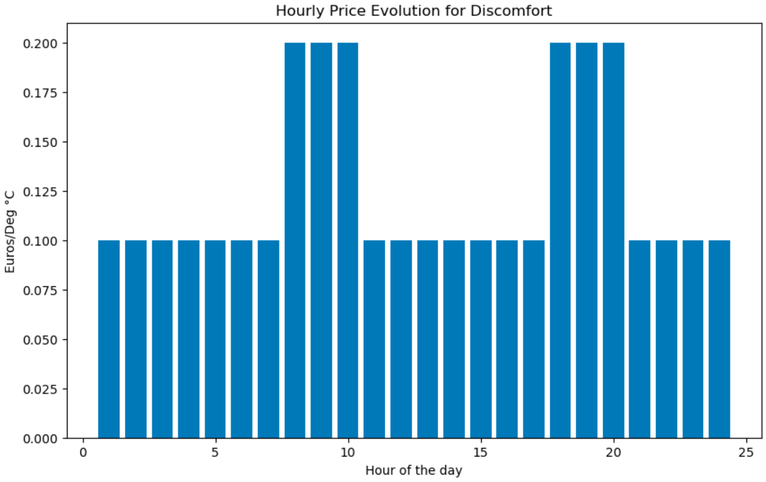


Figure 4-6: Hourly Discomfort weight evolution

A discomfort weight factor to penalize the purchase of power in these periods is included in the algorithm model. The Figure 4-6 shows the influence of this strategy on peak reduction, for this result a weight factor of ratio (2:1) is used i.e., it is twice more costly to use heat pump in the peak demand period than in off-peak ones.

Building Type	Number of DR Events (Hours)	Baseline Peak Demand (kWh)	Optimized Peak Power (kWh)	Peak Savings (kWh)	Peak savings compared to baseline (%)
K45	6	16.66	10.78	5.88 kWh	35.28 %
K15	6	13.39	8.11	5.28 kWh	39.41%

Table 5: Demand Response (Peak Shavings) quantified.

Figure 4-7 shows the relative difference between the peak shavings as observed in both buildings simulated. As observed from the results, the building with K15 insulation level shows the most potential for peak demand shavings.

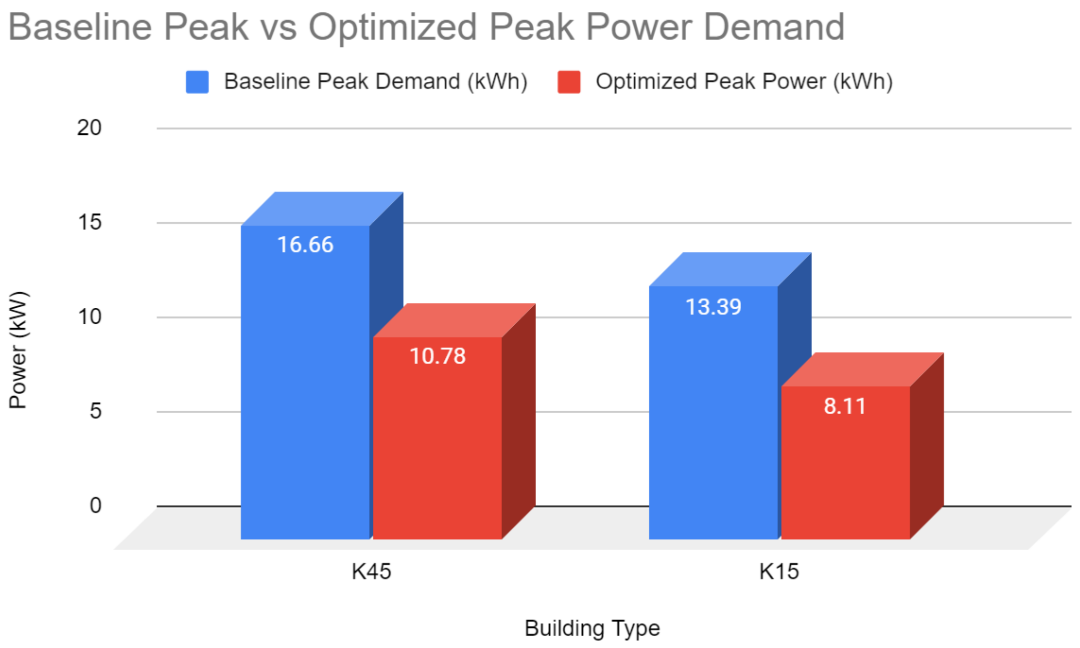


Figure 4-7: Peak Demand (Baseline vs Optimized Power)

4.5. Heat Pump Overconsumption

While the heat pump consumption is closely linked to thermal comfort maintenance and cost savings, there is a negative effect of the optimization strategy to shave peak demand by increasing usage in off-peak periods to compensate for the lower temperature setpoints in the peak demand periods. This is defined as periods with room temperature raised above the 20°C reference comfort level and compared with the baseline power consumption for the heat pump set to this normal temperature at all hours of the day.

The equation to quantify the overconsumption of HP power is given as:

$$\begin{aligned}
&Diff = O_{HP} - B_{HP} \\
&O_{indices} = \{i : O_{HP}[i] > B_{HP}\ [i] for\ i\ in\ (24\ hours)\} \\
&D_O = \{Diff[i]\ for\ all\ i\ in\ (O_{indices})\} \\
&H_O = abs|O_{indices}| \\
&P_O = \sum \frac{\sum(D_O)}{\sum(B_{HP}[i]\ for\ all\ i\ in\ (O_{indices})} * 100
\end{aligned}$$

- O_{HP} represent the optimized heat pump power output array,
- B_{HP} represent the initial (baseline) heat pump power output array set for consumption to maintain temperature at 20°C,
- $O_{indices}$ represent the indices where the optimized power is greater than the initial power,
- D_O represent the difference in power at the O_i (overconsumption_difference),
- H_O represent the number of hours of over consumption (overconsumption_hours)
- P_O represent the percentage of overconsumption (overconsumption percentage)

Here, $|O_{indices}|$ represents the cardinality of the set, or the number of elements in the set, which corresponds to the number of hours of over consumption.

Finally, upon observation of the results even though the overall costs in terms of power purchase is reduced, the heat pump overconsumption at off-peak hours results in some energy losses even negative savings due to increased use of heat pump. The results obtained are quantified as follows:

Building Type	**Over Consumption (No. Of Hours)**	**Total overconsumed (kWh)**	**Overconsumption as Percentage of baseline consumption (%)**
K45	8	5.73 kWh	28.64 %
K15	12	9.13 kWh	38.89%

Table 6: Heat pump overconsumption in off-peak hours

Figure 4-8 below shows the periods where the optimized power of the exceeds the baseline consumption of the heat pump set to keep room at 20°C at every hour.

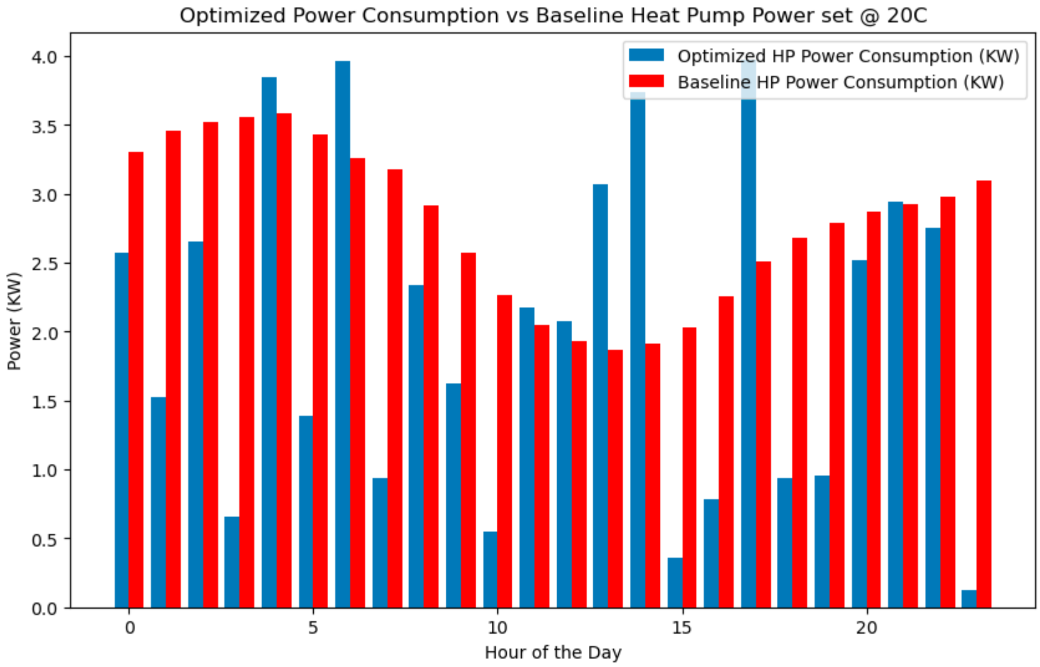


Figure 4-8: Building (K45) plot result for optimized vs baseline consumption

The blue bars represent the optimized heat pump consumption, and the red bars represents the baseline consumption. For the Building (K45) the hours where the optimized power consumptions go above the initial calculated amount to keep room at baseline comfort levels are identified at [4, 6, 11, 12, 13, 14, 17, 21] hours respectively.

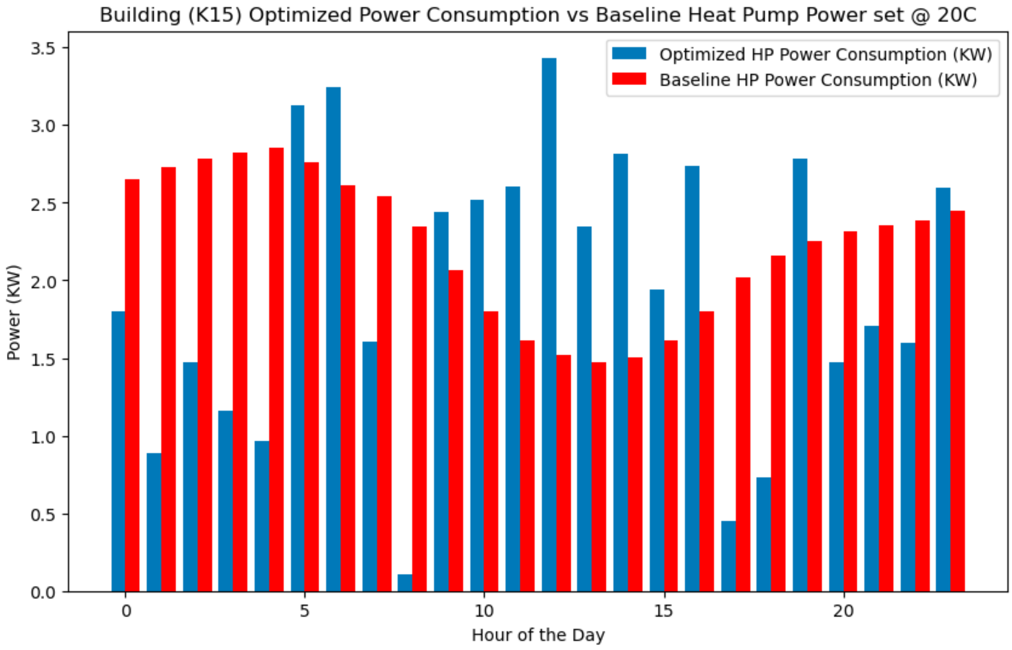


Figure 4-9: Building (K15) plot result for optimized vs baseline consumption

Figure 4-9 shows results for the Building (K15) the hours where the optimized power consumptions go above the initial calculated amount to keep room at baseline comfort levels are identified at [5, 6, 9, 10, 11, 12, 13, 14, 15, 16, 19, 23] hours respectively.

It is observed from the simulation results that the building with K15 insulation levels showed more potential with shaving off peak demand however this led to overconsumption at more hours of the day when compared with the baseline operation. And the opposite is observed for the building with K45 insulation levels, as it showed a smaller number of hours with overconsumption compared to the baseline operation.

Finally, while both building types, overconsumed at several hours over the simulation duration, the thermal comfort specification was met at all hours of the day and overall power consumption reduced compared to the baseline operation.

4.6. Discussion of the optimization results

This study included a dynamic simulation of temperature shifts within a building, using a strategy of numerical calculations for the energy balance of heat gains and losses, and the impacts of human activity as defined by the occupancy pattern. Focusing on a winter scenario set for February 2020, this generated a detailed thermal load profile, which the heat pump was required to supply for both **K45** and **K15** buildings, each with a **180m^2** floor area. The energy simulations results showed a daily heating load demand of roughly **234.9 kWh** and **204.6 kWh** respectively, indicating a **13%** disparity in total heating energy demand - a variance primarily attributable to the difference in insulation levels. Using the product manufacturer’s specified COP for the heat pump, and held constant for this analysis, the electrical power demands for the heat pump were estimated to be **61.3 kWh and 53.4 kWh for each building type**.

For the Demand Response implementation, the **DEAP genetic algorithm package, Python-based** and highly efficient, was employed to optimize the heat pump consumption across the two insulation cases, simulating their roles in price-based demand response programs, guided by day-ahead electricity pricing. An integral constraint, designed to maintain the thermal comfort and denoted by a constant room temperature of 20 °C with an acceptable operational range of +/- 2 °C, was effectively observed across the entire simulation period.

In both building types, a trend of overheating to the upper constraint limit of 22 °C was apparent during mornings and mid-day. This likely denotes the algorithm's strategic response to lower off-peak pricing. The optimization process yielded a **total cost savings of 28.56% and 14.52% for the K45 and K15 insulated** buildings respectively, attributable to the optimized scheduling of heat pump consumption. In relation to demand response events defined as peak price periods, the **K15 insulated building demonstrated a superior peak shaving of 39.41%, compared to the 35.28% achieved by the K45 insulation level.**

Conclusively, while both building types showcased promising capabilities to shift energy consumption to off-peak periods and maintain defined thermal comfort ranges, instances of overconsumption were evident. This was driven by the algorithm's bias towards optimization during periods of lower electricity costs and the thermal inertia because of the buildings' insulation levels acting as storage.

4.7. Sustainability and Environmental Impact

The optimization of the heat pump power compared to the baseline operation as presented in this study showcases the potential for significant reductions in energy consumption across both building insulation types. However, the corresponding environmental impact of this reduction is not as straightforward to ascertain, as it is linked with the energy mix powering the electricity grid at the specific time of use. Therefore, while heat pumps can reduce overall heating demand, they can also induce a surge in electricity demand through overconsumption at off-peak periods as maybe defined Additionally, the operational flexibility as simulated in this study allows for enhanced integration of variable renewable energy sources into the grid, further contributing to the mitigation of greenhouse gas emissions.

The potential benefits notwithstanding, certain aspects warrant further consideration, because the material resources employed in the manufacturing of heat pumps and their end-of-life disposal or recycling are areas of environmental concern. However, these impacts are usually offset by the potential emission savings across the full lifetime operation of the heat pump, particularly when the operation is optimized as proposed in this study. In summary, the strategic use and management of heat pumps, especially through optimized operational algorithms, can play a significant role in advancing energy efficiency and sustainability within the built environment.

5. CONCLUSIONS

This thesis work analyzed the potential role of heat pumps in demand response (DR) programs to provide grid flexibility without sacrificing thermal comfort, and within the context of residential buildings in Belgium, specifically focusing on varying levels of insulation as thermal mass for storage. The key challenge addressed was the necessity to optimize energy consumption patterns to align with day-ahead pricing signals without compromising the thermal comfort of the building occupants.

The study introduced a novel approach by considering the thermal mass of the two building types (K15 and K45) within the Belgian residential building sector and deployed a genetic algorithm for optimizing the operation of the heat pumps. The uniqueness of the research lies not just in the amalgamation of these two elements, but also in the methodical application within the Belgian residential buildings' context.

Our key findings demonstrate that, for a winter scenario set for February 2020, the daily heating load demand for K45 and K15 buildings, both with a 180m^2 floor area, were approximately 234.9 kWh and 204.6 kWh respectively. This 13% discrepancy in heating energy demand primarily resulted from the buildings' different insulation levels. Furthermore, optimization led to reduction in peak demand use of heat pumps and considerable cost savings, with a reduction of 28.56% for the K45 building and 14.52% for the K15 building, reflecting the benefits of optimized scheduling of heat pump operation. In terms of implications, these findings shed light on how intelligent optimization algorithms can significantly contribute to shifting the peak energy demand to off-peak periods. As such, they provide valuable insights into how DR programs could be improved by incorporating heat pump operations.

However, the study was not without limitations. The lack of empirical data to validate the building's energy model and limited computational power to extend the simulation over a longer period are challenges that future research can aim to address. An exciting potential direction for future research could be the integration of relative humidity with room temperature to measure comfort levels, and the examination of different temperature setpoints for comfort as a strategy to check for optimal scheduling of heat pump operations. Furthermore, considering an economic comparison of a thermal storage tank integrated into the building system could also provide insights into the feasibility and economic efficiency of this option.

In summary, this research highlights the potential of heat pump operation optimization in DR programs to provide grid flexibility. The findings suggest that substantial energy could be shifted away from peak demand periods without significant sacrifice of occupants' thermal comfort, creating new pathways for the enhancement of energy efficiency and sustainable practices within the residential sector.

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7. Bibliography

References

[1] 'EEA greenhouse gases — data viewer — European Environment Agency'. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (accessed Jun. 26, 2023).

[2] S. Hafner, A. Jones, and A. Anger-Kraavi, 'Economic impacts of achieving a net-zero emissions target in the power sector', *J. Clean. Prod.*, vol. 312, p. 127610, Aug. 2021, doi: 10.1016/j.jclepro.2021.127610.

[3] 'Research, Development and Innovation Reports'. https://www.entsoe.eu/publications/research-and-development/#position-papers-and-technical-reports (accessed Jun. 26, 2023).

[4] *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)*, vol. 153. 2010. Accessed: Jun. 26, 2023. [Online]. Available: http://data.europa.eu/eli/dir/2010/31/oj/eng

[5] H. Cappelle, 'Energy balance of Belgium for 2018'. https://energy.at-site.be/eurostat-2021/EU/Belgium/?year=2018 (accessed Jun. 26, 2023).

[6] 'Energy consumption in households'. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households (accessed Jun. 26, 2023).

[7] J. Staab, *Erneuerbare Energien in Kommunen*. Wiesbaden: Springer Fachmedien Wiesbaden, 2018. doi: 10.1007/978-3-658-19907-4.

[8] B. V. Mathiesen *et al.*, 'Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy', Aalborg Universitet, Report, Dec. 2019.

[9] 'REPowerEU', *European Commission - European Commission*. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131 (accessed Jun. 26, 2023).

[10] 'ENTSO-E Vision: A Power System for a Carbon Neutral Europe'. https://vision.entsoe.eu/ (accessed Jun. 26, 2023).

[11] Y.-K. Wu, Y.-H. Li, and Y.-Z. Wu, 'Overview of power system flexibility in a high penetration of renewable energy system', in *2018 IEEE International Conference on Applied System Invention (ICASI)*, Chiba: IEEE, Apr. 2018, pp. 1137–1140. doi: 10.1109/ICASI.2018.8394484.

[12] E. Wurtz and International Building Performance Simulation Association, Eds., *13th International Conference of the International Building Performance Simulation Association (Building Simulation 2013): Chambery, France, 25-28 August 2013*. Red Hook, NY: Curran Associates, Inc, 2014.

[13] R. D'hulst, W. Labeeuw, B. Beusen, S. Claessens, G. Deconinck, and K. Vanthournout,

'Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in Belgium', *Appl. Energy*, vol. 155, pp. 79–90, Oct. 2015, doi: 10.1016/j.apenergy.2015.05.101.

[14] 'IEA (2022), The Future of Heat Pumps, IEA, Paris'. [Online]. Available: https://www.iea.org/reports/the-future-of-heat-pumps, License: CC BY 4.0

[15] 'SEDC Report 2017: Explicit Demand Response in Europe – Mapping the Markets | ETIP SNET'. https://smart-networks-energy-transition.ec.europa.eu/news/sedc-report-2017-explicit-demand-response-europe-mapping-markets (accessed Jun. 26, 2023).

[16] 'ENTSO-E Transparency Platform'. https://transparency.entsoe.eu/dashboard/show (accessed Jun. 26, 2023).

[17] L. Romero Rodríguez, J. Sánchez Ramos, S. Álvarez Domínguez, and U. Eicker, 'Contributions of heat pumps to demand response: A case study of a plus-energy dwelling', *Appl. Energy*, vol. 214, pp. 191–204, Mar. 2018, doi: 10.1016/j.apenergy.2018.01.086.

[18] 'Renewable Energy for self-sustAinable island CommuniTies | REACT | Project | Fact sheet | H2020 | CORDIS | European Commission'. https://cordis.europa.eu/project/id/824395 (accessed Jun. 26, 2023).

[19] M. E. Corporation, 'Demand-response Demonstration Experiment with Heat Pumps Begins under EU', *MITSUBISHI ELECTRIC EMEA*. https://emea.mitsubishielectric.com/en/news/releases/global/2023/0531-a/index.page (accessed Jun. 26, 2023).

[20] 'O.2.4.4 A fully operational virtual energy storage network providing flexibility for the power system', *HPT - Heat Pumping Technologies*. https://heatpumpingtechnologies.org/publications/o-2-4-4-a-fully-operational-virtual-energy-storage-network-providing-flexibility-for-the-power-system/ (accessed Jun. 26, 2023).

[21] 'Solution: Room Temperature Programming - tiko Energy'. https://tiko.energy/solution-room-temperature-programming/ (accessed Jun. 26, 2023).

[22] 'Brussels Exemplary Buildings Program + Passive House Law of 2011 – Building Innovations'. https://www.buildinginnovations.org/policy/brussels-exemplary-buildings-program-passive-house-law-of-2011/ (accessed Jun. 26, 2023).

[23] 'Concerted Action EPBD', *epbd-ca.eu*. https://epbd-ca.eu/home (accessed Jun. 26, 2023).

[24] S. Gendebien, E. Georges, S. Bertagnolio, and V. Lemort, 'Methodology to characterize a residential building stock using a bottom-up approach: a case study applied to Belgium', *Int. J. Sustain. Energy Plan. Manag.*, pp. 71-88 Pages, Feb. 2015, doi: 10.5278/IJSEPM.2014.4.7.

[25] J. F. Nicol and M. Wilson, 'A critique of European Standard EN 15251: strengths, weaknesses and lessons for future standards', *Build. Res. Inf.*, vol. 39, no. 2, pp. 183–193, Apr. 2011, doi: 10.1080/09613218.2011.556824.

[26] 'JRC Photovoltaic Geographical Information System (PVGIS) - European Commission'.

https://re.jrc.ec.europa.eu/pvg_tools/en/ (accessed Jun. 26, 2023).

[27] ‘Calcula solares órbita azimute e zênite’. http://www.solartopo.com/posicao-do-sol.htm (accessed Jun. 26, 2023).

[28] R. Judkoff, B. Polly, M. Bianchi, and J. Neymark, ‘Building Energy Simulation Test for Existing Homes (BESTEST-EX) Methodology: Preprint’, NREL/CP-5500-51655, 1029029, Nov. 2011. doi: 10.2172/1029029.

[29] H. Ebadi-Dehaghani and M. Nazempour, ‘Thermal Conductivity of Nanoparticles Filled Polymers’, in *Smart Nanoparticles Technology*, A. Hashim, Ed., InTech, 2012. doi: 10.5772/33842.

[30] J. Nam, H.-S. Ryou, D.-J. Kim, S.-W. Kim, J.-S. Nam, and S. Cho, ‘Experimental and Numerical Studies on the Failure of Curtain Wall Double Glazed for Radiation Effect’, *Fire Sci. Eng.*, vol. 29, no. 6, pp. 40–44, Dec. 2015, doi: 10.7731/KIFSE.2015.29.6.040.

[31] G. Kokogiannakis, J. Darkwa, and C. Aloisio, ‘Simulating Thermochromic and Heat Mirror Glazing Systems in Hot and Cold Climates’, *Energy Procedia*, vol. 62, pp. 22–31, 2014, doi: 10.1016/j.egypro.2014.12.363.

[32] T. L. Bergman and F. P. Incropera, Eds., *Fundamentals of heat and mass transfer*, 7th ed. Hoboken, NJ: Wiley, 2011.

[33] H. Suehrcke, E. L. Peterson, and N. Selby, ‘Effect of roof solar reflectance on the building heat gain in a hot climate’, *Energy Build.*, vol. 40, no. 12, pp. 2224–2235, Jan. 2008, doi: 10.1016/j.enbuild.2008.06.015.

[34] A. Mukhtar, K. C. Ng, and M. Z. Yusoff, ‘Design optimization for ventilation shafts of naturally-ventilated underground shelters for improvement of ventilation rate and thermal comfort’, *Renew. Energy*, vol. 115, pp. 183–198, Jan. 2018, doi: 10.1016/j.renene.2017.08.051.

[35] M. T. Mustafa, A. F. M. Arif, and K. Masood, ‘Approximate Analytic Solutions of Transient Nonlinear Heat Conduction with Temperature-Dependent Thermal Diffusivity’, *Abstr. Appl. Anal.*, vol. 2014, pp. 1–12, 2014, doi: 10.1155/2014/423421.

[36] M. García-Fuente, D. González-Peña, and C. Alonso-Tristán, ‘A Numerical Simulation of an Experimental Melting Process of a Phase-Change Material without Convective Flows’, *Appl. Sci.*, vol. 12, no. 7, p. 3640, Apr. 2022, doi: 10.3390/app12073640.

[37] E. Halawa and J. Van Hoof, ‘The adaptive approach to thermal comfort: A critical overview’, *Energy Build.*, vol. 51, pp. 101–110, Aug. 2012, doi: 10.1016/j.enbuild.2012.04.011.

[38] E. W. Shaw, ‘Thermal Comfort: analysis and applications in environmental engineering, by P. O. Fanger. 244 pp. DANISH TECHNICAL PRESS. Copenhagen, Denmark, 1970. Danish Kr. 76, 50’, *R. Soc. Health J.*, vol. 92, no. 3, pp. 164–164, Jun. 1972, doi: 10.1177/146642407209200337.

[39] ‘CAIROX BELGIUM’. https://www.cairox.be/EN/documentation/J01.800.3G-R-AQUA-CGW-ID-A1-A2W-heat-pumps-R32-with-DHW-heater/?cf=298659965b10ba62987c16 (accessed Jun. 26, 2023).

[40] D. Fischer and H. Madani, 'On heat pumps in smart grids: A review', *Renew. Sustain. Energy Rev.*, vol. 70, pp. 342–357, Apr. 2017, doi: 10.1016/j.rser.2016.11.182.

[41] *Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast) (Text with EEA relevance.)*, vol. 158. 2019. Accessed: Jun. 26, 2023. [Online]. Available: http://data.europa.eu/eli/reg/2019/943/oj/eng

[42] 'DEAP documentation — DEAP 1.3.3 documentation'. https://deap.readthedocs.io/en/master/ (accessed Jun. 26, 2023).

Appendix I – Building Elements' Composition

Element	Material (from external to internal)	Thickness
Floor	Concrete	120 [mm]
Roof	Steel sheet	1 [mm]
	Polyethylene sheet	25 [mm]
	Rock wool	80 [mm]
	Steel sheet	0.6 [mm]
Walls 2 and 4	Laminated glass	20 [mm]
	Low emissivity glass	8 [mm]
	Air layer	12 [mm]
	Low emissivity glass	12 [mm]
Walls 1 and 3	Laminated glass	20 [mm]
	Low emissivity glass	8 [mm]
	Low emissivity glass	12 [mm]

Appendix II – Timestep Calculation

Building Element	Diffusion Time [min]
Wall 1	15.74
Wall 2	15.85
Wall 3	15.74
Wall 4	15.85
Floor	242.18
Roof	4893.80