MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

# MODELING, VALIDATION AND SUSTAINABILITY ASSESSMENT OF SELECTED DISTRICT ENERGY SYSTEMS

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Director: Amedeo Ceruti

Múnich

Mayo de 2024

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# Resumen

La enorme contribución de las zonas urbanas a las emisiones de gases de efecto invernadero urge a desarrollar medidas de eficiencia energética para reducir estas emisiones. La modelización energética de edificios urbanos es una forma de modelizar cómo afectan a la demanda de energía estas medidas y la interacción entre los edificios de un distrito. El objetivo de este proyecto es modelizar y validar la demanda energética en edificios de zonas seleccionadas de Alemania.

Para ello, se modelizará una vivienda multifamiliar de dos plantas de la década de 1970. Su entorno estará formado por 4 edificios de aproximadamente las mismas dimensiones, cada uno frente a una de las fachadas del edificio. El programa de modelización energética de edificios urbanos que se utilizará para la modelización es City Energy Analyst. Este edificio estará situado en una pequeña ciudad del sur de Alemania. Esto implica que los datos meteorológicos para la simulación serán de esta zona.

En primer lugar, se alterarán algunos parámetros de la envolvente de la vivienda multifamiliar para explorar cómo afectan estos parámetros a la demanda de energía. Estos parámetros incluyen la adición de un sótano, con y sin calefacción, reformas normales y avanzadas, el cambio de la relación ventana-pared de las 4 fachadas, el cambio de la capacidad calorífica interna, la alteración de la estanqueidad del edificio y el sombreado. Para todos estos escenarios se comparará el consumo de electricidad, la demanda de calefacción, la demanda de agua caliente y la demanda total de energía para calefacción con la del caso base. Los resultados también se compararán con los de otros estudios similares, si están disponibles.

A continuación, se modificarán algunos parámetros de confort de la misma vivienda multifamiliar para comprobar su impacto en la demanda energética. Se trata de la densidad de ocupación, es decir, el número de $m^2$ por persona, las temperaturas de consigna y de retroceso del sistema de calefacción y los horarios de estas temperaturas. Al igual que en el caso de los parámetros de la envolvente, se compararán con el caso base y los resultados se evaluarán con arreglo a las conclusiones de otros estudios.

Además, una vez realizadas las simulaciones para la vivienda multifamiliar y analizado por separado el efecto de los parámetros en la demanda energética, se llevará a cabo una simulación con varios edificios residenciales de una pequeña ciudad del sur de Alemania. Las tipologías de los edificios son viviendas unifamiliares, adosadas, multifamiliares o bloques de apartamentos, que abarcan desde finales del siglo XIX hasta 2015. La demanda energética de estos edificios se modelizará y se comparará con los datos de consumo reales de la zona. Tras la simulación para los edificios residenciales de la zona, se realizará otra simulación para los edificios no residenciales de la misma zona. Existen muchos trabajos que realizan un análisis de sensibilidad para diferentes características de los edificios, tanto de la envolvente como de los parámetros de confort. Sin embargo, no hay muchos que validen estos análisis con datos reales de consumo.

Finalmente, se ejecutará un Análisis de Ciclo de Vida general para los casos explorados. City Energy Analyst dispone de una herramienta para calcular el Análisis del Ciclo de Vida de un escenario. Sin embargo, los parámetros necesarios para llevarlo a cabo correctamente no son completamente fiables. Por lo tanto, sólo se explorará brevemente.

# Abstract

The enormous contribution of urban areas to greenhouse gas emissions urges the development of energy-efficiency measures to reduce these emissions. Urban building energy modelling is a way to model how these measures and the interaction between buildings in a district affect energy demand. This project's objective is to model and validate energy demand in buildings of selected areas in Germany.

In order to do so, one two-story multi-family home from the 1970s will be modelled. Its surroundings will consist of 4 buildings of approximately the same dimensions, each one in front of one of the building's façades. The urban building energy modelling program which will be used for the modelling is City Energy Analyst. This building will be located in a small city in South Germany. This implies that the weather data for the simulation will be from this area.

Firstly, some of the multi-family home's envelope parameters will be altered to explore how these parameters affect energy demand. These parameters include adding a cellar, with and without heating, normal and advanced renovations, changing the window to wall ratio of the 4 façades, changing the internal heat capacity, altering the tightness of the building, and the shading. For all these scenarios their electricity consumption, space heating demand, hot water demand, and total energy demand for heating will be compared to that of the base case. The results will also be assessed with existing papers, which investigate similar subjects, if available.

Next, for the same multi-family home, some of its comfort parameters will be modified to test how they impact energy demand. These will include occupancy density, which is the number of $m^2$ per person, the setpoint and setback temperatures of the heating system, and the schedules of these temperatures. Just as for the envelope parameter scenarios, these will be compared to the base case and the results will also be evaluated by other paper's findings.

Moreover, once the simulations have been done for the multi-family home and the effect of the parameters on energy demand have been separately analyzed, a simulation with several residential buildings in a small city in South Germany will be carried out. The buildings' typologies are single-family homes, terraced houses, multi-family homes, or apartment blocks, ranging from the late 1800s up to 2015. The energy demand for these will be modelled and compared to real consumption data from the area. After the simulation for the residential buildings of the area, another simulation for the non-residential buildings of the same area will be performed. There are many existing papers that carry out a sensitivity analysis for different building characteristics, both envelope and comfort parameters. However, there are not many that validate these analyses with real consumption data.

Finally, a general Life Cycle Analysis for the explored cases will be executed. City Energy Analyst has a tool to calculate the Life Cycle Analysis of a scenario. Nevertheless, the parameters required to properly conduct it are not completely reliable and the exact calculation of the Life Cycle Analysis for every scenario falls outside the scope of this Master Thesis. Therefore, this will only be briefly explored.

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# Abbreviations

| **Abbreviation** | **Meaning** |
|---|---|
| UBEM | Urban Building Energy Modelling |
| CEA | City Energy Analyst |
| GIS | Geographic Information System |
| HVAC | Heating, Ventilation and Air Conditioning |
| EFH | Single-family home |
| MFH | Multi-family home |
| TH | Terraced home |
| LCA | Life Cycle Assessment |

# 1 Introduction

## 1.1 Motivation

As we navigate an era of increasing environmental consciousness and pursue sustainable development goals, the importance of transitioning towards renewable and efficient energy systems is evident. In this context, investigating and optimizing district energy systems can become a crucial area of research. This master thesis aims to address the challenges of this investigation by modeling and validating the energy demand of selected German districts with open-source models and provide valuable insights to the field.

Urban areas contribute to more than 70% of the end-use energy in the world and more than 70% of greenhouse gas emissions [1]. This is due to the great increase in population there has been in the last century and the shift there has been from rural to urban areas. This trend will continue to grow exponentially, and with that, the energy demand will also increase dramatically, as shown in Figure 1. More specifically, the impact of heating in housing alone in the global greenhouse emissions is over 20% [2].

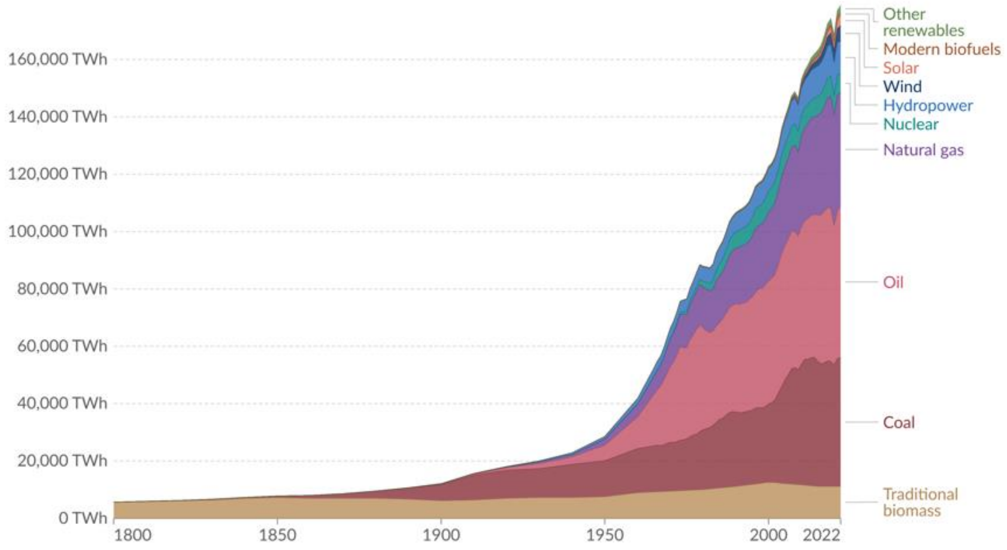

**Figure 1: Global primary energy consumption by source [2]**

The European Union has very ambitious net-zero emissions goals for the next decades. For instance, by the year 2030 there is a target of 40% reduction in greenhouse gas emissions compared to 1990. Renewable energies must also adopt a greater relevance in the final energy by increasing its share to at least 32% and energy consumption is required to decrease by 32,5% to improve energy efficiency [3]. This transition into renewable energy will also guarantee the energy access for all, given that, with the population growth previously mentioned, limited fossil fuel resources will not suffice to satisfy energy demand [4].

Particularly in the building sector, enhancing energy efficiency measures would be the most effective way to decarbonization. This includes implementing strong efficiency standards for new buildings, doubling the renovation rate of present infrastructure, and improving the refurbishment methods to achieve further energy demand reductions [5]. Data proving the effectiveness of these methods is limited and implementing some of these strategies, such as renovating a building, can be highly expensive. Therefore, it is important to make simulations.

This paper will carry out a sensitivity analysis for a multi-family home in Southern Germany by using a simulation tool for energy demand of buildings. It will also validate the results by comparing them to previous research. Furthermore, it will simulate the energy demand of a group of buildings in the same area as the multi-family home and contrast the results with real measured data from these buildings.

## 1.2 Outline of the Thesis

Firstly, chapter one is an introduction to the topic. It includes the motivation for this Master Thesis, the task, which briefly explains what is to be done in each section and how it will be carried out, and the outline, which summarizes the contents of each chapter.

Chapter two contains the state of art of the subject. In other words, it will describe the previous work there is on urban building energy models, and more specifically it will clarify what City Energy Analyst is and mention research that has been developed with its aid.

Furthermore, in chapter three, the methodology will be explained. This will include the databases and variables that the program uses, as well as the chosen scenarios for the sensitivity analysis.

Moreover, chapter four will display the results of the sensitivity analysis. It will also contain a case study for a small city in Southern Germany. The case study will compare the simulated results to real data.

In chapter five, the results of the previous chapter will be discussed. There will be a validation of these results with existing studies, which assess similar aspects. Recommendations for the future will also be made in this chapter.

Additionally, chapter six will address the life cycle assessment of a building. It will contain a concise explanation of scope emissions and life cycle assessments.

Finally, chapter seven will be the summary and outlook of the Master Thesis. It will sum up the most relevant points of the study and give recommendations of what could be done in the future.

# 2 State of Art

Buildings are responsible for 40% of the World’s energy consumption and the consequential carbon emissions [6]. Therefore, there is a pressing need to enhance energy efficiency in residential areas. Various methods, including renovating older buildings, implementing energy storage, transitioning to renewable energy sources, or adopting distributed generation, could contribute to achieving this goal. The successful implementation of these strategies requires a comprehensive understanding of a building's energy performance, which can be achieved by the use of top-down or bottom-up urban building energy models (UBEM).

Top-down energy models are successful in estimating a scenario where additional buildings of a particular type were constructed or converted into a different type, but they are less suitable for larger scales, where bottom-up models come into play [7]. Bottom-up models base its calculation on the individual energy consumption of each building [8].

Reinhart et al. [7] state in their paper that, for a building energy model of a neighborhood to be reliable, three steps need to be followed: data input, thermal modeling, and validation. The data input consists of weather data, the buildings’ geometry, the construction standard, and the use schedules. Thermal modeling varies, depending on the UBEM tool used. The simplest workflows take one building per archetype and scale it by either multiplying by the number of buildings per archetype or a function weighted by the floor area of the buildings. However, the problem with this method is that it does not take into account the fact that the surroundings of each building affect its performance. Finally, previous studies demonstrated that errors for simulated results compared to measured data range between 7% and 21% for heating loads and between 1% and 19% for total energy use.

City Energy Analyst (CEA) is a free, open-source tool, developed by a group of scientists from Zurich, which predicts energy demand in buildings. It started its development in 2013 and aims to analyze and optimize energy systems in city districts. What distinguishes City Energy Analyst from its predecessors is its incorporation of more detailed information on energy sources and consideration of attributes such as solar radiation, shading, surroundings, and the geometry and envelope of the building.

CEA uses a hybrid model, integrating both statistical and analytical models. It relies on several databases to facilitate its analyses. These include a weather database encompassing data on temperatures, humidity, and solar transmissivity. An urban Geographic Information System (GIS) database contains information on building characteristics such as area, height, window-to-wall ratio, construction year, and renovation history, along with details about their surroundings. Additionally, an archetypes database provides insights into the standard features of various building types, covering aspects like building envelopes, HVAC systems, and annual consumption. The distributions database includes schedules for occupancy, temperature and humidity setpoints in buildings, and minimum ventilation rates. Finally, a sensors database incorporates measured data essential for calculating energy services in non-standard buildings [9].

Many studies and estimations of future energy demand have been carried out using City Energy Analyst. For instance, Oraiopoulos et al. [10] estimated the future energy demand in a community in Switzerland. In order to do so, they considered various scenarios, including environmental scenarios, building retrofit strategies, in which different HVAC systems, envelope renovations, and operational situations were considered, as well as different urban development scenarios. This study concluded that the demand for cooling of non-residential buildings in urban and sub-urban communities will undergo the most significant impact due to climate change. Additionally, it suggests that the present rate of implementation of building retrofit strategies is insufficient to attain the targeted reduction in energy demand in Switzerland by the year 2050.

Another study by Geske et al. [11] explores how different input data, such as number of stories, heating setpoint, or U-values, impacts urban building energy modelling by modelling buildings from a small German town. Several scenarios were carried out, each one improving the precision of the similarity to reality. The results of the study concluded that with every scenario improving the information it contained, the heating demand decreased, getting closer to the real heating demand. However, the results for the electricity demand did not follow the same pattern. This is because, according to Mosteiro-Romero et al. [12],electricity demand is dependent on usage. Therefore, scenarios in which the usage was altered, by specifying the use-type of the buildings, changing the number of stories, or including vacancy information, for instance, electricity demand changed. However, in scenarios where only refurbishment was considered, for example, electricity demand remained the same.

Moreover, Mosteiro-Romero et al. [12] studied the effects of different input parameters on energy demand simulation. They took a sample of building in Zurich, Switzerland and quantified the effect each parameter had on heating and cooling demands. To do so, they firstly classified the buildings by occupation type, i.e. residential, office, hospital or education. Then, they classified the buildings by their envelope factor, which measures how much the building's envelope contributes to the heat loss of the building, and finally, they analyzed the spatial effects. They concluded overall that the greatest influence on space cooling demand was temperature setpoints and setbacks, whereas space heating was more affected by envelope characteristics.

# 3 Methodology

In this section, the databases and variables required to operate a simulation in City Energy Analyst will be stated and explained. Additionally, the scenarios for each case of the sensitivity analysis, as well as the decision-making process for these scenarios will be described in detail.

## 3.1 Variables

City Energy Analyst requires a series of variables from different databases in order to achieve a successful simulation of energy demand. The database used have been developed outside from CEA and later imported to the program to run the simulations. These variables will be explained in the following section.

Some of these variables will be altered in different scenarios throughout this study to analyze how sensible energy demand is to each of the changed variables.

Zone

This section refers to the dimensions of the buildings which are going to be analyzed. The variables which are included in the section “Zone” are the following:

- Floors_ag: Number of the building’s floors above ground
- Floors_bg: Number of the building’s floors below ground
- Height_ag: Height of the building above ground [m]
- Height_bg: Height of the building below ground [m]

Typology

The typology section clarifies what type of building is being studied, as well as the function it has. It includes the following variables:

- Year: Year of construction of the building
- Standard: Construction standard - code to identify the type of building and the year of construction
- 1st_use: What type of first use the building has, e.g. residential, hotel, office, school, etc.
- 1st_use_r: Fraction of gross floor area for the first use type
- 2nd_use: What type of second use the building has, e.g. residential, hotel, office, school, etc.
- 2nd_use_r: Fraction of gross floor area for the second use type
- 3rd_use: What type of third use the building has, e.g. residential, hotel, office, school, etc.

- 3rd_use_r: Fraction of gross floor area for the third use type

Architecture

The architecture section refers to the envelope characteristics of the building. It contains the following variables:

- Void deck: Number of floors with an open envelope
- Es: Fraction of gross floor area with demand of electricity
- Hs_ag: Fraction of gross floor area above ground with demand of air conditioning (heating and cooling)
- Hs_bg: Fraction of gross floor area below ground with demand of air conditioning (heating and cooling)
- Ns: Fraction of net floor area
- Wwr_north: Window-to-wall ratio in in the North-facing façade
- Wwr_east: Window-to-wall ratio in in the East-facing façade
- Wwr_south: Window-to-wall ratio in in the South-facing façade
- Wwr_west: Window-to-wall ratio in in the West-facing façade
- Type_cons: Type of construction assembly - code to identify the type of construction
    - Cm_Af: Internal heat capacity per unit of area [J/km$^2$]
- Type_leak: Tightness level assembly - code to identify the type of tightness
    - N50: Number of air exchanges per hour at a pressure of 50 Pa
- Type_roof: Roof construction assembly - code to identify the type of roof
    - U_roof: Thermal transmittance of the roof [W/m$^2$K]
    - A_roof: Solar absorption coefficient of the roof. Defined according to ISO 52016-1
    - E_roof: Emissivity of external surface of the roof. Defined according to ISO 52016-1
    - R_roof: Reflectance in the red spectrum of the roof. Defined according to ISO 52016-1
    - GHG_roof_kgCO2: Embodied emissions per m$^2$ of roof (entire building life cycle)
- Type_shade: Shading system assembly - code to identify the type of shading
    - Rf_sh: Shading coefficient when shading device is active. Defined according to ISO 52016-1
- Type_wall: External wall construction assembly - code to identify the type of external wall
    - U_wall: Thermal transmittance of the wall [W/m$^2$K]

  - A_wall: Solar absorption coefficient of the wall. Defined according to ISO 52016-1
  - E_wall: Emissivity of external surface of the wall. Defined according to ISO 52016-1
  - R_wall: Reflectance in the red spectrum of the wall. Defined according to ISO 52016-1
  - GHG_wall_kgCO2: Embodied emissions per $m^2$ of wall (entire building life cycle)
- Type_part: Internal partitions construction assembly - code to identify the type of internal wall (same variables as Type_wall)
- Type_floor: Internal floor construction assembly - code to identify the type of internal floor
  - U_base: Thermal transmittance of the floor [$W/m^2K$]
  - GHG_floor_kgCO2: Embodied emissions per $m^2$ of floor (entire building life cycle)
- Type_base: Basement floor construction assembly - code to identify the type of basement floor (same variables as Type_floor)
- Type_win: Window assembly - code to identify the type of window
  - U_win: Thermal transmittance of the window [$W/m^2K$]
  - G_win: Solar heat gain coefficient. Defined according to ISO 52016-1
  - E_win: Emissivity of external surface of the window. Defined according to ISO 52016-1
  - F_F: Window frame coefficient. Defined according to ISO 52016-1
  - GHG_win_kgCO2: Embodied emissions per $m^2$ of window (entire building life cycle)

Internal loads

The internal loads section refers to the heat loads produced by equipment or people inside the building. It includes the following variables:

- Occ_m2p: Occupancy density [$m^2$/pers]
- Qs_Wp: Peak sensible heat load of people [W/pers]
- X_ghp: Moisture released by occupancy at peak conditions
- Ea_Wm2: Peak specific electrical load due to computers and devices [$W/m^2$]
- El_Wm2: Peak specific electrical load due to artificial lighting [$W/m^2$]
- Epro_Wm2: Peak specific electrical load due to industrial processes [$W/m^2$]
- Qcre_Wm2: Peak specific cooling load due to refrigeration (cooling rooms) [$W/m^2$]

- Ed_Wm2: Peak specific electrical load due to servers/data centers [W/m$^2$]
- Ev_kWveh: Peak capacity of electrical battery per vehicle [kW/veh]
- Qcpro_Wm2: Peak specific process cooling load [W/m$^2$]
- Qhpro_Wm2: Peak specific process heating load [W/m$^2$]
- Vww_ldp: Peak specific daily hot water consumption [ldp]
- Vw_ldp: Peak specific fresh water consumption (includes hot and cold water) [ldp]

Indoor comfort

This section contains parameters that refer to the set values of temperature, humidity and ventilation for user comfort. Specifically, it includes the following variables:

- Tcs_set_C: Temperature setpoint for cooling system [ºC]
- Tcs_setb_C: Temperature setback point for cooling system [ºC]
- Ths_set_C: Temperature setpoint for heating system [ºC]
- Ths_setb_C: Temperature setback point for heating system [ºC]
- RH_min_pc: Lower bound of relative humidity [%]
- RH_max_pc: Upper bound of relative humidity [%]
- Ve_lsp: Minimum outdoor air ventilation rate per person for air quality [l/s/pers]

Air-conditioning systems

The air-conditioning systems section includes the parameters of all the HVAC equipment. The following variables are included:

- Type_cs: Type of cooling HVAC assembly - code to identify the type of cooling HVAC
    - Class_cs: Class of the cooling system
    - Convection_cs: Convective part of the power of the cooling system in relation to the total power
    - Qcsmax_Wm2: Maximum heat flow permitted by cooling system per m$^2$ gross floor area [W/ m$^2$]
    - dTcs_C: Set-point correction for the space emission systems [ºC]
    - Tscs0_ahu_C: Nominal supply temperature of the water side of the air-handling units [ºC]
    - dTcs0_ahu_C: Nominal temperature increase on the water side of the air-handling units [ºC]
    - Tc_sup_air_ahu_C: Supply air temperature of the air-handling units [ºC]
    - Tscs0_aru_C: Nominal supply temperature of the water side of the air-recirculating units [ºC]

  - dTcs0_aru_C: Nominal temperature increase on the water side of the air-recirculating units [ºC]
  - Tc_sup_air_aru_C: Supply air temperature of the air-recirculating units [ºC]
  - Tscs0_scu_C: Nominal supply temperature of the water side of the sensible cooling units [ºC]
  - dTcs0_scu_C: Nominal temperature increase on the water side of the sensible cooling units [ºC]
- Type_hs: Type of heating HVAC assembly - code to identify the type of heating HVAC
  - Class_hs: Class of the heating system
  - Convection_hs: Convective part of the power of the heating system in relation to the total power
  - Qhsmax_Wm2: Maximum heat flow permitted by heating system per $m^2$ gross floor area [W/ $m^2$]
  - dThs_C: Set-point correction for the space emission systems [ºC]
  - Tshs0_ahu_C: Nominal supply temperature of the water side of the air-handling units [ºC]
  - dThs0_ahu_C: Nominal temperature increase on the water side of the air-handling units [ºC]
  - Th_sup_air_ahu_C: Supply air temperature of the air-handling units [ºC]
  - Tshs0_aru_C: Nominal supply temperature of the water side of the air-recirculating units [ºC]
  - dThs0_aru_C: Nominal temperature increase on the water side of the air-recirculating units [ºC]
  - Th_sup_air_aru_C: Supply air temperature of the air-recirculating units [ºC]
  - Tshs0_shu_C: Nominal supply temperature of the water side of the sensible heating units [ºC]
  - dThs0_shu_C: Nominal temperature increase on the water side of the sensible heating units [ºC]
- Type_dhw: Type of hot water HVAC assembly - code to identify the type of hot water HVAC
  - Tsww0_C: Typical supply water temperature
  - Qwwmax_Wm2: Maximum heat flow permitted by hot water system per $m^2$ gross floor area [W/ $m^2$]
- Type_ctrl: Type of heating and cooling control HVAC assembly - code to identify the type of control HVAC
  - dT_Qhs: Correction temperature of emission losses due to control system heating [ºC]

  - dT_Qcs: Correction temperature of emission losses due to control system cooling [ºC]
- Type_vent: Type of ventilation HVAC assembly - code to identify the type of ventilation HVAC
  - MECH_VENT: Mechanical ventilation on [true/false]
  - WIN_VENT: Window ventilation on [true/false]
  - HEAT_REC: Heat recovery on [true/false]
  - NIGHT_FLSH: Night flush on [true/false]
  - ECONOMIZER: Economizer on [true/false]
- Heat_starts: Start of the heating season
- Heat_ends: End of the heating season
- Cool_starts: Start of the cooling season
- Cool_ends: End of the cooling season

Supply systems

The supply systems section refers to the technologies that supply energy for the HVAC systems, hot water, and electricity. It includes the following variables:

- Type_cs: Type of cooling supply assembly - code to identify the type of cooling supply
  - System: Type of system
  - Feedstock: Feedstock used by the system
  - Scale: Whether the system is used at the building or the district scale
  - Efficiency: Efficiency of the system
  - CAPEX_USD2015kW: Capital costs per kW
  - LT_yr: Lifetime of this technology
  - O&M_%: Operation and maintenance cost factor (as a percentage of the investment cost)
  - IR_%: Interest rate charged on the loan for the capital cost
- Type_hs: Type of heating supply assembly - code to identify the type of heating supply (same variables as Type_cs)
- Type_dhw: Type of hot water supply assembly - code to identify the type of hot water supply (same variables as Type_cs)
- Type_el: Type of electrical supply assembly - code to identify the type of electrical supply (same variables as Type_cs)

Schedules

The schedules section allows the user to modify the hourly schedule of the following:

- Occupancy
- Appliances
- Lighting
- Servers
- Water
- Heating
- Cooling
- Processes
- Electromobility

For occupancy the input variable is the proportion of people which are in the building with respect to the maximum amount of people that are in the building at a time. Similarly, for appliances, lighting, servers, water, processes, and electromobility the input is the proportion of what is being used out of the maximum use at a given hour. For heating and cooling, however, the input is whether the temperature is set to the set temperature, the setback temperature, or the system is off.

Variables from most databases will be changed in the sensitivity analysis to verify the effects on demand. However, none of the variables from air-conditioning systems and supply systems will not be altered. The specific variables, which will be analyzed will be further explained in the next section.

## 3.2 Sensitivity Analysis

The end uses that contribute the most to energy demand in a building – almost 70% – are space heating, space cooling, hot water, and lighting. The remaining 30% is due to electronics, appliances, and ventilation [6]. This section will concentrate on changing a series of parameters of a building and analyze the patterns of the change in space heating, hot water, and electricity demand. Ventilation is left out of the analysis, due to the small contribution it has, whereas space cooling will not be included because it is not taken into consideration in the simulation.

Specifically, the values to be observed and analyzed are the total electricity consumption (E_sys), the end-use space heating demand (Qhs_sys), the end-use hot water demand (Qww_sys), and the total energy demand for heating (QH_sys), which is a sum of the two previous quantities and the process heating demand (Qhpro_sys), which this paper will not focus on.

The sensitivity analysis will be compared to a base case, from which certain parameters will be changed. These parameters will be separated into two sub-sections: envelope parameters and occupation and indoor comfort parameters. The base case will be described in the following section.

### 3.2.1 Base Case

The base case was constructed by creating a two-story multi-family home from the 1960s with no cellar in QGIS, which is an open-source Geographic Information System (GIS). This program allows the user to insert buildings with a wide range of parameters in a specific area in the World. Then it was introduced into City Energy Analyst, together with the necessary databases, mentioned in the previous section, to be modelled.

Additionally, four buildings of similar areas and the same height were included in the base case, as the surroundings of the object to be analyzed. Each of these buildings were placed in front of each façade of the studied object, that is, one North of it, one to the South, one to the East, and the last one to the West, at approximately a distance of 40 meters.

This case will be simulated in a suburban area in Southern Germany, with the corresponding weather and terrain conditions.

Figure 2 illustrates the base case described above.

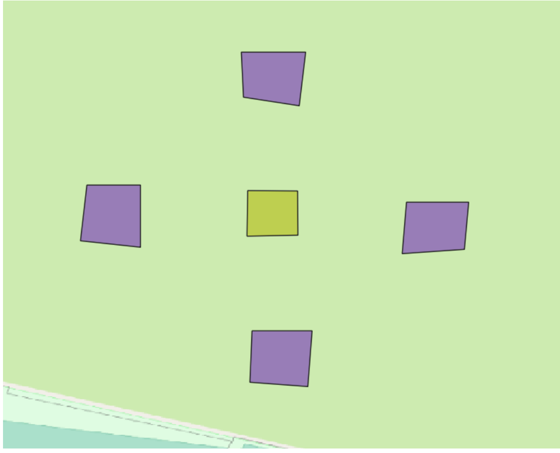

**Figure 2: Base case constructed in QGIS**

The characteristics of the building are gathered in Table 39 in the first appendix and will be explained below.

Residential buildings can be one of three types: single-family home (EFH), multi-family home (MFH), or terraced home (TH). The letter that comes after this code corresponds to the year the building was built. These letters go from A to L, which comprise constructions form before 1859 to 2030 in different intervals. In this case, the building in question is a multi-family home (MFH) built between the years 1969 and 1978 (F).

The dimensions of the building, that is, the floor area (Aroof_m2), number of floors (floors_ag and floors_bg), and height (height_ag and height_bg) were determined in QGIS by drawing the building with a certain area and inserting the desired number of floors and height above and below ground. The gross floor area (GFA_m2) is a consequence of the floor area multiplied by the number of floors. The conditioned area (Af_m2) is the gross floor area multiplied by the fraction of area with air-conditioned demands (Hs_ag and Hs_bg).

Furthermore, the void deck was left at 0 because the building has no open terraces. The fraction of net floor area (Ns) refers to the fraction of the building which can actually be occupied or used by the residents. It was set at 0,85, meaning 15% of the gross floor area is used up by walls, structural elements and common spaces. The same fraction was assigned to the fraction of gross floor area with electrical demands (Es) and the fraction of gross floor area above ground with air conditioning demands (Hs_ag). This same fraction for the area below ground (Hs_bg), however, is 0 because in this case there are no floors below ground. All the window-to-wall ratios were computed with the TABULA values of typical areas for walls and windows in each building typology, by dividing the total area of the windows in each façade by the area of the walls in the corresponding façade. TABULA is a webtool developed by Intelligent Energy Europe initiatives to share typical building typologies of different European countries and their implementation. The values mentioned in this paragraph are all found in the archetypes database.

The following values are all included in the assemblies' database, more specifically in the envelope database. The internal heat capacity per unit area (Cm_Af) refers to the amount of heat energy the building envelope can store per unit area, which influences the building's response to changes in temperature. The value chosen for this parameter corresponds to the standard value from TABULA. The tightness of the building, represented by the number of air exchanges per hour at a pressure of 50 Pascals (n50), coincides with the value for a medium tightness in TABULA. Moreover, the U-values for the roof, external walls, base, and windows (U_roof, U_wall, U_base, U_win) match the U-values in TABULA for the type of building in question, a multi-family home from de 1970s in Germany. The U-value for the internal floors has been established as the same value as for the base. However, the internal walls have a different U-value than the external walls. The U-value for these, as well as all the other parameters related to the partition walls (a_wall, e_wall, r_wall, GHG_wall_kgCO2m2) are the values corresponding to an internal partition in brick. These last parameters are not to be confused with the same parameters for the external walls, which will be later clarified. All the parameters related to radiation for all the surfaces (a_roof, e_roof, r_roof, a_wall, e_wall, r_wall, G_win, e_win) are defined according to ISO 52016-1, depending on the material used for each surface. The windows have an additional parameter, F_F, which is the window frame fraction coefficient. This is also defined according to ISO 52016-1. Finally, the shading coefficient (rf_sh) corresponds to the coefficient assigned to vertical shading by ISO 52016-1. Vertical shading refers to elements that run vertically, for instance vertical blinds.

Moreover, the parameters for the internal loads chosen for the base case are the values which CEA has as default values. The occupancy density (Occ_m2p), which refers to the space there is per person in a building, is set as 30 $m^2$/person, which is slightly below the average for Germany [13]. The peak sensible heat load of people (Qs_Wp) is 70 W/person, which almost coincides with the sensible heat load of people in an office, 75 W/person [14]. The moisture released by occupancy at peak conditions (X_ghp) is 80g/h/person. The peak specific electrical loads due to computers and devices and due to artificial lighting are 8 $W/m^2$ and 2,7 $W/m^2$ respectively. The former value is close, but not within, the range proposed by Domínguez-Muñoz et al. [15], however, the latter is further from the range proposed by the same study. After these parameters, there are many parameters, whose value for the base case is 0 (Epro_Wm2, Qcre_Wm2, Ed_Wm2, Ev_kWveh, Qcpro_Wm2, Qhpro_Wm2). This is because, since a residential building is being studies, objects, rooms, or processes, which these parameters refer to, such as industrial processes, data centers, or cooling rooms, are not taken into account. The peak specific daily hot water consumption (Vww_ldp) is set as 40 l/day/person and the peak specific daily fresh water consumption (hot or cold) (Vw_ldp) is 140 l/day/person. Water consumption in a residential building can be due to bathing, cooking, drinking, doing laundry, or washing dishes.

Finally, the indoor comfort parameters are also the default values of CEA. The temperature setpoint and setback for cooling (Tcs_set_C and Tcs_setb_C) are 26ºC and 28ºC respectively. However, since this paper does not focus on the cooling aspect of the energy demand, these parameters do not affect the results. The temperature setpoint and setback for heating (Ths_set_C and Ths_setb_C) are set to 21ºC and 18ºC respectively. Additionally, the lower and upper bound of relative humidity (RH_min_pc and RH_max_pc) are 30% and 60%. The minimum outdoor air ventilation rate per person for air quality is 8,33 l/s/person.

A table with the temperature schedules for heating for the base case is shown in Table 40 in the first appendix. Initially, heating is turned during the whole day and the setpoint temperature is set all throughout the day.

### 3.2.2 Envelope Parameters

Firstly, some parameters of the envelope will be altered. The envelope of a building is exterior of the building, including walls, windows, doors, roofs and floors. This is what protects the interior of the building from the outside weather conditions.

Case 1: Renovations

There are 2 renovation scenarios: normal renovation and advanced renovation. Both scenarios consider a change in the tightness (n50), the U-value of the roof (U_roof), the external walls (U_wall), the base floor (U_base), and the windows (U_win), as well as the solar heat gain coefficient (G_win), the emissivity (e_win), and the embodied emissions of the windows (GHG_win_kgCO2). The rest of the parameters stay the same.

Table 1 shows the parameters that have been changed for this case in each scenario and compares them to the base case's parameters.

**Table 1: Changed parameters for case 1**

| | No renovation | Normal renovation | Advanced renovation |
|---|---|---|---|
| N50 | 2,5 | 1,0 | 4,0 |
| U_roof [W/m$^2$K] | 0,51 | 0,19 | 0,09 |
| U_wall [W/m$^2$K] | 1 | 0,22 | 0,13 |

| | | | |
|---|---|---|---|
| U_base [$W/m^2K$] | 0,77 | 0,28 | 0,21 |
| U_win [$W/m^2K$] | 3 | 1,3 | 0,8 |
| G_win | 0,75 | 0,67 | 0,5 |
| E_win | 0,89 | 0,02 | 0,02 |
| GHG_win_kgCO2 [$kgCO_2/m^2$] | 62 | 123 | 123 |

The values for each of these parameters have been taken from TABULA. TABULA has a normal and advanced renovation scenario for each of the building typologies and these values are specifically from the normal and advance renovations of a multi-family home from the 1970s (MFH_F) in Germany.

Case 2: Cellars

In this case, the effect of having a cellar will be analyzed. In addition, the effect of having heating in the cellar will be considered. Therefore, the parameters that will be altered in these scenarios will be the fraction of air-conditioned gross floor area (Af_m2), the gross floor area itself (GFA_m2), the height below ground (height_bg), the number of floors below ground (floors_bg) and the fraction of gross floor area below ground with air-conditioning demands (Hs_bg).

The parameters that differ from the base case are the following:

**Table 2: Changed parameters for case 2**

| | No cellar | Cellar, 0% heating | Cellar, 50% heating | Cellar, 85% heating |
|---|---|---|---|---|
| Af_m2 [$m^2$] | 742 | 742 | 961 | 1113 |
| GFA_m2 [$m^2$] | 873 | 1310 | 1310 | 1310 |
| Height_bg [m] | 0 | 3 | 3 | 3 |
| Floors_bg | 0 | 1 | 1 | 1 |
| Hs_bg | 0 | 0 | 0,5 | 0,85 |

Adding a cellar adds one floor below ground to the building (floors_bg) with the same height (height_bg) and area as the floors the building already had above ground. Hence, the gross floor area (GFA_m2) for the three scenarios, other than the base case (no cellar), is the same and equal to 1,5 times the gross floor area of the base case, since the building already had two floors. It was decided that each scenario would have a different proportion of heating of the cellar. Consequently, the values for the fraction of gross floor area below ground with air conditioning demands (Hs_bg) are different for each scenario. The first scenario has no heating in the cellar, so its Hs_bg is 0; the second has 50% of the cellar heated, making its Hs_bg equal to 0,5; and the third scenario has the same heating proportion in the cellar as there is in the floors above ground, 85%, so its Hs_bg is 0,85. These values play a part in the conditioned area (Af_m2). They are multiplied by the gross floor area of the cellar and added to the conditioned area of the base case.

### Case 3: Window to Wall Ratio

This case will analyze how changing the window to wall ratio affects energy demand. The ratio will be increased or decreased by 20% in each scenario. Firstly, each façade will be changed one by one, meaning that the North window to wall ratio will be increased and decreased by 20% first, followed by the East façade, the South façade and the West façade. Next, two façades will be altered at once until all combinations are achieved, then three façades, and, finally, all four façades at the same time.

### Case 3.1: One Façade at a Time +20%

The following table shows the parameters that change with respect to the base case in this case:

**Table 3: Changed parameters for case 3.1**

| | Standard | North | East | South | West |
|---|---|---|---|---|---|
| Wwr_north | 0,0787 | 0,0944 | 0,0787 | 0,0787 | 0,0787 |
| Wwr_east | 0,187 | 0,187 | 0,224 | 0,187 | 0,187 |
| Wwr_south | 0,225 | 0,225 | 0,225 | 0,270 | 0,225 |
| Wwr_west | 0,187 | 0,187 | 0,187 | 0,187 | 0,224 |

As previously explained in the variables section, the values for the window to wall ratio of the base case were computed by dividing the total area of the windows in each façade of a typical multi-family home from the 1970s in Germany by the area of the walls in the corresponding façade. The values for the areas were taken from TABULA. Then, for each of the other scenarios, the window to wall ratio of one of the façades was increased by 20%, while the rest of the window to wall ratios remained the same.

### Case 3.2: One Façade at a Time -20%

The following table shows the parameters that change with respect to the base case in this case:

**Table 4: Changed parameters for case 3.2**

| | Standard | North | East | South | West |
|---|---|---|---|---|---|
| Wwr_north | 0,0787 | 0,0630 | 0,0787 | 0,0787 | 0,0787 |
| Wwr_east | 0,187 | 0,187 | 0,150 | 0,187 | 0,187 |
| Wwr_south | 0,225 | 0,225 | 0,225 | 0,180 | 0,225 |
| Wwr_west | 0,187 | 0,187 | 0,187 | 0,187 | 0,150 |

Similarly to case 3.1, for each of the scenarios different from the base case, the window to wall ratio of one of the façades was altered by decreasing its value by 20%, while the rest of the window to wall ratios stayed constant.

### Case 3.3: Two Façades at a Time +20%

The following table shows the parameters that change with respect to the base case in this case:

**Table 5: Changed parameters for case 3.3**

| | Standard | North, East | North, South | North, West | East, South | East, West | South, West |
|---|---|---|---|---|---|---|---|
| Wwr_north | 0,0787 | 0,0944 | 0,0944 | 0,0944 | 0,0787 | 0,0787 | 0,0787 |
| Wwr_east | 0,187 | 0,224 | 0,187 | 0,187 | 0,224 | 0,224 | 0,187 |
| Wwr_south | 0,225 | 0,225 | 0,270 | 0,225 | 0,270 | 0,225 | 0,270 |
| Wwr_west | 0,187 | 0,187 | 0,187 | 0,224 | 0,187 | 0,224 | 0,224 |

For this case, the value of the window to wall ratio of two façades will be increased by 20% for each scenario, while the rest of the values stay constant. A scenario for all the possible combinations has been created.

### Case 3.4: Two Façades at a Time -20%

The following table shows the parameters that change with respect to the base case in this case:

**Table 6: Changed parameters for case 3.4**

| | Standard | North, East | North, South | North, West | East, South | East, West | South, West |
|---|---|---|---|---|---|---|---|
| Wwr_north | 0,0787 | 0,0630 | 0,0630 | 0,0630 | 0,0787 | 0,0787 | 0,0787 |
| Wwr_east | 0,187 | 0,150 | 0,187 | 0,187 | 0,150 | 0,150 | 0,187 |
| Wwr_south | 0,225 | 0,225 | 0,180 | 0,225 | 0,180 | 0,225 | 0,180 |
| Wwr_west | 0,187 | 0,187 | 0,187 | 0,150 | 0,187 | 0,150 | 0,150 |

The window to wall ratios will also be altered for two façades at a time, but in this case, the values will be decreased by 20%. All the possible combinations will be satisfied by the created scenarios.

### Case 3.5: Three Façades at a Time +20%

The following table shows the parameters that change with respect to the base case in this case:

**Table 7: Changed parameters for case 3.5**

| | Standard | North, East, South | North, East, West | North, South, West | East, South, West |
|---|---|---|---|---|---|
| Wwr_north | 0,0787 | 0,0944 | 0,0944 | 0,0944 | 0,0787 |
| Wwr_east | 0,187 | 0,224 | 0,224 | 0,187 | 0,187 |
| Wwr_south | 0,225 | 0,270 | 0,225 | 0,270 | 0,270 |
| Wwr_west | 0,187 | 0,187 | 0,224 | 0,224 | 0,224 |

This time, the window to wall ratio of three façades will be increased by 20% at the same time. The remaining façade will have the same window to wall ratio as the matching façade in the base case. All the possible combinations have been taken into consideration.

### Case 3.6: Three Façades at a Time -20%

The following table shows the parameters that change with respect to the base case in this case:

**Table 8: Changed parameters for case 3.6**

| | Standard | North, East, South | North, East, West | North, South, West | East, South, West |
|---|---|---|---|---|---|
| Wwr_north | 0,0787 | 0,0630 | 0,0630 | 0,0630 | 0,0787 |
| Wwr_east | 0,187 | 0,150 | 0,150 | 0,187 | 0,150 |
| Wwr_south | 0,225 | 0,180 | 0,225 | 0,180 | 0,180 |
| Wwr_west | 0,187 | 0,187 | 0,150 | 0,150 | 0,150 |

This case is the same as case 3.5, with the exception that, instead of increasing the window to wall ratios by 20%, they are decreased by 20%.

Case 3.7: Four Façades at a Time +20%

The following table shows the parameters that change with respect to the base case in this case:

**Table 9: Changed parameters for case 3.7**

| | Standard | North, East, South, West |
|---|---|---|
| Wwr_north | 0,0787 | 0,0944 |
| Wwr_east | 0,187 | 0,224 |
| Wwr_south | 0,225 | 0,270 |
| Wwr_west | 0,187 | 0,224 |

In this case, there is only one scenario apart from the base case because the window to wall ratios of all four façades have been altered at once by increasing their value by 20%.

Case 3.8: Four Façades at a Time -20%

The following table shows the parameters that change with respect to the base case in this case:

**Table 10: Changed parameters for case 3.8**

| | Standard | North, East, South, West |
|---|---|---|
| Wwr_north | 0,0787 | 0,0630 |
| Wwr_east | 0,187 | 0,150 |
| Wwr_south | 0,225 | 0,180 |
| Wwr_west | 0,187 | 0,150 |

In this case, the window to wall ratios of all four façades are decreased by 20% at the same time in only one scenario.

### Case 4: Construction Standard

In this case, the effect in energy demand in relation to the change in the construction standard will be investigated. More specifically, the parameter which will be altered is the internal heat capacity per unit area (Cm_af).

The scenarios chosen for this case are the light, medium, and heavy construction standards of City Energy Analyst, with their respective Cm_Af values.

The following table shows the parameters that change with respect to the base case in this case:

**Table 11: Changed parameters for case 4**

| | Construction Tabula | Construction AS1: Light | Construction AS2: Medium | Construction AS3: Heavy |
|---|---|---|---|---|
| Cm_Af [J/Km$^2$] | 162000 | 110000 | 165000 | 300000 |

### Case 5: Tightness

The effect on tightness in the energy demand will be studied in this case. What is meant by tightness is how sealed the building is. The parameter which measures this is n50, which is the number of air exchanges per hour at a pressure of 50 Pa. The lower n50, the higher the tightness because there are less air exchanges per hour.

There are two scenarios which will be analyzed in this case apart from the base case, to which the scenario with medium tightness corresponds. The other two scenarios are the minimum and maximum values for tightness in TABULA.

The following table shows the parameters that change with respect to the base case in this case:

**Table 12: Changed parameters for case 5**

| | Tabula medium | Tabula minimum | Tabula high |
|---|---|---|---|
| N50 | 2,5 | 1,0 | 4,0 |

Case 6: Shading

This case will analyze how shading affects energy demand. The parameter to be changed is the shading coefficient when the shading device is active, rf_sh. The values chosen for this parameter in each scenario are defined by ISO 52016-1.

There are two scenarios which will be compared in this case. The scenario with the vertical shading corresponds to the base case and the other scenario has horizontal shading.

The following table shows the parameters that change with respect to the base case in this case:

**Table 13: Changed parameters for case 6**

| | Vertical | Horizontal |
|---|---|---|
| Rf_sh | 0,6 | 0,8 |

## 3.3 Internal Loads and Indoor Comfort Parameters

In the following sections, some internal loads and indoor comfort parameters, such as the occupancy density, setpoint and setback temperatures, and the schedules of the setpoint and setback temperatures, will be varied in order to investigate how these affect energy demand.

Case 7: Occupancy Density

The effect of occupancy density will be explored in this case. What is meant by occupancy density is the amount of space there is per person in the house. It will be measured in $m^2$ per person. The higher the occupancy density, the lower the space person, meaning the value would be smaller.

This case will have three scenarios apart from the base case. It is worth mentioning that the base case considers an occupancy density of 30 $m^2$ per person, which, taking into account that the building has two stories of approximately 450 $m^2$ each, means that there are approximately 30 people living in the multi-family house. The first scenario will consider that there are 2 apartments per floor – of approximately 215 $m^2$ each – with 4 people per apartment. This would make a total of 16 people and 55 $m^2$ per person. The second scenario has 3 apartments per floor and 2 people per apartment. This makes 12 people in total and 73 $m^2$ per person. Finally, a scenario with 4 apartments per floor and 5 people per apartment will be considered. This would be 40 people in total and 22 $m^2$ per person. The Federal

Statistical Office of Germany states the average living space per person as 46 m$^2$, which is within the numbers of the scenarios [13].

The following table shows the parameters that change with respect to the base case in this case:

**Table 14: Changed parameters for case 7**

| | Base Case | 4 apartments, 4 people/apart. | 3 apartments, 2 people/apart. | 8 apartments, 5 people/apart. |
|---|---|---|---|---|
| Occ_m2p [m$^2$/pers] | 30 | 55 | 73 | 22 |

Case 8: Temperature Setpoints and Setbacks

This case will analyze how changing the temperature setpoints and setbacks affect energy demand. Temperature setpoints are the objective temperatures that are set when there are people in the building. Temperature setbacks are used when occupancy is low or during the night in order to decrease the energy consumption.

This case will only take into consideration the setpoints and setbacks for the heating. The base case has a setpoint of 21ºC and a setback of 18ºC. For the other three scenarios in this case, setpoints of 17ºC, 19ºC and 23ºC will be used. 17ºC and 23ºC are used as minimum and maximum based on a study by Sperber et al. [16]. 19ºC is used as an objective value, since after the energy crisis in Europe, German users have been recommended to lower their heating setpoint temperatures to 19ºC to decrease energy consumption [17]. The setback temperatures are 3ºC below the setpoint temperatures for each case, following the base case. Setback temperatures will not affect this case at all, since the temperature schedules are set to setpoint temperatures at all hours of the day.

The following table shows the parameters that change with respect to the base case in this case:

**Table 15: Changed parameters for case 8**

| | Base Case | Minimum | Optimal | Maximum |
|---|---|---|---|---|
| Ths_set_C [ºC] | 21 | 17 | 19 | 23 |
| Ths_setb_C [ºC] | 18 | 14 | 16 | 20 |

Case 9: Temperature Schedules

This case will change the hours in which setpoint, and setback temperatures are used. As explained in the previous case, setback temperatures are used when occupancy is low or during the night.

The base case does not use setback temperatures at all. This has also been the case for all the previous cases studied in this paper. Two more scenarios will be studied in this case. The first one sets the setback temperature during the night, more specifically from

11pm to 7am. This scenario could be the case for a household in which people work at home. The other scenario uses the setback temperature during the working hours in addition to the night hours. The working hours considered are from 9am to 4pm, which are less than 8 hours due to the fact that 1 hour to heat the home before arriving is considered.

The following table shows the parameters that change with respect to the base case in this case:

**Table 16: Changed parameters for case 9**

| | Base Case | Setback during the night | Setback during the night and weekdays |
|---|---|---|---|
| Temperature setpoint Saturday [h] | 0-24 | 7-23 | 7-23 |
| Temperature setback Saturday [h] | - | 0-7; 23-24 | 0-7; 23-24 |
| Temperature setpoint Sunday [h] | 0-24 | 7-23 | 7-23 |
| Temperature setback Sunday [h] | - | 0-7; 23-24 | 0-7; 23-24 |
| Temperature setpoint weekday [h] | 0-24 | 7-23 | 7-9; 16-23 |
| Temperature setback weekday [h] | - | 0-7; 23-24 | 0-7; 9-16; 23-24 |

Case 10: Temperature Setpoints, Setbacks and Schedules

Since the results of case 8 will not be affected by the temperature setbacks which have been set in each scenario for that case, this case will mix two scenarios from the previous two cases to explore how changing the setback temperature, as well as the setpoint temperature, affects energy demand.

The scenario proposed decreases the setpoint and setback temperatures by 2ºC with respect to the base case, which is the optimal scenario from case 8. In addition to that, the temperature schedule will also be changed to the scenario with the setback temperatures at night from case 9.

The following table shows the parameters that change with respect to the base case in this case:

**Table 17: Changed parameters for case 10**

| | Base Case | Optimal temperature + Setback during the night |
|---|---|---|
| Ths_set_C [ºC] | 21 | 19 |
| Ths_setb_C [ºC] | 18 | 16 |
| Temperature setpoint Saturday [h] | 0-24 | 7-23 |
| Temperature setback Saturday [h] | - | 0-7; 23-24 |
| Temperature setpoint Sunday [h] | 0-24 | 7-23 |
| Temperature setback Sunday [h] | - | 0-7; 23-24 |
| Temperature setpoint weekday [h] | 0-24 | 7-23 |
| Temperature setback weekday [h] | - | 0-7; 23-24 |

# 4 Results

## 4.1 Sensitivity Analysis

This section will present the results of the sensitivity analysis carried out for each of the cases described in the methodology section.

As previously mentioned, the values which will be shown as results are the total electricity consumption (E_sys), the end-use space heating demand (Qhs_sys), the end-use hot water demand (Qww_sys), and the total energy demand for heating (QH_sys), which is the sum of the two previous quantities and the process heating demand (Qhpro_sys), which this paper will not focus on.

<u>Case 1: Renovations</u>

The results for this case are the following:

**Table 18: Results for case 1**

| | No renovation | Normal renovation | Advanced renovation |
|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,6 | 15,5 |
| Qhs_sys [MWh/yr] | 56,9 | 8,69 | 2,84 |
| Qww_sys [MWh/yr] | 21,9 | 21,6 | 21,5 |
| QH_sys [MWh/yr] | 78,8 | 30,2 | 24,3 |

The quantities in which a substantial decrease in demand is observed are the space heating demand and, consequently, the total energy demand for heating. Since the total heat demand includes the space heating demand and its decrease is mainly due to the space heating demand, only the former will be commented on in the discussion section.

The electricity and hot water demand do not change almost at all.

<u>Case 2: Cellars</u>

The results for this case are the following:

**Table 19: Results for case 2**

| | No cellar | Cellar, 0% heating | Cellar, 50% heating | Cellar, 85% heating |
|---|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 23,4 | 23,4 | 23,5 |
| Qhs_sys [MWh/yr] | 56,9 | 55,8 | 69,6 | 79,4 |
| Qww_sys [MWh/yr] | 21,9 | 30,3 | 30,3 | 30,3 |
| QH_sys [MWh/yr] | 78,8 | 86,1 | 100 | 110 |

In this case, all four quantities are affected in every scenario. Electricity demand increases by 50% when the cellar is added and then remains constant, regardless of the amount of heating in the cellar. The heating demand is different in every scenario. First, it decreases slightly with the cellar with no heating scenario and then it increases proportionally to the conditioned area (Af_m2). The hot water demand, just as the electricity demand, increases with the addition of the cellar and then stays the same for the other scenarios. The increase in hot water demand is smaller in proportion than the increase in electricity demand: 39%.

Case 3: Window to Wall Ratio

The results for case 3 will be divided in sub-cases, just as the explanation for the methodology of each sub-case in the previous section. However, the observations for the results tables of each sub-case will be summarized at the end, after the last table of results of case 3.

Case 3.1: One Façade at a Time +20%

The results for this case are the following:

**Table 20: Results for case 3.1**

| | Standard | North | East | South | West |
|---|---|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 57,2 | 57,4 | 56,8 | 57,3 |
| Qww_sys [MWh/yr] | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 |
| QH_sys [MWh/yr] | 78,8 | 79,1 | 79,2 | 78,7 | 79,1 |

Case 3.2: One Façade at a Time -20%

The results for this case are the following:

**Table 21: Results for case 3.2**

| | Standard | North | East | South | West |
|---|---|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 56,7 | 56,5 | 57,1 | 56,7 |
| Qww_sys [MWh/yr] | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 |
| QH_sys [MWh/yr] | 78,8 | 78,6 | 78,3 | 78,9 | 78,5 |

Case 3.3: Two Façades at a Time +20%

The results for this case are the following:

**Table 22: Results for case 3.3**

| | Standard | North, East | North, South | North, West | East, South | East, West | South, West |
|---|---|---|---|---|---|---|---|
| Wwr_north | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 |
| Wwr_east | 57,0 | 57,7 | 57,1 | 57,5 | 57,4 | 57,7 | 57,2 |
| Wwr_south | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 |
| Wwr_west | 78,8 | 79,5 | 78,9 | 79,3 | 79,2 | 79,6 | 79,0 |

Case 3.4: Two Façades at a Time -20%

The results for this case are the following:

**Table 23: Results for case 3.4**

| | Standard | North, East | North, South | North, West | East, South | East, West | South, West |
|---|---|---|---|---|---|---|---|
| Wwr_north | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 |
| Wwr_east | 57,0 | 56,2 | 56,9 | 56,4 | 56,6 | 56,2 | 56,8 |
| Wwr_south | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 |
| Wwr_west | 78.,8 | 78,1 | 78,7 | 78,3 | 78,5 | 78,0 | 78,7 |

Case 3.5: Three Façades at a Time +20%

The results for this case are the following:

**Table 24: Results for case 3.5**

| | Standard | North, East, South | North, East, West | North, South, West | East, South, West |
|---|---|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 | 15.687 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 57,6 | 58,0 | 57,4 | 57,6 |
| Qww_sys [MWh/yr] | 21,9 | 21,9 | 21,9 | 21,9 | 21,8 |
| QH_sys [MWh/yr] | 78,8 | 79,4 | 79,8 | 79,2 | 79,5 |

Case 3.6: Three Façades at a Time -20%

The results for this case are the following:

**Table 25: Results for case 3.6**

| | Standard | North, East, South | North, East, West | North, South, West | East, South, West |
|---|---|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 | 15,7 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 56,3 | 55,9 | 56,5 | 56,3 |
| Qww_sys [MWh/yr] | 21,9 | 21,9 | 21,9 | 21,9 | 21,9 |
| QH_sys [MWh/yr] | 78,8 | 78,2 | 77,8 | 78,4 | 78,2 |

Case 3.7: Four Façades at a Time +20%

The results for this case are the following:

**Table 26: Results for case 3.7**

| | Standard | North, East, South, West |
|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 57,9 |
| Qww_sys [MWh/yr] | 21,9 | 21,8 |
| QH_sys [MWh/yr] | 78,8 | 79,7 |

Case 3.8: Four Façades at a Time -20%

The results for this case are the following:

**Table 27: Results for case 3.8**

| | Standard | North, East, South, West |
|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 56,1 |
| Qww_sys [MWh/yr] | 21,9 | 21,9 |
| QH_sys [MWh/yr] | 78,8 | 77,9 |

The changes in demand for this case are not significant. The only quantities that have a noticeable change are the space heating demand and the total energy demand for heating. Since the latter is a consequence of the former, only the space heating demand will be analyzed.

Case 4: Construction Standard

The results for this case are the following:

**Table 28: Results for case 4**

| | Construction Tabula | Construction AS1: Light | Construction AS2: Medium | Construction AS3: Heavy |
|---|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 57,2 | 56,9 | 56,6 |
| Qww_sys [MWh/yr] | 21,9 | 21,9 | 21,9 | 21,9 |
| QH_sys [MWh/yr] | 78,8 | 79,1 | 78,8 | 78,5 |

The space heating demand increases moderately with a lighter construction and increases with a heavier construction. A lighter construction corresponds to a smaller internal heat capacity (Cm_Af). The medium construction has a very similar space heating demand to the base case because the values for the internal heat capacity in both scenarios is practically the same. This variation in demand has an effect on the total energy demand for heating.

The electricity and hot water demand stay the same in all scenarios.

Case 5: Tightness

The results for this case are the following:

**Table 29: Results for case 5**

| | Tabula medium | Tabula minimum | Tabula high |
|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 53,2 | 60,9 |
| Qww_sys [MWh/yr] | 21,9 | 21,9 | 21,9 |
| QH_sys [MWh/yr] | 78,8 | 75,0 | 82,8 |

The results table for this case shows that the smaller the number of air exchanges per hour (n50), which means a higher tightness, the lower the space heating demand. The variation in the total energy demand for heating is caused solely by the space heating demand.

The electricity and hot water demand also stay the same in all scenarios for this case.

Case 6: Shading

The results for this case are the following:

**Table 30: Results for case 6**

| | Vertical | Horizontal |
|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 57,0 | 53,1 |
| Qww_sys [MWh/yr] | 21,9 | 21,8 |
| QH_sys [MWh/yr] | 78,8 | 75,0 |

The results in Table 30 show that horizontal shading requires approximately 6% less space heating demand than vertical shading.

The electricity and hot water demand are not affected in any scenarios.

Case 7: Occupancy Density

The results for this case are the following:

**Table 31: Results for case 7**

| | Base Case | 4 apartments, 4 people/apart. | 3 apartments, 2 people/apart. | 8 apartments, 5 people/apart. |
|---|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 56,9 | 58,0 | 58,4 | 56,2 |
| Qww_sys [MWh/yr] | 21,9 | 15,0 | 13,2 | 27,7 |
| QH_sys [MWh/yr] | 78,8 | 73,0 | 71,6 | 83,9 |

As can be observed in Table 31, the only value that does not change from scenario to scenario is the electricity consumption.

The heating demand in this case only varies a maximum of 3%. The lower the occupancy density, meaning more space per person, the higher the heat demand.

Hot water demand has substantial changes with respect to the base case in all scenarios. It decreases with a lower occupancy density. The maximum variation in this case is a 40% decrease for the scenario with 3 apartments and 2 people per apartment.

In this case, the effects on the total energy demand for heating are mainly caused by the changes in hot water demand although space heating demand also contributes moderately.

Case 8: Temperature Setpoints and Setbacks

The results for this case are the following:

**Table 32: Results for case 8**

| | Base Case | Minimum | Optimal | Maximum |
|---|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,6 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 56,9 | 36,1 | 46,1 | 68,4 |
| Qww_sys [MWh/yr] | 21,9 | 22,1 | 22,0 | 21,7 |
| QH_sys [MWh/yr] | 78,8 | 58,2 | 68,1 | 90,1 |

Electricity demand and hot water demand remain practically unaffected compared to other parameters.

Space heating demand is highly affected by changing the temperature setpoint for heating. The intervals at which demand changes when changing the setpoint temperature by 2ºC are practically the same, approximately 20%.

The effects on total energy demand for heating are caused by space heating demand.

Case 9: Temperature Schedules

The results for this case are the following:

**Table 33: Results for case 9**

| | Base Case | Setback during the night | Setback during the night and weekdays |
|---|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 56,9 | 52,9 | 50,4 |
| Qww_sys [MWh/yr] | 21,9 | 21,9 | 21,9 |
| QH_sys [MWh/yr] | 78,8 | 74,8 | 72,3 |

Similarly to the previous case, the space heating demand is the quantity most affected in this case. The effects, however, are smaller than in the previous case. The setback temperature during the night scenario decreases demand by 7% and, when the setback temperature is also set during some hours on weekdays, the decrease is of 11%.

Electricity demand and hot water demand are not affected.

Case 10: Temperature Setpoints, Setbacks and Schedules

The results for this case are the following:

**Table 34: Results for case 10**

| | Base Case | Optimal temperature + Setback during the night |
|---|---|---|
| E_sys [MWh/yr] | 15,7 | 15,7 |
| Qhs_sys [MWh/yr] | 56,9 | 42,0 |
| Qww_sys [MWh/yr] | 21,9 | 22,0 |
| QH_sys [MWh/yr] | 78,8 | 64,1 |

Space heating demand decreases by 26% when the setpoint and setback temperatures are decreased by 2ºC, and the setback temperature is set during the night.

Electricity and hot water demand are not affected by this change.

## 4.2 Case Study

The case study to be analyzed is a group of buildings in a small city in Southern Germany.

This will be achieved by building a dataset with all the buildings from this area and selecting a group of buildings from which the energy consumption data is known. These buildings will be separated into residential and non-residential buildings and modelled in City Energy Analyst.

From the rest of the buildings in the area, some will be used as surroundings. This selection will be made by choosing the buildings which are less than 50 meters away from the buildings which are going to be simulated.

The objective of this section is to validate the simulations of City Energy Analyst with real consumption data.

## 4.3 Residential Buildings

The separation of the residential buildings from the rest of the buildings in the dataset will be achieved in QGIS. They will be selected in the attribute table by filtering the buildings with function “Residential Building”. These selected buildings will then be added to a new layer named “Residential Buildings” and a shapefile will be created from it to be able to model it in CEA.

There is a total of 103 residential buildings in the dataset. These buildings' typologies are single-family homes, terraced houses, multi-family homes, or apartment blocks, ranging from the late 1800s up to 2015.

The results of the simulation in City Energy Analyst are shown in Table 45 in the third Appendix. These results were compared to real energy consumption data, which is shown in Table 45 in the third Appendix.

Figure 3 shows the energy demand calculated by CEA plotted against the real energy consumption data.

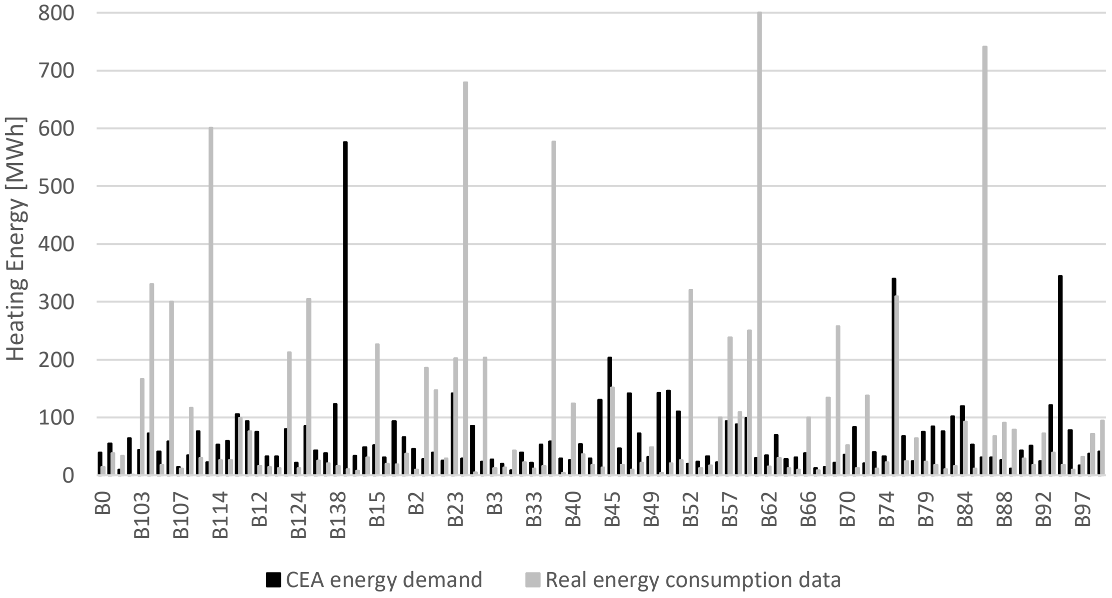

**Figure 3: Comparative of the calculated energy demand in CEA and the real consumption data**

As can be observed, the energy demand calculated by City Energy Analyst varies from the real data. This could be for many reasons, including the fact that the comparison is not between the same quantities. Consumption is usually greater than demand because there are internal losses in the heating system and in the ducts of the building, where the heat is transported. These losses are not taken into account in City Energy Analyst. Additionally, warm water is constantly in use, even during the summer for sanitary reasons. It is necessary to maintain a temperature of 60ºC in the water so that bacteria do not reproduce. Therefore, warm water is forced to flow in order for the water temperature not to drop below 60ºC. This causes a lot of energy losses, which are not taken into account in the CEA model.

The total sum of the real energy consumption for these buildings was approximately 10100 MWh, whereas the total energy demand estimated by CEA for the buildings was approximately 6740 MWh. This is an underestimation of 50%, which apparently is not too far off from the real number. However, this can be misleading because some demands are overcalculated and others are undercalculated, so the number are compensated.

Nevertheless, Figure 3 clearly demonstrates that the numbers differ considerably from one another.

As a matter of fact, there are some buildings whose energy demand calculated by CEA differs more than 10 times from the real energy consumption. Figure 4 shows a graph of the real consumption data divided by the energy demand calculated by CEA, which will more clearly illustrate how far off the calculated values are from the real data.

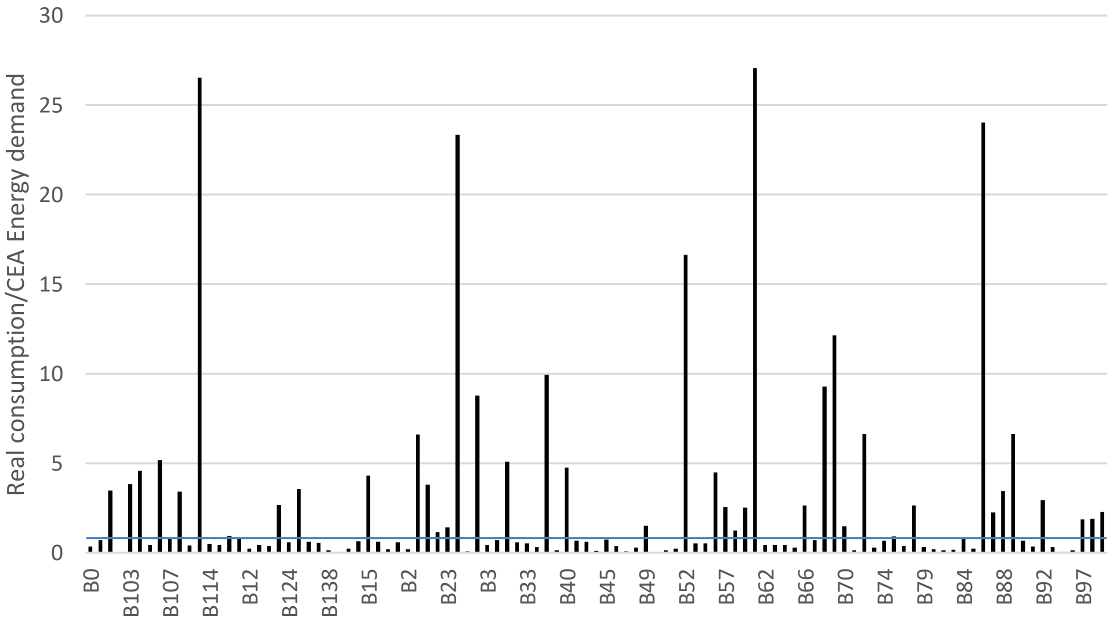

**Figure 4: Relationship between real energy consumption data and energy demand calculated in CEA**

The blue line is y=1, to see which buildings are closer to the real consumption. The buildings which are further away from this line will be investigated to see what the causes of this difference. The buildings which are below the line seem to be closer to the real demand, even if the real consumption is 20 times smaller than the calculated demand. However, these will also be analyzed.

Table 35 contains the results of the data points exhibiting the most significant deviations. Only the buildings which have energy demand 10 times larger or smaller than the real consumption data will be commented on.

**Table 35: Results for the buildings with the most significant deviations**

| | City Energy Analyst | | | Real Data | | | | |
|---|---|---|---|---|---|---|---|---|
| Name | Standard | Af_m2 [m2] | QH_sys [MWh/yr] | Standard | Full load [h] | Max Demand [kW] | Total Demand [MWh/yr] | Real Data/CEA |
| B102 | MFH_H | 490 | 63,8 | MFH_H | 38,8 | 6,30 | 0,257 | 0,004 |
| B111 | TH_E | 90 | 22,7 | EFH_I | 2610 | 219 | 601 | 26,5 |
| B14 | AB_E | 4000 | 576 | AB_E | 1150 | 8,48 | 10,2 | 0,018 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| B27 | EFH_H | 180 | 29,1 | EFH_H | 2350 | 275 | 679 | 23,3 |
| B28 | EFH_E | 580 | 85,1 | EFH_E | 422 | 12,1 | 5,35 | 0,063 |
| B47 | EFH_E | 960 | 141 | EFH_E | 1310 | 7,16 | 9,86 | 0,070 |
| B5 | EFH_E | 890 | 143 | EFH_E | 419 | 8,94 | 3,94 | 0,028 |
| B52 | TH_E | 110 | 19,3 | TH_E | 2560 | 119 | 321 | 16,6 |
| B60 | EFH_E | 150 | 29,6 | EFH_E | 2480 | 307 | 800 | 27,1 |
| B7 | EFH_H | 140 | 21,2 | EFH_H | 714 | 344 | 258 | 12,1 |
| B86 | EFH_E | 110 | 30,9 | EFH_I | 3560 | 198 | 741 | 24,0 |
| B94 | MFH_E | 2820 | 344 | MFH_E | 2020 | 8,26 | 17,5 | 0,051 |

Firstly, building B102 has a demand calculated by City Energy Analyst approximately 250 times greater than the actual energy consumption of that building. When the full load hours for this building is observed, it can be noticed that the value is less than 40 hours. This leads to believe that this building is not in use.

Building B111 has a real energy consumption 26 times the demand calculated in CEA. After investigating the building in Google Maps, it was discovered that the number of stories that was considered in City Energy Analyst did not coincide with the real building. In fact, the true number of stories is 3, whereas CEA only counts 1. This would only increase the demand calculated by CEA by 3 times, which would leave the real consumption still more than 8 times what is calculated by CEA. However, this would now fall into the group of buildings whose calculated demand is less than 10 times greater or smaller than the real data.

Next, B14 has a real energy consumption more than 50 times smaller than the energy demand in CEA. This could be due to the fact that this building is an apartment block and possibly all the apartments are not occupied. This theory is backed up with the maximum demand. It is only 8kW, which is quite small for an apartment block. This value is closer to the values of a single-family home.

B27 has a real energy consumption approximately 23 times the energy demand estimated in CEA. By observing the maximum demand for this building, it can be concluded that possibly the consumption of more buildings is included in the energy consumption of this building. This is because 275 kW is excessive for a single-family home.

Furthermore, building B28 has a real energy consumption more than 15 times smaller than the energy demand in City Energy Analyst. By looking at the full load hours, the fact that it is smaller than the average full load hours can be noticed. This suggests that the building is not in use during the whole year, which explains why the consumption is considerably smaller than the estimated demand.

Moreover, the next two buildings, B46 and B5, will be assessed together, since they are similar in size and they both have real consumptions much smaller than what CEA calculated. It is worth mentioning that the area of these buildings is more than the average single-family home of this area. This leads to believe that probably they are multi-family homes instead of single-family homes. However, the maximum demand for both buildings is that of a typical single-family home. This could mean that the building is not fully occupied. Additionally, B5 has very few full load hours, meaning that the building is probably not in use during the whole year.

Just as the previous two buildings, the following three buildings, B53, B60, and B7, will also be reviewed together due to the fact that they are similar in size and the relationship between the real data and the estimated demand is alike. After looking at the buildings in Google Maps, it has been confirmed that these three buildings are terraced homes. This would not change the consumption significantly compared to a single-family home, which is how they have been modelled. However, there is a possibility that the consumption for more than one terraced home has been included in the consumption data. This is also the conclusion drawn when observing the maximum demand, which is higher than the maximum demand for a typical terraced home, leading to believe that more than one building has been included in the consumption assigned to B52, B60 and B7. The explanation for B60 having a relationship real data/estimation less than half the relationship for the other two is the number of full load hours, which is approximately a third of the other two.

Additionally, building B86 has a real demand much larger than the one simulated in CEA. The reasons for this have not been found. The building has been found to be correctly categorized, after searching it in Google Maps and the demand simulated by CEA is within the values of a building of its category and dimensions.

Finally, B94 has a larger area than a typical multi-family home. After, searching for it in Google Maps, it was confirmed that it is an apartment building. The fact that the real consumption data is much smaller than the estimated demand leads to believe that the apartment block is not fully occupied, meaning most apartments are not in use. This is backed up with the maximum demand value, approximately 8 kW, which is lower than the typical power demand for an apartment block of those dimensions.

## 4.4 Non-residential Buildings

Similarly to the process done to the residential buildings, the separation of the non-residential buildings from the rest of the buildings in the dataset will also be achieved in QGIS. The buildings will be selected in the attribute table by filtering the buildings which do not have the function “Residential Building”. These selected buildings will then be added to a new layer named “Non-Residential Buildings” and a shapefile will be created from it to be able to model it in CEA.

There is a total of 49 non-residential buildings in the dataset. However, some of these buildings had the category of HEATED_ED empty, which gave an error when simulating in CEA. Therefore, these buildings were removed from the layer, leaving 36 buildings to simulate. These buildings’ typologies are mostly schools or kindergartens, university buildings, or buildings whose exact functions were unknown, to which a general use category was assigned.

The results of the simulation in City Energy Analyst are shown in Table 45 in the third Appendix. These results were compared to real energy consumption data, which is shown in Table 45 in the third Appendix.

The following figure shows the energy demand calculated by CEA plotted against the real energy consumption data.

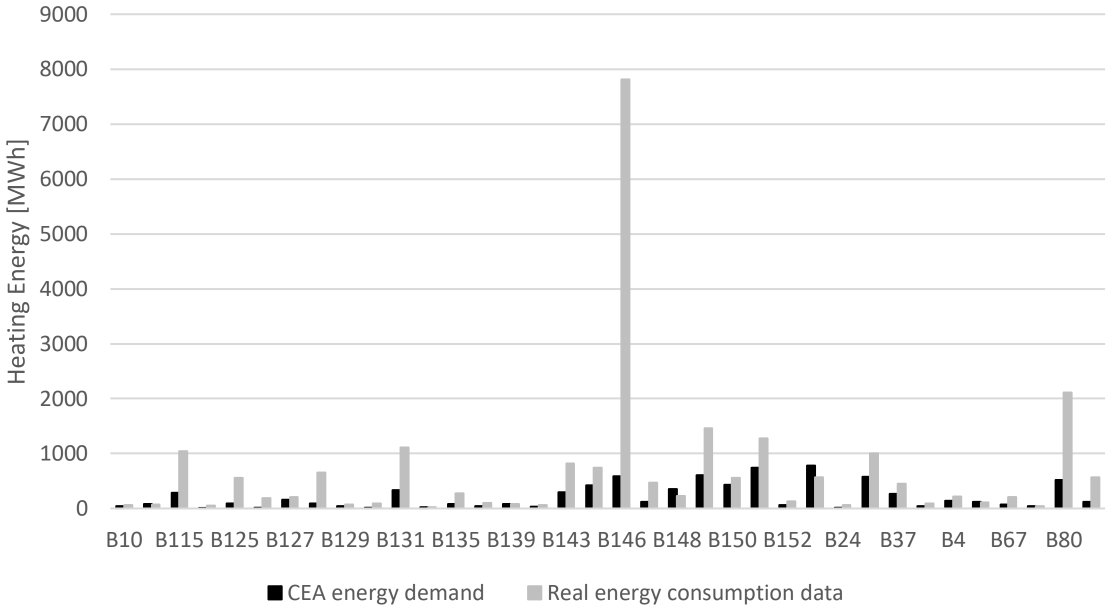

**Figure 5: Comparative of the calculated energy demand in CEA and the real consumption data**

Just as with the residential buildings, the simulation did not achieve the same values as the real data. This could be, like in the previous case, due to the internal losses not being taken into account in City Energy Analyst.

The total sum of the real energy consumption for these buildings was approximately 23580 MWh, whereas the total energy demand estimated by CEA for the buildings was approximately 7715 MWh, which means the demand estimated for this group of buildings was over 3 times less than the real data.

Moreover, the buildings in this group whose energy demand calculated by CEA differs more than 10 times from the real energy consumption are only two, as can be observed in Figure 6.

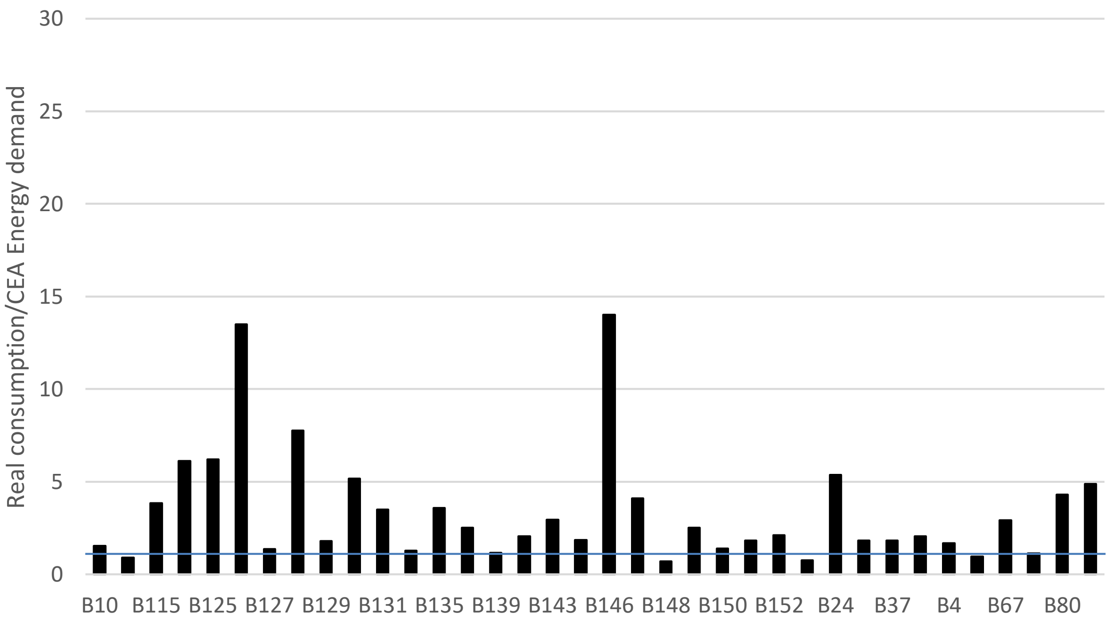

**Figure 6: Relationship between real energy consumption data and energy demand calculated in CEA**

The following table contains the results of the data points exhibiting the most significant deviations. Only the buildings which have energy demand 10 times larger or smaller than the real consumption data will be analyzed. In this case, only two buildings will be included.

**Table 36: Results for the buildings with the most significant deviations**

| | City Energy Analyst | | | Real Data | | | | |
|---|---|---|---|---|---|---|---|---|
| Name | Standard | Af_m2 [m2] | QH_sys [MWh/yr] | Standard | Full load [h] | Max Demand [kW] | Total Demand [MWh/yr] | Real Data/CEA |
| B126 | General use | 6580 | 14,3 | Not specified | 2020 | 91,0 | 193 | 13,5 |
| B146 | General use | 23300 | 585,5 | Not specified | 2210 | 3530 | 8200 | 14,0 |

Firstly, building B126 has real data more than 13 times higher than the estimated demand in this simulation. The reasons for this discrepancy are unknown. However, it is possible that the use of the building used in CEA is incorrect, or that the measured data includes other buildings around B126.

Finally, after a walkthrough of the area, it was discovered that the measured data for building B146 was in fact the measured data for various buildings around B146. This is why the measured data for this building is 14 times bigger than the estimated demand simulated by CEA.

# 5 Discussion

This section will discuss the results presented in the previous section. Graphs with the most relevant results will be included to illustrate the previous results and provide visual aid for the explanations.

It will also validate the results with previous research and give recommendations of what could be done in the future to reduce energy demand in buildings.

## 5.1 Sensitivity Analysis

As observed in the results, energy demand was affected by changing envelope, internal loads, and indoor comfort parameters. All four energy demand types this paper focuses on were affected at least by one of the parameters analyzed, however, the most affected quantity was space heating demand.

Space heating is also the quantity which contributes most to energy demand in general. For instance, if we take a look at the base case, space heating is almost 75% of the total energy demand for heating and more than three times the electricity demand, as can be seen in Figure 7. This is why space heating demand is the quantity where the focus to reduce demand should be.

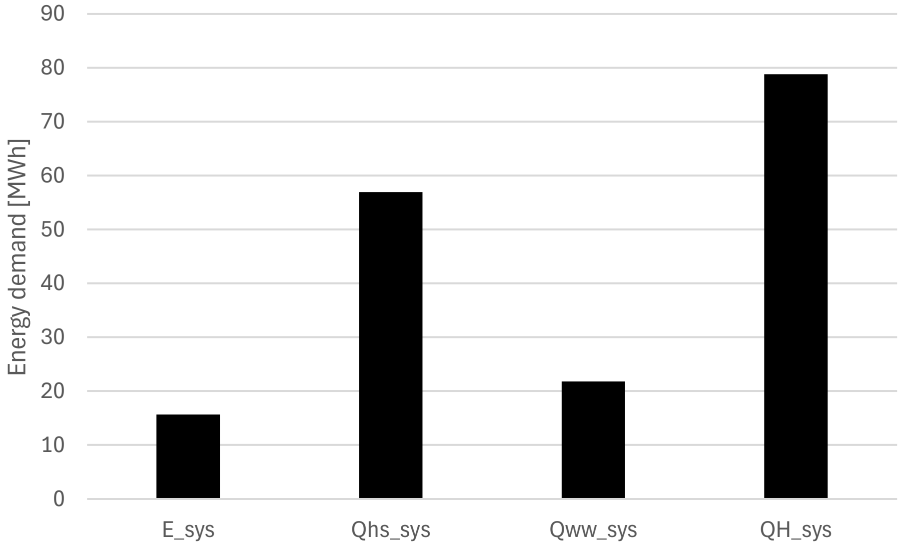

**Figure 7: Energy demand for the base case**

### 5.1.1 Envelope Parameters

As previously mentioned, the envelope of a building is the outer shell of the building, which protects its inside from the outside weather conditions. Therefore, it is reasonable that these parameters affected demand noticeably in some cases.

The most affected quantity in the sensitivity analysis of all envelope parameters was space heating demand. In general, the more insulated a building is, the lower the space heating demand will be, which was proven by the results of the envelope parameters' sensitivity analysis and will be explained in detail below.

Hot water demand was only impacted by the case in which a cellar was added. This will be further explored below.

The electricity demand also varied only when a floor, in this case a cellar, was added to the building. This is because the electrical loads in CEA are proportional to the area [9].

Case 1: Renovations

In the results section, it was stated that space heating demand was the quantity most affected by renovations. Figure 8 shows the space heating demand for the three scenarios simulated in this case.

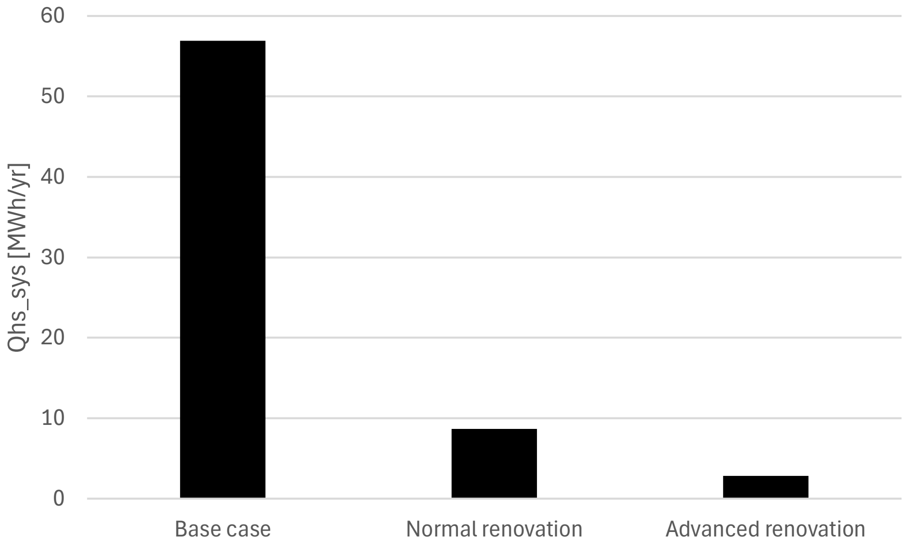

**Figure 8: Space heating demand for case 1**

Given that many parameters have been changed at once, it is not possible to analyze how the individual parameters affect the demand. However, it can be observed that by decreasing the U-values – renovations use materials with lower U-values – the space heat demand also decreases. This is because the U-values quantify the amount of heat that can be transmitted through a material; the lower the value, the less heat that can be transmitted. Therefore, by choosing materials with lower U-values in the renovations, the material prevents more heat from escaping to the exterior and as a consequence, less heating is needed to provide comfort. The lower U-values also stop the heat, or lack thereof, from outside from being transmitted inside, also contributing to the decrease in space heating demand.

Additionally, the solar heat gain coefficient assesses the how much solar radiation is admitted through a window. The higher the value, the more radiation admitted. This means that when the solar heat gain coefficient is increased, the heat demand would decrease because part of the heating demand would be provided by solar radiation through the windows. This contradicts with the results observed in case 1, since the solar heat gain coefficient is lower with the renovations. Nevertheless, as previously stated, the effects of changing individual parameters cannot be properly studied in this case.

Something similar happens with the emissivity coefficient. As it increases, more heat is emitted into the room, which means less heating would be needed, yet in this case a lower emissivity coefficient leads to a decrease in demand.

A study carried out by Lombardi et al. [18] shows that renovations can reduce space heating loads by 31 to 37%. The study considered single-family buildings from construction periods from before 1975 to 2020, with different U-values for their envelope elements, depending on the construction period and climatic zone. The U-values chosen for the object of study of this paper fall within the ranges of the U-values of Lombardi et al.'s study. The U-values for the considered renovation also a range of values, which resemble the normal renovation scenario more than the advanced renovation scenario. The reason why the reduction potential of Lombardi et al.'s study is smaller than the one estimated by CEA is because the sensitivity analysis in this paper considers one multi-family home from one specific construction period, the 1970s, in Germany, whereas the other study considers many single-family buildings in Italy from construction periods from the 1970s onwards.

Case 2: Cellars

All quantities of demand were affected by adding a cellar and changing the heating proportion of it. The greatest effect in proportion was the electricity demand, with an increase in 50%. Figure 9 illustrates the changes in demand for each quantity, due to the changes in each scenario for this case.

The changes in demand for each quantity will be explored below.

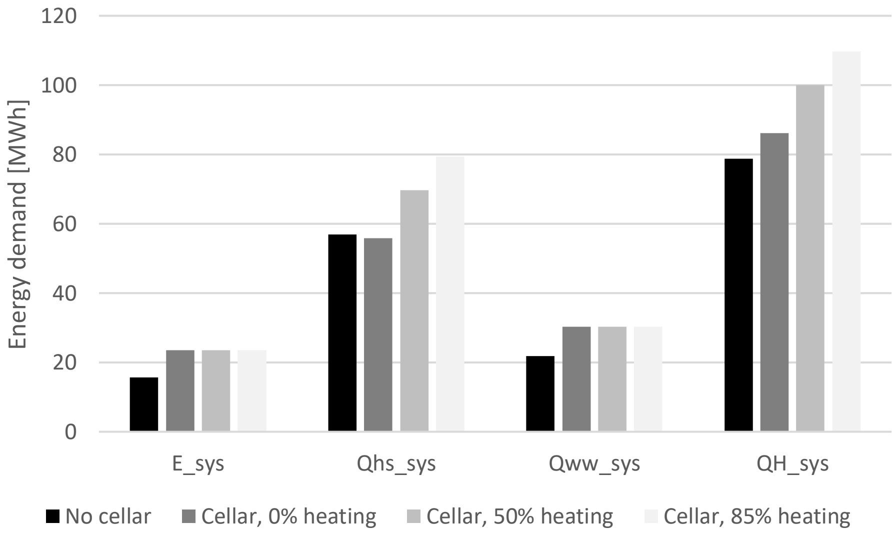

**Figure 9: Energy demand for case 2**

Firstly, the electricity demand will be analyzed. Figure 10 shows the electricity demand for each scenario in case 2.

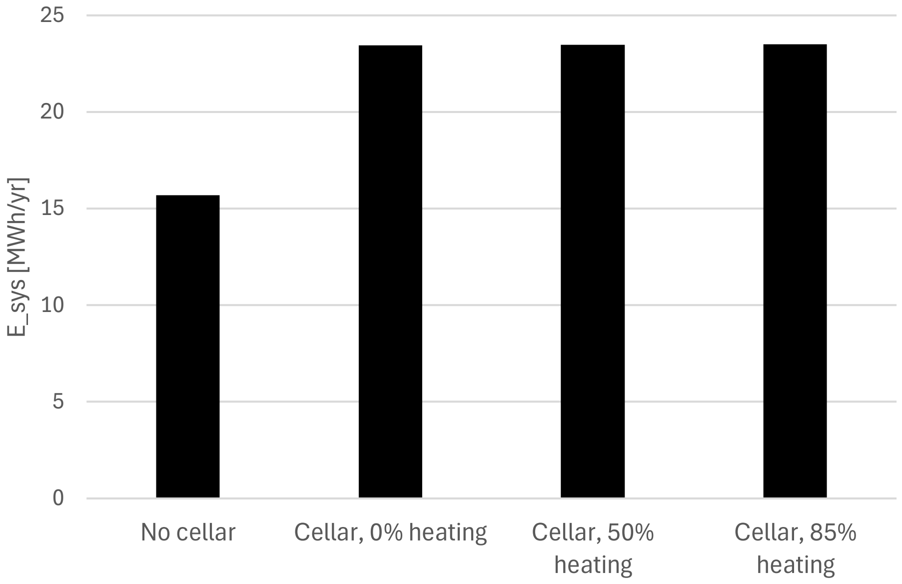

**Figure 10: Electricity consumption for case 2**

It can be observed in Figure 10 that the electricity consumption for the three scenarios with a cellar is practically the same. This is probably because the electricity demand is almost solely affected by the gross floor area, and not affected by change in space heating. This assumption has been reached due to the fact that the electricity consumption has increased in approximately 50%, which is the exact increase in gross floor area. As previously mentioned, electricity demand includes lighting, appliances and electronics. However, the contribution of lighting to energy demand is considerably higher than the contribution of appliances and electronics [6]. This is why electricity demand is highly affected by gross floor area: the amount of lighting in a building is proportional to the gross floor area. The more area there is, the more amount of lighting is required to illuminate the whole area, especially in this case, since cellars do not have natural light. Also, the calculation of electricity demand by City Energy Analyst is directly proportional to the area of the building, as previously mentioned [9].

Next, the space heating demand will be investigated. Figure 11 shows the space heating demand for each scenario in case 2.

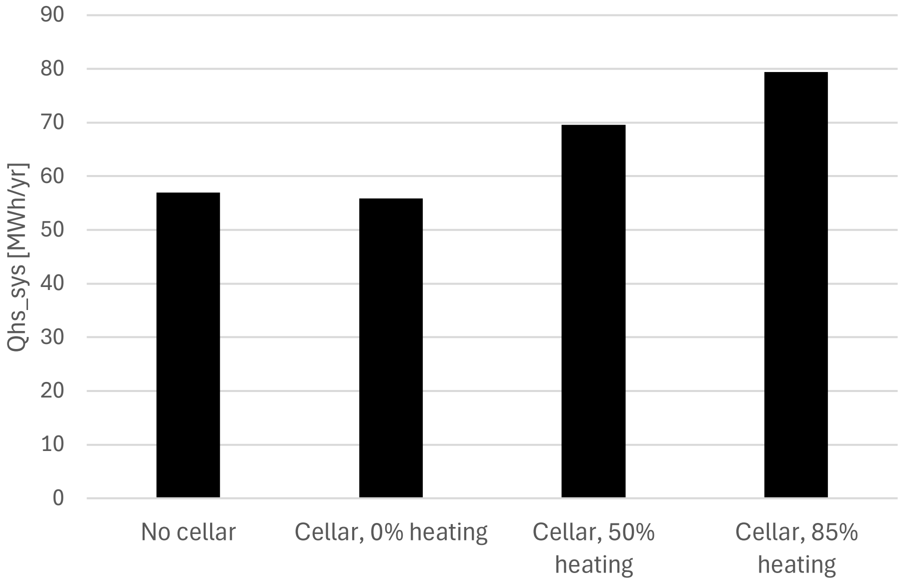

**Figure 11: Space heating demand for case 2**

The increase in space heating demand is 22% for the cellar with 50% heating and 39% for the cellar with 85% heating. This is almost directly the percentage increase in gross floor area, which is 50% in both cases, multiplied by the amount of heating in the cellar (in percentage). This is logical, since the change in each scenario, other than adding a cellar, is directly increasing the space heating.

The scenario with no heating in the cellar has a 2% decrease in space heating demand with respect to the base case. This could be because the cellar could act as an insulator for the building, since it is surrounded by thermal mass, which has a higher temperature than the outside air during the winter. This 2% decrease is also included in the other two scenarios, which is why the percentage increase in space heating demand is not exactly directly the percentage increase in conditioned area (Af_m2).

Now, the hot water demand for each scenario in this case will be explored. Figure 12 shows the hot water demand for case 2.

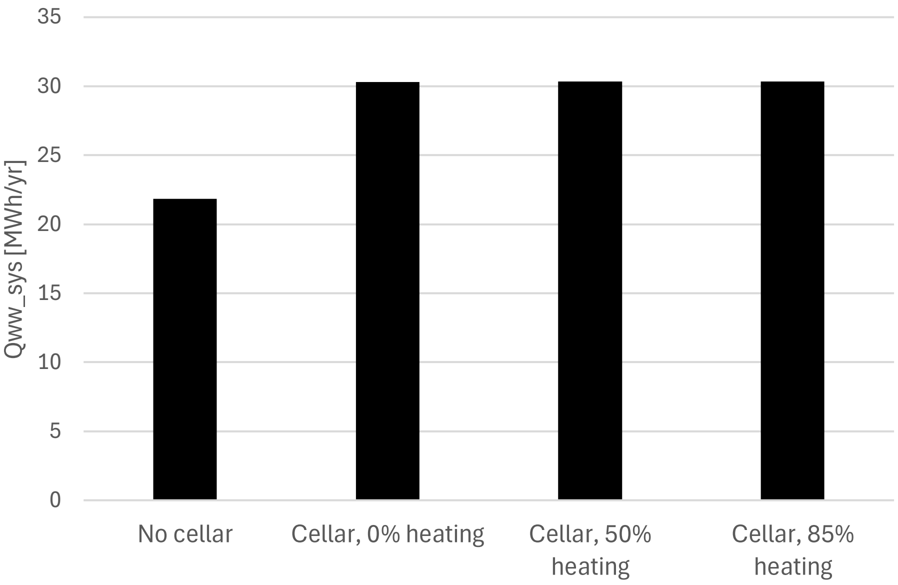

**Figure 12: Hot water demand for case 2**

Similar to the electricity consumption, Figure 12 shows that the hot water demand for the three scenarios with a cellar is almost equal, which leads to believe that hot water demand is also proportional to the gross floor area and not affected by the changes in space heating. However, the percentage change in demand in this case, 39%, is not the same as the percentage change in gross floor area, 50%. This could be because hot water is used for bathing, cooking, cleaning, and doing laundry, amongst other activities. Adding a cellar increases the amount of cleaning in the building but does not change significantly the other activities.

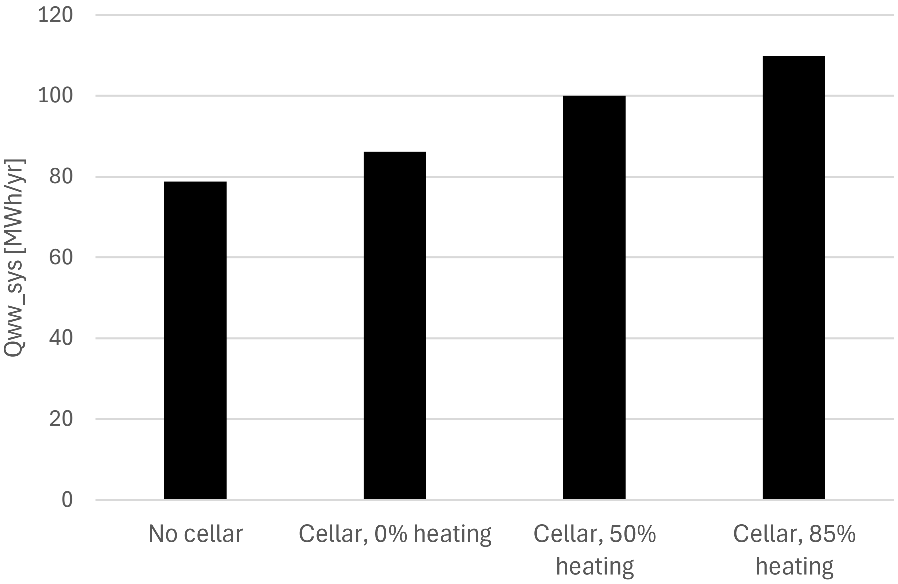

**Figure 13: Total energy demand for heating for case 2**

The change in total energy demand for heating is a combination of the changes in space heating demand and hot water demand, together with the process heating demand, which will not be analyzed. This is why in Figure 13 almost a sum of both changes can be noticed.

### Case 3: Window to Wall Ratio

The results of case 3 show that window to wall ratio is not an important factor when it comes to reducing energy demand. Only space heating demand had a noticeable change in the different scenarios, and even this was negligible. This is why the graphs that illustrate these changes will be presented as percentage changes in demand with respect to the base case. Otherwise, no change would be visually appreciated.

For case 3, the first two sub-cases (one façade at a time ±20%) will be analyzed separately and the rest of cases will be analyzed together, since there is a pattern in the changes in demand that can be applied to all of them.

### Case 3.1 and 3.2: One Façade at a Time ±20%

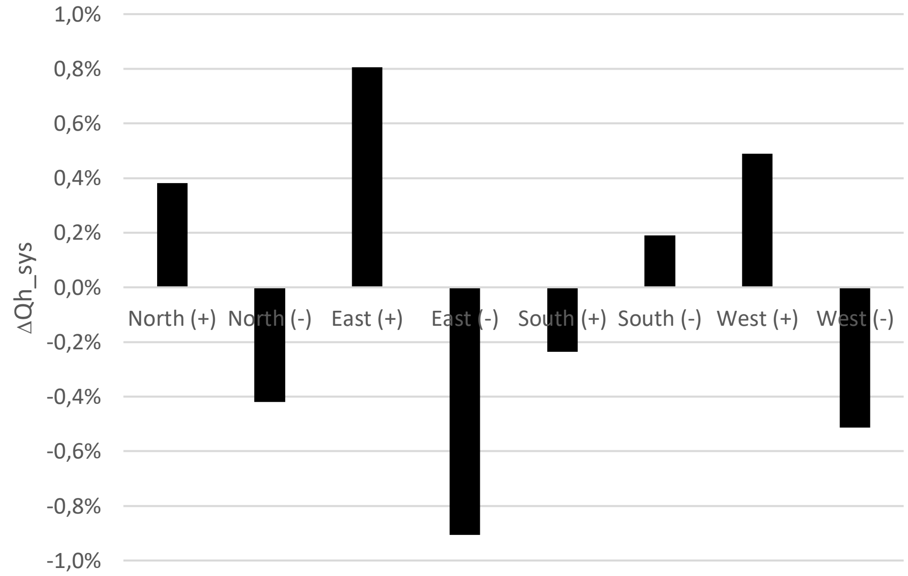

**Figure 14: Changes in space heating demand for heating for cases 3.1 and 3.2**

As can be seen in Figure 14, an increase in the window to wall ratio leads to an increase in space heating demand, except for the South façade. This is because windows usually have a higher U-value than walls, leading to a higher heat loss through them.

The ratios in the standard scenario are not the same for all four façades; the Northern façade started with a ratio smaller than half the rest of the values. Therefore, since the increase in ratios was done as a percentage, the total change for the Northern façade was smaller than for the rest, which explains why its effect in space heating demand is smaller than for the Eastern and Western façade.

The exception of the Southern façade is because in the Northern hemisphere, the Southern façades face the Sun, which means that the radiation is the highest in this side, which compensates the increase in heat loss. This, however, would mean that an increase in the window to wall ratio in the Northern façade would lead to the highest increase in demand, which is not the case, but as previously explained, this effect is counterbalanced by the smaller total increase in window to wall ratio, leading to a lower increase in heat loss.

The variation in demand as a consequence of changing the window to wall ratio is less than 1%, meaning this parameter does not affect energy demand significantly. It is worth mentioning that changing the window to wall ratio of one façade by 20% means that the window to wall ratio of the whole building changes by 5%, which is a small variation. However, as will be observed by the following cases, even a variation of 20% in the window to wall ratio of the whole building will not affect energy demand distinctly.

A study by Marino et al. [19] shows that varying the window to wall ratio of a building barely changes the heating demand. The electricity demand, however, should be affected because lighting demand should decrease with a higher window to wall ratio.  research investigated buildings in 12 cities in Italy for three different building types, classified by their envelope characteristics.

The results for decreasing the window to wall ratio of each façade by 20% are very similar to the previous case but opposite.

Cases 3.3 - 3.8:

The graphs for the changes in demand will be presented showing the increase and decrease in window to wall ratio together, firstly for two façades at a time, then three façades at a time, and, finally, four façades at a time.

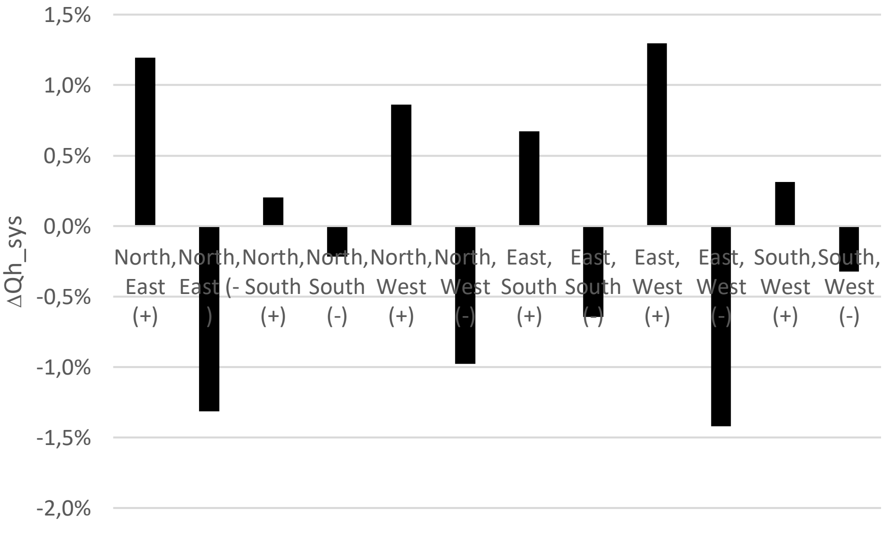

**Figure 15: Changes in space heating demand for heating for cases 3.3 and 3.4**

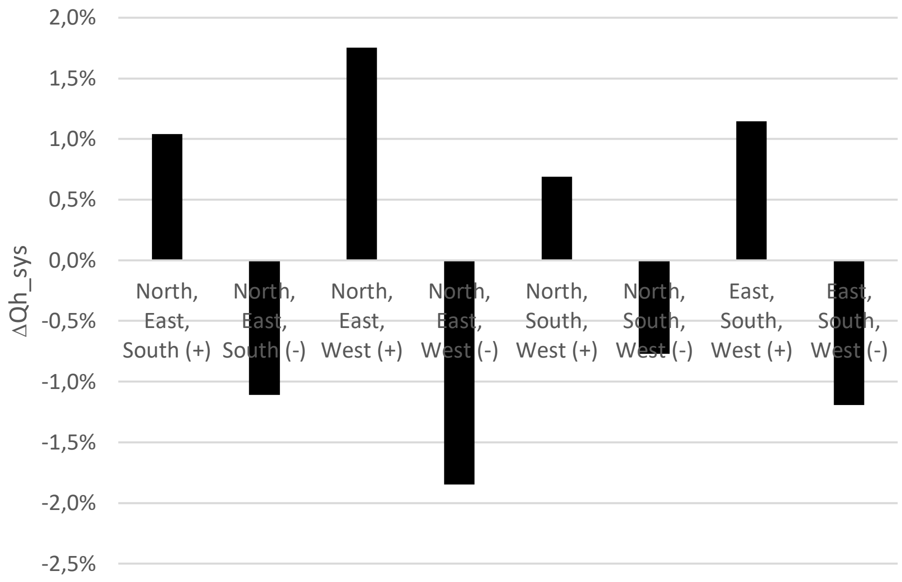

**Figure 16: Changes in space heating demand for heating for cases 3.5 and 3.6**

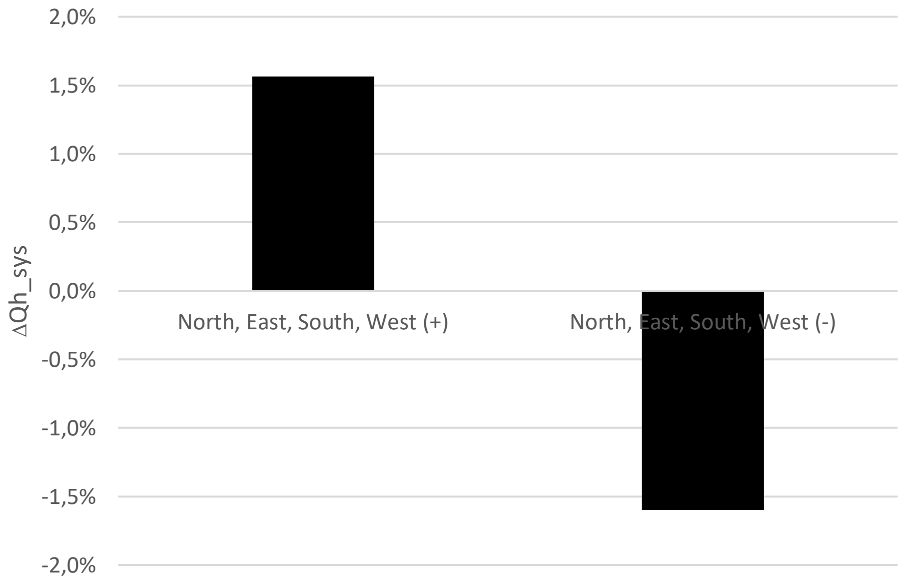

**Figure 17: Changes in space heating demand for heating for cases 3.7 and 3.8**

All these results show that the effect of combining an increase or decrease in the window to wall ratio of more than one façade is directly the sum of the increase or decrease of the energy demand due to changing the window to wall ratio of each façade separately.

As previously stated, it can de deduced that changing window to wall ratio in a building does not significantly affect the energy demand given that, even when changing the ratio in all four façades by 20%, the change in space heating demand varies by less than 2%.

Case 4: Construction Standard

The effect of the construction standard on energy demand was minimal. The only value slightly affected was the space heating demand. A graph with the percentage variations of space heating demand for case 4 instead of the absolute values is presented in Figure 18, since otherwise the change would not be appreciated.

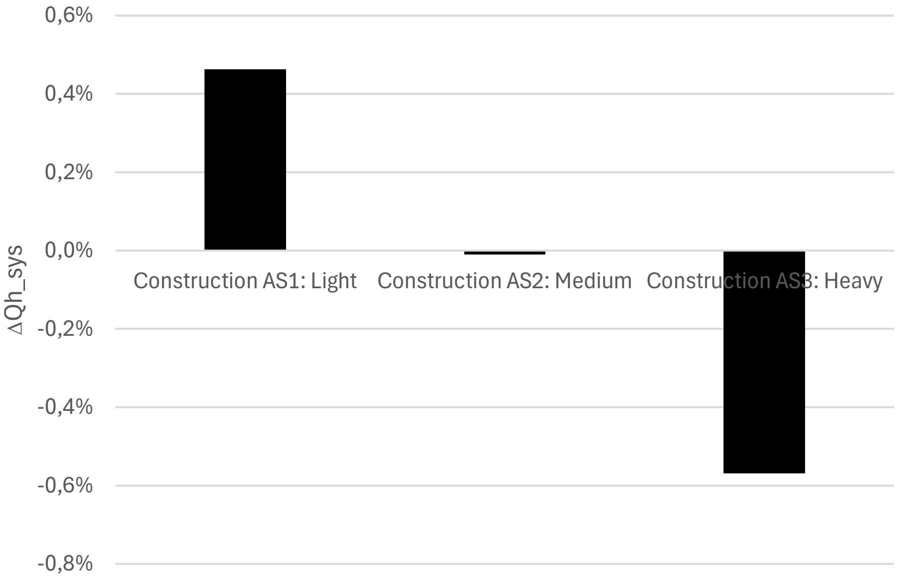

**Figure 18: Changes in space heating demand for heating for case 4**

The higher the internal heat capacity, the lower the space heating demand. This is because the internal heat capacity of a material quantifies the amount of heat a material can store and then release into the ambient. This means that the higher this value, the more capacity a material has to release heat, reducing heating demand.

Nevertheless, the relationship is not directly proportional because a decrease of approximately 33% in internal heat capacity affected the demand by an increase of approximately 0,5%, and an increase of 85%, which is more than double 33%, led to a decrease in demand of less than 0,6%.

Case 5: Tightness

The only noticeable effect by changing the tightness was on space heating demand. Figure 19 presents a graph with the space heating demand for the different scenarios in case 5.

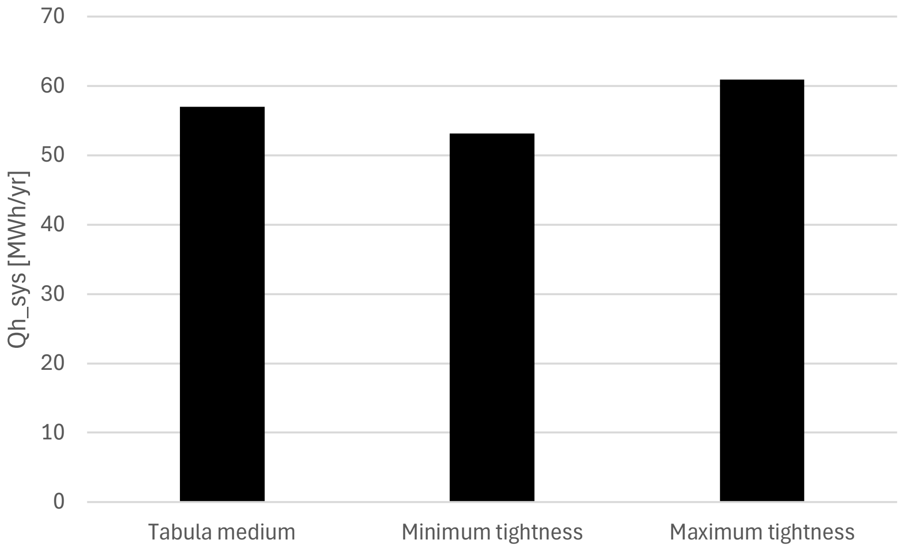

**Figure 19: Space heating demand for case 5**

Figure 19 suggests that the lower n50, the lower the space heating demand. This is logical because it means that there are less air exchanges per hour, implying that there is less heat loss from the inside and less cold air coming from the outside.

Nothing can be inferred about the proportionality between demand and tightness because the changes made are the same in increase and decrease of tightness, leading to an equal increase and decrease in change in demand respectively.

Nevertheless, the effect tightness has on space heating demand is not substantial, since increasing or decreasing the air exchanges per hour by 40% only changes the space heating demand by less than 7%.

Case 6: Shading

The results for case 6 show that shading only affects space heating demand.

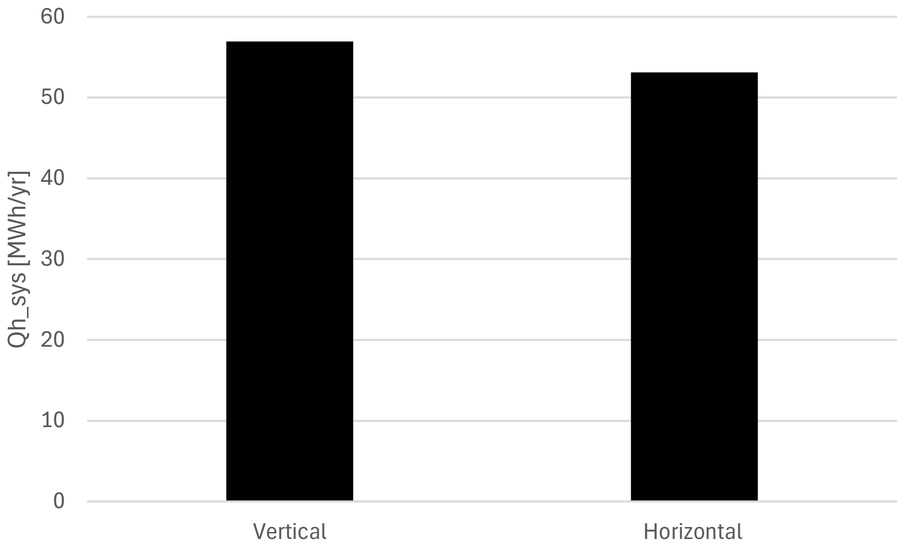

**Figure 20: Space heating demand for case 6**

It can be seen in Figure 20 that the higher the shading coefficient, the lower the space heating demand. This is contrary to what could have been predicted because it would make sense that less shading leads to more solar radiation through the window and, therefore, a lower space heating demand.

The effect, however, is not very significant, since the space heating demand only varies by less than 7% when the shading coefficient has been altered by 25%.

### 5.1.2 Internal Loads and Indoor Comfort Parameters

The internal loads refer to the heat loads caused by residents or equipment in the building, such as appliances or computers. In this case, the parameter changed was the occupancy density, which is not exactly the heat load due to people. However, by changing the occupancy density, the heat load due to people changes by $m^2$. The indoor comfort parameters are setpoint and setback temperatures, ventilation rates or humidity ranges to ensure user comfort in the building.

Changing occupancy density affected space heating demand, since the amount of heat which is given off to the ambient was altered by this change, thus affecting the amount of extra heat needed in a room. The alteration of indoor comfort parameters also caused an effect on space heating demand because the changes of these parameters affect the power used by the equipment providing heating, in this case, because more or less power will be required to reach the different setpoints of the heating device.

Hot water demand was only impacted by the occupancy density. The reasons for this will be explained below.

The electricity demand was not affected by changes in the parameters of this section, since the electricity demand estimated by CEA does not depend on usage [9], contrary to what was stated by Mosteiro-Romero et al. [12].

Case 7: Occupancy Density

The heating demand in this case only varies a maximum of 3%. The lower the occupancy density, the higher the heat demand because of the heat load due to people, as previously mentioned. However, this contribution is not significant, as seen in the results.

Figure 21 shows the warm water demand for each scenario of case 7.

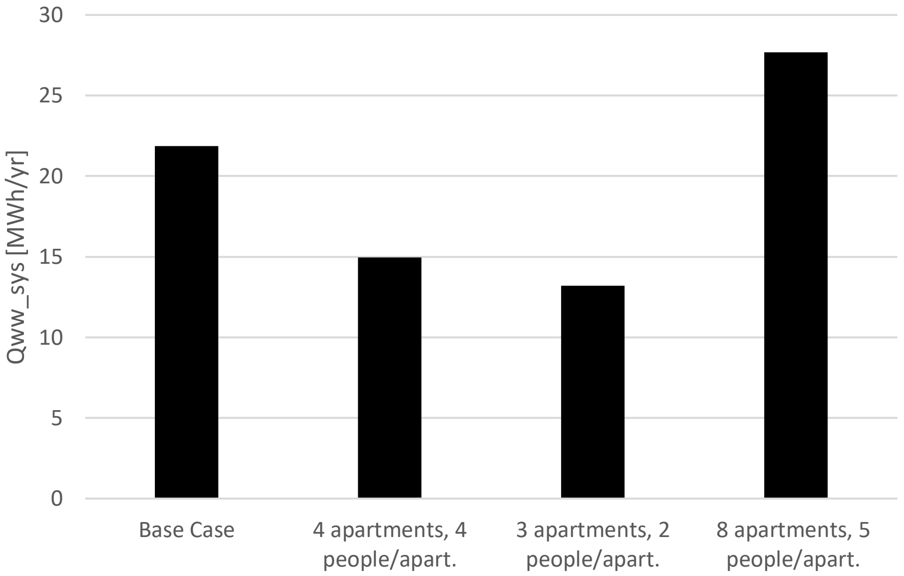

**Figure 21: Changes in warm water demand for case 7**

A higher occupancy density leads to a higher demand in warm water, as seen in Figure 21. Warm water is mostly used for showers, cooking, laundry, cleaning, and sometimes heating. Except for the case of heating, the rest of these activities are repeated more when there are more people living in the building. Therefore, it makes sense that the demand for warm water increases when the occupancy density increases.

Scenario 1 has a decrease of 14 people, which is approximately 50% of the initial amount of people in the building. The decrease in warm water demand for this scenario was approximately 30%, as demonstrated in Figure 21. For scenario 2, the decrease in people was 24 people, corresponding to an 80% decrease with respect to the base case. The decrease in warm water demand is 40%. Finally, scenario 3 has 10 more people than the base case, an increase in 33%. This scenario has an increase in warm water demand of a little over 25%. This shows that warm water demand is not directly proportional to the number of people living in the building.

Case 8: Temperature Setpoints and Setbacks

The results for case 8 show that only space heating demand is affected by altering setpoint and setback temperatures. Figure 22 presents a graph with the space heating demand of the different scenarios for case 8.

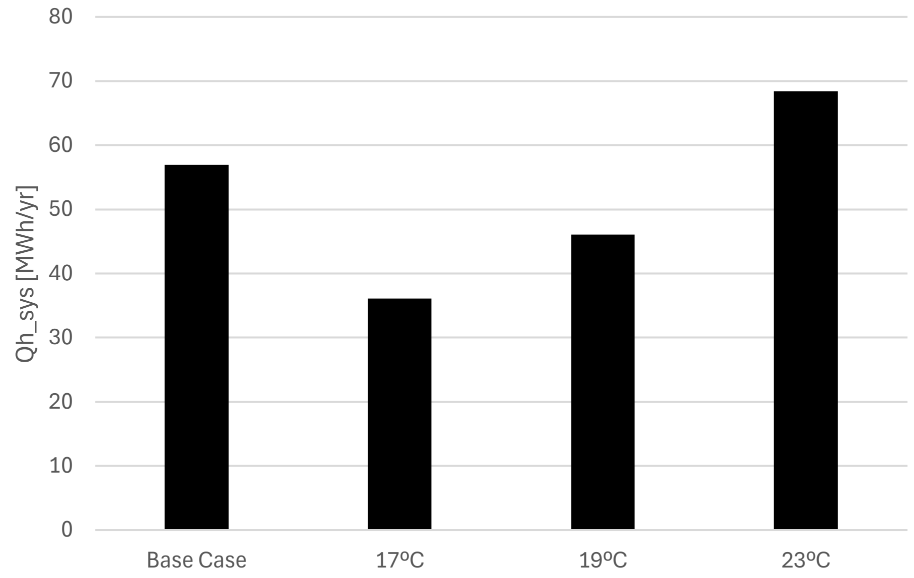

**Figure 22: Space heating demand for case 8**

Figure 22 shows that the lower the setpoint temperature, the lower the space heating demand. This is evident because the system is required to reach a lower temperature, which requires less heat energy.

Sperber et al. (2024) estimated, for a single-family home of the 1970's, a gas consumption of approximately between 18 and 23 MWh/year for a setpoint temperature of 17ºC, between 22 and 26 MWh/year for 19ºC, between 25 and 29 MWh/year for 21ºC, and between 28 and 31 MWh/year for 23ºC. The range in values is because the study was made for two different years; one considered a warm year, and one considered a colder year. Not only the demand is considerably smaller in Sperber et al.'s study than in this case, but also the change in demand between scenarios. This is because the study was made for single-family homes, whereas this case studies a multi-family home. Moreover, setback temperatures were used from 6pm to 10pm in the 2024 study, which was not the case for case 8.

In both Sperber et al.'s study and case 8, the changes in demand seem to be proportional to the changes in setpoint temperatures.

Case 9: Temperature Schedules

Similarly to the previous case, only space heating demand is affected by the temperature schedules.

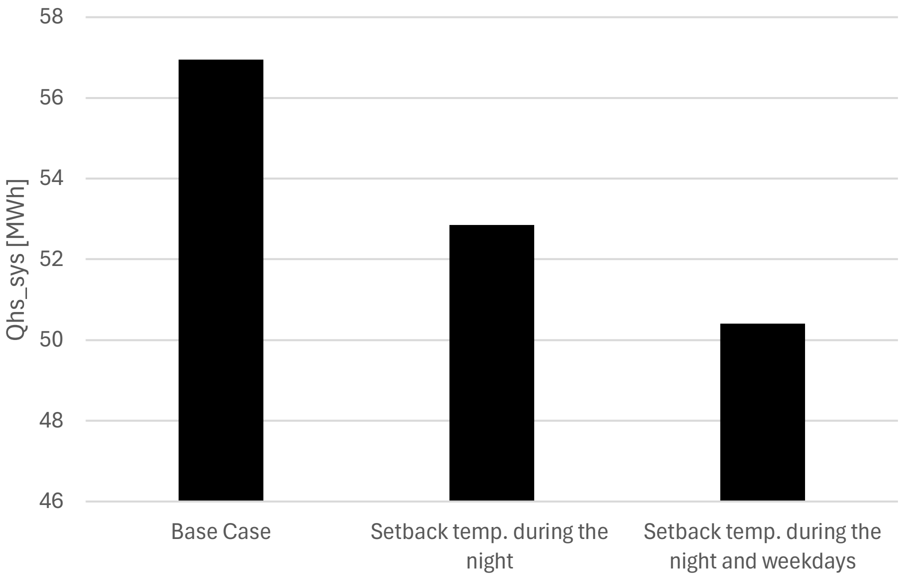

**Figure 23: Changes in space heating demand for case 9**

The more hours the setback temperature is used, the lower the space heating demand will be. This is because using a setback temperature is like lowering the setpoint temperature for a given number of hours, which is what was analyzed in the previous case.

The first scenario uses the setback temperature for 8 hours a day, which is a total of 56 hours per week and 2912 hours in a year. This decreased the space heating demand in a little over 7%. The second scenario has an extra 7 hours of setback temperature from Monday to Friday. This adds up to a total of 91 hours per week and 4732 hours per year. This scenario reduced space heating in more than 11%. This shows that the number of hours that setback temperature is used is directly proportional to space heating demand.

Case 10: Temperature Setpoints, Setback and Schedules

Since it is a combination of scenarios taken from cases 8 and 9, it is justified that the scenarios in this case also only affect space heating demand.

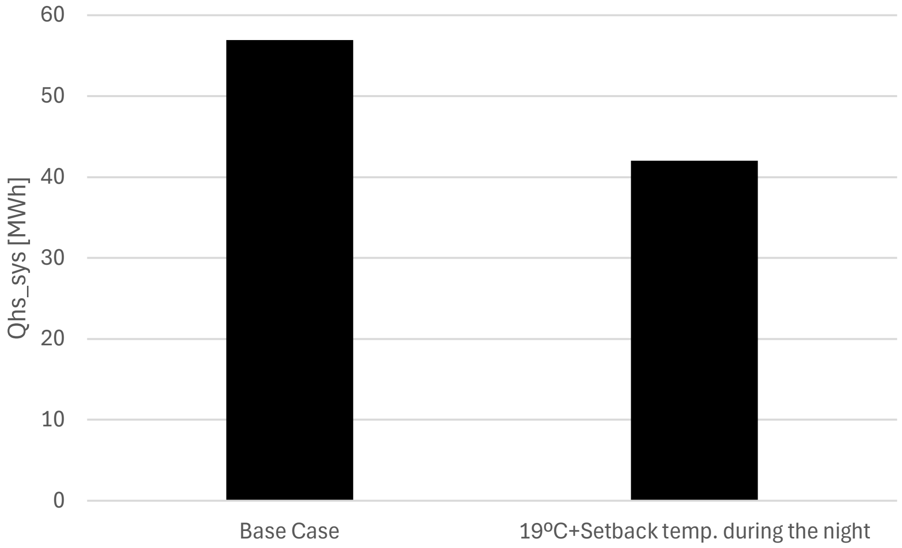

**Figure 24: Changes in space heating demand for case 10**

Figure 24 shows that the decrease in space heating demand for this case is approximately 15 MWh, which is the sum of the decrease for the scenario in case 8, where the setpoint temperature was 19ºC, and the scenario in case 9, where the setback temperature was set during the night. This means that, just as in the case with the window to wall ratio, when scenarios are combined, the effects of each scenario separately are added together.

### 5.1.3 Summary of the Sensitivity Analysis

All of the parameters studied in every case contributes to changes in demand when altered. These changes are greater in some cases than others. Table 37 shows a qualitative analysis of the contribution to the different types of energy demand that each of the parameters studied has.

**Table 37: Qualitative analysis of the contribution of each parameter to energy demand**

| | Renovations | Surface Area | Window to Wall Ratio | Construction Standard | Tightness | Shading | Occupation | Temperature Setpoints and Schedules |
|---|---|---|---|---|---|---|---|---|
| Electricity demand | | ↑↑↑ | | | | | | |
| Space heating demand | ↓↓↓ | ↑↑ | ↑ | ↓ | ↓↓ | ↓↓ | ↓ | ↓↓↓ |
| Hot water demand | | ↑↑ | | | | | ↑↑ | |
| Total energy demand for heating | ↓↓↓ | ↑↑↑ | | ↓ | ↓ | ↓ | ↑↑ | ↓↓ |

It can be observed in Table 37 that all parameters affect space heating demand in some way. This is the type of demand for which more efficiency measures have to be developed for, since it is the one which most contributes to total demand, as seen in the results. The cases where this quantity was most affected was when renovations were simulated and when temperature setpoints and schedules were altered.

The European Union aims to have 40% of its buildings refurbished to become nearly zero energy buildings (NZEB) by 2050. NZEB are buildings which use almost exclusively the energy they have available on-site from renewable sources. They have the potential to save more than 90% in energy, which is what was achieved with the advanced refurbishment scenario in case 1 [20].

In the case of temperature setpoints, it was observed that a 20% reduction in space heating demand could be achieved by lowering the setpoint temperature by 2ºC. Considering the base case had a setpoint of 21ºC, this means that by changing the temperature setpoint by 10%, the effects were double. If the schedules measure is added to this, the effect achieved is even greater. Lowering the setpoint temperature is something that can easily be carried out by individuals at home, which impacts energy demand considerably. This means that governments should make this recommendation to citizens to contribute to lower space heating demand.

Additionally, hot water demand is affected by surface area and occupancy. There is not much that can be done about reducing hot water demand according to this scenario. However, hot water demand is half the space heating demand in the base case, so, by reducing it, the effects on the total demand will not be life changing.

Finally, the simulations for electricity demand were inaccurate, since they only took into account the changes in surface area and not the usage [12]. Therefore, this study does not indicate well the measures that could be taken in order to reduce electricity demand.

## 5.2 Case Study

The results show that the real consumption of the studied buildings differs from the estimated demand by CEA. The table below shows the comparison between the deviation from reality of the residential and non-residential buildings.

**Table 38: Comparison of the deviation of residential and non-residential buildings**

| | Residential Buildings | Non-residential Buildings |
|---|---|---|
| Total deviation | 1,5 | 3,2 |
| Mean deviation | 2,8 | 3,4 |
| Mean positive deviation | 6,6 | 3,7 |
| Mean negative deviation | 8,6 | 1,2 |

The total deviation was calculated by dividing the measured data by the simulated data in CEA. The mean deviation was calculated by taking the average of all the total deviations. Additionally, the mean positive deviation was calculated by taking the mean of all the deviations which were greater than one, meaning the real data was greater than the simulated demand. Finally, the negative deviation was calculated by taking the mean of all the deviations which were smaller than one, meaning the simulated demand was larger than the real data.

The first two values make it seem as though the estimation for non-residential buildings is much worse than the one for residential buildings. However, the fact that almost none of the non-residential buildings overestimated the demand, and those which did were very close to the real value has to be taken into consideration. This means that the compensation which happened for the residential buildings did not happen in this case. This is why a difference between the positive and negative deviations was made.

The mean positive and negative deviations show that the simulation for non-residential buildings was more accurate than for the residential buildings. As previously mentioned, the non-residential buildings which overestimated demand were very close to reality, only 20% above it. The underestimation for this type of buildings was almost 4 times lower than reality, which is still in the same order of magnitude. The average underestimation and overestimation for residential buildings was almost 7- and 9-times reality respectively, which is more than double than for the non-residential buildings.

The inaccuracies for the estimation of demand by CEA have been found to be caused by lack of information on building occupancy, the fact that some buildings measure the consumption of various buildings around it, and occasional misinformation on the number of stories or typology of a building.

# 6 Life Cycle Assessment

This section will explain how the life cycle assessment of the scenarios analyzed above could be carried out using City Energy Analyst. However, the actual life cycle assessment of the scenarios falls outside the scope of this Master Thesis.

Firstly, a life cycle assessment evaluates the inputs, outputs and environmental impacts of a defined system during its life cycle [20]. It has four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal and scope definition establishes the function of the system, the functional unit, which is the unit in which the inputs and outputs are measured, and the system boundaries. The inventory analysis deals with the data collection for the process within the system's boundaries. It includes energy and raw material inputs, products, co-products and waste, and emissions to the air or discharges to water or soil. Moreover, the impact assessment's objective is to evaluate the effects of environmental harm on humans and ecosystems. Finally, the interpretation consists of three stages: evaluation, where the main conclusions are drawn, reporting, and critical review.

For the particular case of a building's life cycle assessment, the following steps would be taken in order to carry it out.

Goal and scope: The function of the system would be the construction and operation of the building. The functional unit could be m$^2$, just as in a study performed by Adalberth et al. [7], where they analyze which of the phases of the buildings' life cycle had the greatest impact on the environment. Another option for the functional unit could be the number of people living in the building, in the case of residential buildings, which was one of the functional units used by Norman et al. [8] in their study. Finally, in the case of a cradle-to-grave analysis, which is the most popular system used [23], the system boundaries would include the stages from achieving the raw materials to the waste treatment of the debris, once the building is demolished at the end of its life cycle.

Inventory analysis: The essential information regarding building materials for the construction phase are the type and quantity used and it is usually obtained from the bill of materials. For the operation of the building, the input is mainly energy for heating, cooling, hot water, lighting, and appliances. Energy input must also be considered in the construction stage, previously mentioned, and the maintenance stage. This last stage includes replacing equipment and materials during the lifespan of the building [23].

Impact assessment: For this stage, there are two approaches: the mid-points method assesses impacts related to climate change, such as eutrophication or acidification, whereas the end-points method focuses on the damages caused to human beings and the environment [24].

Interpretation: This phase mainly consists of evaluating the impact assessment and validating the data by executing sensitivity analyses and comparing it to previous research papers [23].

There is another tool called life cycle energy analysis, which takes into account all the energy inputs that go into a building, from its manufacturing to its demolition, including its use. It includes embodied energy, operating energy and demolition energy. The embodied energy is the energy contained in all the materials that were required to construct the building and its installations, including the energy required to extract the materials, transport them and assemble them. The operating energy is the energy used to maintain the comfort conditions of the building, that is, energy for heating, cooling, hot water, lighting, etc. Demolition energy is the energy required to tear down the building at the end of its life [20].

City Energy Analyst has a function, which calculates the emissions and primary energy due to building, construction, operation, dismantling, and induced mobility in a particular scenario. It separates the emissions in embodied emissions and operation emissions. The embodied emissions are the emissions caused by the construction and dismantling of the building, including the emissions of retrieving the materials, transporting them, assembling them, and their waste treatment. The operation emissions are the emissions caused by the supply systems, including how the energy is produced.

# 7 Summary and Outlook

## 7.1 Summary

This Master Thesis has focused on using UBEM, specifically CEA, to model how different energy efficiency measures affect the demand in buildings and to estimate the energy demand of various buildings in a selected area of study.

Firstly, a multi-family home in the South of Germany was used to conduct a sensitivity analysis on it by changing different parameters of the building. These parameters included envelope, occupation, and indoor comfort parameters. The objective of this sensibility analysis was to investigate how these parameters affected energy demand, specifically electricity, space heating, and hot water demand, as well as the total energy demand for heating. The results of the sensitivity analysis showed that space heating demand is by far the biggest contributor of total energy demand in buildings, and that changing the values of the parameters affected this quantity the most out of all four quantities analyzed. Electricity demand was affected by surface area and hot water demand was affected by surface area and occupation.

Furthermore, the energy demand of a group of buildings of a selected southern German area was estimated by CEA and then the simulation was validated by real data of the consumption of these buildings. The results of the simulation were different to the measured data of the energy consumption of the buildings. This is because the dataset used to model the buildings was not fully accurate, which led to miscalculations. Additionally, CEA has a series of assumptions which simplify the calculations, leading to less accurate results.

Finally, an LCA was carried out for a general case of the construction and operation of a building.

## 7.2 Outlook

This study has proved that renovating older buildings is the most effective method to improve energy efficiency in buildings. The recommendation is to reach European Union goals to have 40% of buildings refurbished to nearly zero emission buildings by 2050.

Another efficient measure to improve energy efficiency would be lowering setpoint temperatures for heating from 21ºC to 19ºC. This will decrease the space heating demand of buildings by 20%, as well as benefitting the user by reducing energy costs.

CEA estimates energy demand in buildings in a satisfactory way. However, the electricity demand calculation, for instance, takes into account a series of assumptions that simplify the model, making the estimation inaccurate. This means that this UBEM software is not the best option to estimate electricity demand.

# 8 Alignment with Sustainable Development Goals

The Sustainable Development Goals are 17 objectives adopted by all member states of the United Nations to make sure there is prosperity for all by 2030. This Master Thesis aligns with the following goals.

Firstly, the thesis is in direct alignment with SDG 7: Affordable and Clean Energy, which highlights the importance of ensuring universal access to affordable, reliable, sustainable and modern energy. It focuses on the modeling, validation and evaluation of urban energy systems in order to promote efficient and sustainable energy solutions that benefit urban communities.

Moreover, the sustainability assessment component of the thesis bears close relevance to various other Sustainable Development Goals. For instance, SDG 11: Sustainable Cities and Communities emphasizes the importance of making cities inclusive, safe, resilient, and sustainable. By evaluating the sustainability of district energy systems, the thesis directly contributes to achieving sustainable urbanization and infrastructure.

Additionally, it addresses SDG 13: Climate Action by exploring energy systems that can contribute to combatting climate change impacts. Urban energy systems, if designed and operated sustainably, have the potential to reduce greenhouse gas emissions, improve energy efficiency, and encourage renewable energy integration, thus supporting efforts to combat climate change and its impacts.

Finally, aligns with SDG 9: Industry, Innovation, and Infrastructure, as it involves modeling and validating innovative energy infrastructure systems. By promoting innovation in energy technologies and infrastructure development, the research contributes to fostering inclusive and sustainable industrialization and innovation, as outlined in SDG 9.

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# Appendix

## A) First Appendix

Parameters of the base case

**Table 39: Characteristics of the base case**

| Building Type | MFH_F |
|---|---|
| Af_m2 [m$^2$] | 742,206 |
| Aroof_m2 [m$^2$] | 436,590 |
| GFA_m2 [m$^2$] | 873,183 |
| Height_ag [m] | 6 |
| Floors_ag | 2 |
| Height_bg [m] | 0 |
| Floors_bg | 0 |
| Void_deck | 0 |
| Es | 0,85 |
| Hs_ag | 0,85 |
| Hs_bg | 0 |
| Ns | 0,85 |
| Wwr_north | 0,07869 |
| Wwr_east | 0,187066 |
| Wwr_south | 0,225233 |
| Wwr_west | 0,187066 |
| Cm_Af [J/m$^2$K] | 162.000 |
| N50 | 2,5 |

| | |
|---|---|
| U_roof [$W/m^2K$] | 0,51 |
| A_roof | 0,55 |
| E_roof | 0,91 |
| R_roof | 0,45 |
| GHG_roof_kgCO2m2 [$kgCO_2/m^2$] | 112 |
| Rf_sh | 0,6 |
| Type part wall | Internal partition in brick |
| U_wall [$W/m^2K$] | 1 |
| A_wall | 0,6 |
| E_wall | 0,95 |
| R_wall | 0,4 |
| GHG_wall_kgCO2m2 [$kgCO_2/m^2$] | 112 |
| U_floor [$W/m^2K$] | 0,77 |
| U_base [$W/m^2K$] | 0,77 |
| GHG_floor_kgCO2m2 [$kgCO_2/m^2$] | 113 |
| U_win [$W/m^2K$] | 3 |
| G_win | 0,75 |
| E_win | 0,89 |
| F_F | 0 |
| GHG_win_kgCO2m2 [$kgCO_2/m^2$] | 62 |
| Occ_m2p | 30 |
| Qs_Wp | 70 |
| X_ghp | 80 |
| Ea_Wm2 | 8 |
| El_Wm2 | 2,7 |

| | |
|---|---|
| Epro_Wm2 | 0 |
| Qcre_Wm2 | 0 |
| Ed_Wm2 | 0 |
| Ev_kWveh | 0 |
| Qcpro_Wm2 | 0 |
| Qhpro_Wm2 | 0 |
| Vww_ldp | 40 |
| Vw_ldp | 140 |
| Tcs_set_C | 26 |
| Tcs_setb_C | 28 |
| Ths_set_C | 21 |
| Ths_setb_C | 18 |
| RH_min_pc | 30 |
| RH_max_pc | 60 |
| Ve_lsp | 8,333 |

**Table 40: Schedule for setpoint and setback temperatures of the base case**

| Day | Setpoint temperature hours | Setback temperature hours |
|---|---|---|
| Saturday | 0-24 | - |
| Sunday | 0-24 | - |
| Weekday | 0-24 | - |

# B) Second Appendix

## Sensitivity analysis

**Table 41: Parameters of the cases for the sensitivity analysis of the envelope parameters**

| | | Typology | Areas | | | Zone | | | | Architecture | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Building Type | Af_m2 | Aroof_m2 | GFA_m2 | height_ag | floors_ag | height_bg | floors_bg | Void deck | Es | Hs_ag | Hs_bg | Ns | wwr_north | wwr_east | wwr_south | wwr_west | Cm_Af [J/km2] | n50 | U_roof [W/m2K] | a_roof | e_roof | r_roof | GHG_roof_kgCO2m2 | rf_sh | Type part wall | U_wall [W/m2 | a_wall | e_wall | r_wall | GHG_wall_kgCO2m2 | U_base [W/m2K] | GHG_floor_kgCO2m2 | U_win [W/m2K] | G_win | e_win | F_F | GHG_win_kgCO2m2 |
| Case 1: Renovations | Base case | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Normal renovation | MFH_F_NR | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 1,0 | 0,19 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 0,22 | 0,6 | 0,95 | 0,4 | 112 | 0,28 | 113 | 1,3 | 0,67 | 0,02 | 0,3 | 123 |
| | Advanced renovation | MFH_F_AR | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 1,0 | 0,09 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 0,13 | 0,6 | 0,95 | 0,4 | 112 | 0,21 | 113 | 0,8 | 0,5 | 0,02 | 0,3 | 123 |
| Case 2: Cellars | No cellar | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Cellar, 0% heating | MFH_F | 742,206 | 436,59 | 1309,775 | 6 | 2 | 3 | 1 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Cellar, 50% heating | MFH_F | 960,501 | 436,59 | 1309,775 | 6 | 2 | 3 | 1 | 0 | 0,85 | 0,85 | 0,5 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Cellar, 85% heating | MFH_F | 1113,309 | 436,59 | 1309,775 | 6 | 2 | 3 | 1 | 0 | 0,85 | 0,85 | 0,85 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| Case 3: Window to wall ratio 1 by 1 | Standard | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,094428 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,062952 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | East +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,2244792 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | East -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,1496528 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | South +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,2702796 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | South -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,1801864 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | West +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,2244792 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | West -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,1496528 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| Case 4: Window to wall ratio 2 by 2 | Standard | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, East +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,094428 | 0,2244792 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, East -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,062952 | 0,1496528 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, South +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,094428 | 0,187066 | 0,2702796 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, South -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,062952 | 0,187066 | 0,1801864 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, West +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,094428 | 0,187066 | 0,225233 | 0,2244792 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, West -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,062952 | 0,187066 | 0,225233 | 0,1496528 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | East, South +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,2244792 | 0,2702796 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | East, South -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,1496528 | 0,1801864 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | East, West +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,2244792 | 0,225233 | 0,2244792 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | East, West -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,1496528 | 0,225233 | 0,1496528 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | South, West +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,2702796 | 0,2244792 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | South, West -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,1801864 | 0,1496528 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| Case 5: Window to wall ratio 3 by 3 | Standard | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, East, South +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,094428 | 0,2244792 | 0,2702796 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, East, South -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,062952 | 0,1496528 | 0,1801864 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, East, West +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,094428 | 0,2244792 | 0,225233 | 0,2244792 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, East, West -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,062952 | 0,1496528 | 0,225233 | 0,1496528 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, South, West +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,094428 | 0,187066 | 0,2702796 | 0,2244792 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, South, West -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,062952 | 0,187066 | 0,1801864 | 0,1496528 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | East, South, West +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,2244792 | 0,2702796 | 0,2244792 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | East, South, West -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,1496528 | 0,1801864 | 0,1496528 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| Case 6: Window to wall ratio 4 by 4 | Standard | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, South, East, West +20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,094428 | 0,2244792 | 0,2702796 | 0,2244792 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | North, South, East, West -20% | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,062952 | 0,1496528 | 0,1801864 | 0,1496528 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| Case 7: Construction standard | Construction Tabula | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Construction AS1: Light | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 110000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Construction AS2: Medium | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 165000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Construction AS3: Heavy | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 300000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| Case 8: Tightness | Tabula medium | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Minimum tightness | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 1,0 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Maximum tightness | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 4,0 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| Case 9: Shading | Vertical | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,6 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |
| | Horizontal | MFH_F | 742,206 | 436,59 | 873,183 | 6 | 2 | 0 | 0 | 0 | 0,85 | 0,85 | 0 | 0,85 | 0,07869 | 0,187066 | 0,225233 | 0,187066 | 162000 | 2,5 | 0,51 | 0,55 | 0,91 | 0,45 | 112 | 0,8 | Internal partition in brick | 1 | 0,6 | 0,95 | 0,4 | 112 | 0,77 | 113 | 3 | 0,75 | 0,89 | 0,3 | 62 |

# Table 42: Results of the cases for the sensitivity analysis of the envelope parameters

| | | E_sys [MWh/yr] | Qhs_sys [MWh/yr] | Qww_sys [MWh/yr] | QH_sys [MWh/yr] | E_sys | Qhs_sys | Qww_sys | QH_sys |
|---|---|---|---|---|---|---|---|---|---|
| Case 1: Renovations | Base case | 15,685 | 56,93 | 21,858 | 78,788 | 0% | 0% | 0% | 0% |
| | Normal renovation | 15,567 | 8,69 | 21,594 | 30,284 | -1% | -85% | -1% | -62% |
| | Advanced renovation | 15,551 | 2,844 | 21,507 | 24,351 | -1% | -95% | -2% | -69% |
| Case 2: Cellars | No cellar | 15,685 | 56,93 | 21,858 | 78,788 | 0% | 0% | 0% | 0% |
| | Cellar, 0% heating | 23,454 | 55,836 | 30,318 | 86,154 | 50% | -2% | 39% | 9% |
| | Cellar, 50% heating | 23,485 | 69,625 | 30,339 | 99,964 | 50% | 22% | 39% | 27% |
| | Cellar, 85% heating | 23,508 | 79,401 | 30,351 | 109,751 | 50% | 39% | 39% | 39% |
| Case 3: Window to wall ratio 1 by 1 | Standard | 15,685 | 56,978 | 21,858 | 78,836 | 0,00% | 0,00% | 0,00% | 0,00% |
| | North +20% | 15,686 | 57,195 | 21,858 | 79,053 | 0,01% | 0,38% | 0,00% | 0,28% |
| | North -20% | 15,685 | 56,739 | 21,858 | 78,597 | 0,00% | -0,42% | 0,00% | -0,30% |
| | East +20% | 15,686 | 57,437 | 21,856 | 79,292 | 0,01% | 0,81% | -0,01% | 0,58% |
| | East -20% | 15,684 | 56,462 | 21,86 | 78,322 | -0,01% | -0,91% | 0,01% | -0,65% |
| | South +20% | 15,685 | 56,844 | 21,855 | 78,699 | 0,00% | -0,24% | -0,01% | -0,17% |
| | South -20% | 15,685 | 57,086 | 21,862 | 78,948 | 0,00% | 0,19% | 0,02% | 0,14% |
| | West +20% | 15,686 | 57,257 | 21,854 | 79,111 | 0,01% | 0,49% | -0,02% | 0,35% |
| | West -20% | 15,685 | 56,685 | 21,862 | 78,547 | 0,00% | -0,51% | 0,02% | -0,37% |
| Case 4: Window to wall ratio 2 by 2 | Standard | 15,685 | 56,978 | 21,858 | 78,836 | 0,00% | 0,00% | 0,00% | 0,00% |
| | North, East +20% | 15,687 | 57,659 | 21,856 | 79,515 | 0,01% | 1,20% | -0,01% | 0,86% |
| | North, East -20% | 15,683 | 56,229 | 21,86 | 78,09 | -0,01% | -1,31% | 0,01% | -0,95% |
| | North, South +20% | 15,686 | 57,094 | 21,855 | 78,949 | 0,01% | 0,20% | -0,01% | 0,14% |
| | North, South -20% | 15,685 | 56,855 | 21,862 | 78,716 | 0,00% | -0,22% | 0,02% | -0,15% |
| | North, West +20% | 15,686 | 57,469 | 21,854 | 79,323 | 0,01% | 0,86% | -0,02% | 0,62% |
| | North, West -20% | 15,684 | 56,42 | 21,862 | 78,282 | -0,01% | -0,98% | 0,02% | -0,70% |
| | East, South +20% | 15,686 | 57,36 | 21,853 | 79,213 | 0,01% | 0,67% | -0,02% | 0,48% |
| | East, South -20% | 15,684 | 56,611 | 21,864 | 78,475 | -0,01% | -0,64% | 0,03% | -0,46% |
| | East, West +20% | 15,687 | 57,716 | 21,852 | 79,568 | 0,01% | 1,30% | -0,03% | 0,93% |
| | East, West -20% | 15,683 | 56,168 | 21,864 | 78,033 | -0,01% | -1,42% | 0,03% | -1,02% |
| | South, West +20% | 15,686 | 57,156 | 21,851 | 79,007 | 0,01% | 0,31% | -0,03% | 0,22% |
| | South, West -20% | 15,684 | 56,793 | 21,866 | 78,659 | -0,01% | -0,32% | 0,04% | -0,22% |
| Case 5: Window to wall ratio 3 by 3 | Standard | 15,685 | 56,978 | 21,858 | 78,836 | 0,00% | 0,00% | 0,00% | 0,00% |
| | North, East, South +20% | 15,687 | 57,572 | 21,853 | 79,425 | 0,01% | 1,04% | -0,02% | 0,75% |
| | North, East, South -20% | 15,683 | 56,345 | 21,863 | 78,208 | -0,01% | -1,11% | 0,02% | -0,80% |
| | North, East, West +20% | 15,687 | 57,977 | 21,852 | 79,829 | 0,01% | 1,75% | -0,03% | 1,26% |
| | North, East, West -20% | 15,683 | 55,925 | 21,864 | 77,789 | -0,01% | -1,85% | 0,03% | -1,33% |
| | North, South, West +20% | 15,686 | 57,371 | 21,851 | 79,222 | 0,01% | 0,69% | -0,03% | 0,49% |
| | North, South, West -20% | 15,684 | 56,538 | 21,865 | 78,404 | -0,01% | -0,77% | 0,03% | -0,55% |
| | East, South, West +20% | 15,687 | 57,632 | 21,849 | 79,481 | 0,01% | 1,15% | -0,04% | 0,82% |
| | East, South, West -20% | 15,683 | 56,298 | 21,868 | 78,166 | -0,01% | -1,19% | 0,05% | -0,85% |
| Case 6: Window to wall ratio 4 by 4 | Standard | 15,685 | 56,978 | 21,858 | 78,836 | 0,00% | 0,00% | 0,00% | 0,00% |
| | North, South, East, West +20% | 15,687 | 57,869 | 21,849 | 79,718 | 0,01% | 1,56% | -0,04% | 1,12% |
| | North, South, East, West -20% | 15,683 | 56,068 | 21,868 | 77,936 | -0,01% | -1,60% | 0,05% | -1,14% |
| Case 7: Construction standard | Construction Tabula | 15,685 | 56,952 | 21,858 | 78,81 | 0,00% | 0,00% | 0,00% | 0,00% |
| | Construction AS1: Light | 15,686 | 57,216 | 21,854 | 79,07 | 0,01% | 0,46% | -0,02% | 0,33% |
| | Construction AS2: Medium | 15,685 | 56,946 | 21,858 | 78,804 | 0,00% | -0,01% | 0,00% | -0,01% |
| | Construction AS3: Heavy | 15,682 | 56,628 | 21,863 | 78,491 | -0,02% | -0,57% | 0,02% | -0,40% |
| Case 8: Tightness | Tabula medium | 15,685 | 56,978 | 21,858 | 78,836 | 0,00% | 0,00% | 0,00% | 0,00% |
| | Minimum tightness | 15,671 | 53,171 | 21,852 | 75,023 | -0,09% | -6,68% | -0,03% | -4,84% |
| | Maximum tightness | 15,699 | 60,886 | 21,864 | 82,75 | 0,09% | 6,86% | 0,03% | 4,96% |
| Case 9: Shading | Vertical | 15,685 | 56,952 | 21,858 | 78,81 | 0,00% | 0,00% | 0,00% | 0,00% |
| | Horizontal | 15,677 | 53,14 | 21,823 | 74,963 | -0,05% | -6,69% | -0,16% | -4,88% |

### Table 43: Parameters of the cases for the sensitivity analysis of the occupation and indoor comfort parameters

| | | Internal loads | | | | | | | | | | | | | Indoor comfort | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Occ_m2p | Qs_Wp | X_ghp | Ea_Wm2 | El_Wm2 | Epro_Wm2 | Qcre_Wm2 | Ed_Wm2 | Ev_kWveh | Qcpro_Wm2 | Qhpro_Wm2 | Vww_ldp | Vw_ldp | Tcs_set_C | Tcs_setb_C | Ths_set_C | Ths_setb_C | RH_min_pc | RH_max_pc | Ve_lsp |
| Case 10: Occupancy density | Base Case | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 21 | 18 | 30 | 60 | 8,333333333 |
| | 4 apartments, 4 people/apart. | 55 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 21 | 18 | 30 | 60 | 8,333333333 |
| | 3 apartments, 2 people/apart. | 73 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 21 | 18 | 30 | 60 | 8,333333333 |
| | 8 apartments, 5 people/apart. | 22 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 21 | 18 | 30 | 60 | 8,333333333 |
| Case 11: Temperature Setpoints and Setbacks | Base Case | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 21 | 18 | 30 | 60 | 8,333333333 |
| | 17ºC | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 17 | 14 | 30 | 60 | 8,333333333 |
| | 19ºC | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 19 | 16 | 30 | 60 | 8,333333333 |
| | 23ºC | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 23 | 20 | 30 | 60 | 8,333333333 |
| Case 12: Temperature schedules | Base Case | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 21 | 18 | 30 | 60 | 8,333333333 |
| | Setback temp. during the night | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 21 | 18 | 30 | 60 | 8,333333333 |
| | Setback temp. during the night and weekday | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 21 | 18 | 30 | 60 | 8,333333333 |
| Case 12.1: 11+12 | 19ºC+Setback temp. during the night | 30 | 70 | 80 | 8 | 2,7 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 140 | 26 | 28 | 19 | 16 | 30 | 60 | 8,333333333 |

### Table 44: Results of the cases for the sensitivity analysis of the occupation and indoor comfort parameters

| | | Results | | | | Percentage change | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | E_sys [MWh/yr] | Qhs_sys [MWh/yr] | Qww_sys [MWh/yr] | QH_sys [MWh/yr] | E_sys | Qhs_sys | Qww_sys | QH_sys |
| Case 10: Occupancy density | Base Case | 15,685 | 56,943 | 21,858 | 78,801 | 0% | 0% | 0% | 0% |
| | 4 apartments, 4 people/apart. | 15,685 | 58,03 | 14,955 | 72,985 | 0% | 2% | -32% | -7% |
| | 3 apartments, 2 people/apart. | 15,684 | 58,411 | 13,195 | 71,605 | 0% | 3% | -40% | -9% |
| | 8 apartments, 5 people/apart. | 15,686 | 56,231 | 27,687 | 83,918 | 0% | -1% | 27% | 6% |
| Case 11: Temperature Setpoints and Setbacks | Base Case | 15,685 | 56,936 | 21,858 | 78,795 | 0% | 0% | 0% | 0% |
| | 17ºC | 15,637 | 36,068 | 22,109 | 58,177 | 0% | -37% | 1% | -26% |
| | 19ºC | 15,662 | 46,097 | 21,99 | 68,087 | 0% | -19% | 1% | -14% |
| | 23ºC | 15,707 | 68,405 | 21,719 | 90,124 | 0% | 20% | -1% | 14% |
| Case 12: Temperature schedules | Base Case | 15,685 | 56,943 | 21,858 | 78,801 | 0% | 0% | 0% | 0% |
| | Setback temp. during the night | 15,69 | 52,853 | 21,898 | 74,751 | 0% | -7% | 0% | -5% |
| | Setback temp. during the night and weekday | 15,684 | 50,412 | 21,923 | 72,334 | 0% | -11% | 0% | -8% |
| Case 12.1: 11+12 | 19ºC+Setback temp. during the night | 15,664 | 42,044 | 22,027 | 64,07 | 0% | -26% | 1% | -19% |

# C) Third Appendix

## Case study

**Table 45: Results of the case study**

| | | City Energy Analyst | | | QGIS | | | |
|---|---|---|---|---|---|---|---|---|
| | Name | Building type | Af_m2 | QH_sys_MWhyr | Standard | Full load | Max demand | Total Demand |
| Residential Buildings | B0 | EFH_E | 170 | 39,1 | EFH_E | 1415 | 9,4 | 13,9 |
| | B1 | EFH_E | 220 | 54,3 | EFH_E | 2152 | 17,0 | 38,3 |
| | B101 | TH_J | 140 | 9,8 | EFH_H | 2028 | 15,9 | 33,9 |
| | B102 | MFH_H | 490 | 63,8 | MFH_H | 39 | 6,3 | 0,3 |
| | B103 | EFH_E | 150 | 43,3 | EFH_E | 1875 | 84,5 | 166,4 |
| | B104 | EFH_E | 330 | 72,5 | EFH_E | 3086 | 102,1 | 330,6 |
| | B105 | EFH_E | 180 | 40,8 | TH_I | 1165 | 14,9 | 18,2 |
| | B106 | EFH_E | 270 | 58,1 | EFH_E | 1476 | 193,6 | 299,9 |
| | B107 | TH_J | 170 | 14,4 | TH_K | 1377 | 7,9 | 11,4 |
| | B109 | EFH_E | 150 | 34,0 | EFH_E | 519 | 213,8 | 116,5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | B110 | MFH_H | 710 | 76,1 | MFH_H | 1588 | 17,9 | 29,8 |
| | B111 | TH_E | 90 | 22,7 | EFH_I | 2611 | 219,3 | 601,2 |
| | B114 | MFH_H | 480 | 52,4 | MFH_H | 1979 | 12,6 | 26,1 |
| | B116 | EFH_E | 240 | 59,6 | EFH_E | 2387 | 10,4 | 26,0 |
| | B118 | EFH_E | 710 | 105,2 | MFH_H | 1802 | 52,3 | 98,9 |
| | B119 | EFH_E | 710 | 93,2 | MFH_H | 1911 | 38,1 | 76,4 |
| | B12 | MFH_I | 1.090 | 75,3 | MFH_H | 1452 | 10,6 | 16,1 |
| | B121 | EFH_E | 90 | 32,2 | EFH_E | 1569 | 8,7 | 14,3 |
| | B122 | EFH_H | 190 | 32,8 | EFH_H | 1162 | 9,8 | 12,0 |
| | B123 | EFH_E | 440 | 79,6 | EFH_E | 1492 | 135,6 | 212,6 |
| | B124 | TH_J | 300 | 21,3 | TH_J | 874 | 13,8 | 12,7 |
| | B13 | EFH_E | 440 | 85,3 | MFH_H | 2168 | 133,7 | 304,5 |
| | B132 | TH_C | 100 | 42,6 | TH_C | 2390 | 10,2 | 25,5 |
| | B136 | EFH_E | 120 | 38,2 | EFH_E | 2065 | 9,6 | 20,7 |
| | B138 | EFH_E | 830 | 123,3 | EFH_E | 2107 | 7,3 | 16,1 |
| | B14 | AB_E | 4.000 | 576,0 | AB_E | 1146 | 8,5 | 10,2 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | B140 | EFH_E | 170 | 33,8 | EFH_E | 663 | 11,5 | 8,0 |
| | B141 | TH_J | 730 | 48,2 | TH_J | 1785 | 16,6 | 31,1 |
| | B15 | EFH_E | 230 | 52,4 | EFH_E | 2569 | 83,8 | 226,1 |
| | B16 | EFH_H | 170 | 31,1 | EFH_H | 1868 | 9,9 | 19,4 |
| | B17 | EFH_E | 700 | 93,0 | EFH_E | 1604 | 11,1 | 18,7 |
| | B19 | EFH_E | 340 | 65,3 | EFH_E | 2394 | 14,8 | 37,2 |
| | B2 | EFH_H | 240 | 45,4 | EFH_H | 656 | 13,5 | 9,3 |
| | B20 | EFH_H | 160 | 28,1 | EFH_H | 1295 | 136,4 | 185,5 |
| | B21 | EFH_E | 170 | 38,8 | EFH_E | 2378 | 59,0 | 147,2 |
| | B22 | EFH_E | 130 | 25,4 | EFH_E | 2493 | 11,2 | 29,3 |
| | B23 | EFH_E | 960 | 141,9 | EFH_E | 2173 | 88,8 | 202,6 |
| | B27 | EFH_H | 180 | 29,1 | EFH_H | 2353 | 275,0 | 679,4 |
| | B28 | EFH_E | 580 | 85,1 | EFH_E | 422 | 12,1 | 5,3 |
| | B29 | EFH_E | 130 | 23,1 | EFH_E | 988 | 195,7 | 203,1 |
| | B3 | EFH_E | 130 | 27,4 | EFH_E | 233 | 49,6 | 12,1 |
| | B30 | EFH_H | 80 | 19,5 | EFH_H | 1787 | 7,2 | 13,5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | B31 | TH_K | 130 | 8,5 | EFH_E | 2360 | 17,4 | 43,2 |
| | B32 | EFH_B | 130 | 39,0 | EFH_B | 1540 | 13,9 | 22,4 |
| | B33 | EFH_E | 100 | 21,8 | EFH_E | 1124 | 9,7 | 11,4 |
| | B34 | EFH_E | 240 | 52,7 | EFH_H | 620 | 24,8 | 16,1 |
| | B35 | MFH_I | 670 | 58,0 | MFH_I | 2736 | 200,7 | 576,6 |
| | B36 | EFH_E | 130 | 28,5 | EFH_E | 243 | 15,2 | 3,9 |
| | B40 | EFH_E | 90 | 26,1 | EFH_E | 2177 | 54,4 | 124,3 |
| | B42 | EFH_E | 260 | 54,1 | EFH_E | 1004 | 34,6 | 36,5 |
| | B43 | EFH_H | 170 | 28,8 | EFH_H | 2083 | 8,0 | 17,5 |
| | B44 | EFH_E | 950 | 130,4 | EFH_E | 1066 | 12,1 | 13,5 |
| | B45 | MFH_E | 1.460 | 203,4 | MFH_I | 1532 | 94,4 | 151,8 |
| | B46 | EFH_E | 180 | 46,3 | EFH_E | 2035 | 8,4 | 17,8 |
| | B47 | EFH_E | 960 | 141,5 | EFH_E | 1312 | 7,2 | 9,9 |
| | B48 | MFH_H | 530 | 71,8 | MFH_H | 1532 | 13,3 | 21,3 |
| | B49 | EFH_E | 130 | 31,7 | EFH_E | 2486 | 18,4 | 48,0 |
| | B5 | EFH_E | 890 | 142,7 | EFH_E | 419 | 8,9 | 3,9 |

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|---|---|---|---|---|---|---|---|---|
| | B50 | EFH_E | 960 | 145,8 | EFH_E | 1243 | 16,1 | 21,0 |
| | B51 | EFH_E | 560 | 110,4 | EFH_E | 1784 | 13,8 | 25,8 |
| | B52 | TH_E | 110 | 19,3 | TH_E | 2565 | 119,1 | 320,8 |
| | B53 | EFH_H | 100 | 23,2 | EFH_H | 474 | 23,8 | 11,8 |
| | B55 | EFH_H | 210 | 32,2 | EFH_H | 2259 | 7,2 | 17,1 |
| | B56 | EFH_E | 130 | 22,3 | EFH_E | 1964 | 48,5 | 100,1 |
| | B57 | EFH_E | 460 | 93,9 | EFH_E | 2832 | 80,2 | 238,4 |
| | B59 | EFH_E | 400 | 88,3 | EFH_E | 2585 | 40,1 | 108,9 |
| | B6 | EFH_E | 540 | 99,2 | MFH_H | 1714 | 138,9 | 250,0 |
| | B60 | EFH_E | 150 | 29,6 | EFH_E | 2479 | 307,5 | 800,3 |
| | B62 | MFH_I | 370 | 34,5 | MFH_I | 1439 | 10,1 | 15,2 |
| | B63 | EFH_E | 240 | 69,1 | EFH_E | 2821 | 9,9 | 29,4 |
| | B64 | EFH_H | 180 | 28,1 | EFH_H | 1569 | 7,6 | 12,5 |
| | B65 | EFH_H | 170 | 30,6 | EFH_H | 914 | 9,5 | 9,1 |
| | B66 | MFH_I | 380 | 37,9 | MFH_I | 2404 | 39,5 | 99,8 |
| | B68 | TH_J | 150 | 12,5 | TH_I | 933 | 8,9 | 8,7 |

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|---|---|---|---|---|---|---|---|---|
| | B69 | TH_E | 90 | 14,4 | TH_H | 1787 | 71,4 | 133,9 |
| | B7 | EFH_H | 140 | 21,2 | EFH_H | 714 | 343,6 | 257,6 |
| | B70 | EFH_E | 180 | 35,1 | EFH_E | 1630 | 30,4 | 52,1 |
| | B71 | EFH_E | 440 | 83,1 | EFH_E | 1817 | 6,3 | 12,0 |
| | B72 | EFH_H | 160 | 20,7 | EFH_E | 1756 | 74,5 | 137,4 |
| | B73 | EFH_E | 170 | 39,7 | EFH_E | 995 | 11,2 | 11,6 |
| | B74 | EFH_E | 140 | 32,9 | EFH_E | 1021 | 20,7 | 22,2 |
| | B76 | MFH_E | 2.670 | 339,8 | MFH_E | 3024 | 97,4 | 309,2 |
| | B77 | EFH_E | 290 | 67,4 | TH_I | 2140 | 10,9 | 24,5 |
| | B78 | EFH_H | 140 | 24,2 | EFH_H | 2062 | 29,5 | 63,8 |
| | B79 | MFH_H | 700 | 75,2 | MFH_H | 2968 | 7,6 | 23,8 |
| | B8 | EFH_E | 440 | 84,7 | EFH_E | 1702 | 9,9 | 17,7 |
| | B81 | MFH_H | 560 | 76,0 | EFH_E | 899 | 10,7 | 10,1 |
| | B83 | EFH_E | 520 | 101,4 | EFH_E | 1257 | 12,2 | 16,1 |
| | B84 | MFH_J | 2.820 | 119,1 | MFH_I | 2040 | 43,2 | 92,5 |
| | B85 | TH_J | 870 | 52,8 | MFH_K | 991 | 11,2 | 11,7 |

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|---|---|---|---|---|---|---|---|---|
| | B86 | EFH_E | 110 | 30,9 | EFH_I | 3558 | 198,4 | 741,3 |
| | B87 | EFH_H | 200 | 30,3 | EFH_H | 2085 | 31,0 | 67,9 |
| | B88 | EFH_E | 120 | 26,4 | EFH_E | 1711 | 50,7 | 91,1 |
| | B89 | TH_J | 180 | 11,8 | EFH_E | 1407 | 53,0 | 78,3 |
| | B9 | EFH_E | 170 | 42,8 | EFH_E | 2503 | 11,0 | 28,9 |
| | B90 | TH_J | 990 | 50,6 | TH_J | 1506 | 11,0 | 17,5 |
| | B92 | EFH_E | 140 | 24,5 | EFH_E | 3549 | 19,3 | 72,0 |
| | B93 | MFH_B | 430 | 120,9 | EFH_E | 1516 | 24,3 | 38,7 |
| | B94 | MFH_E | 2.820 | 344,1 | MFH_E | 2022 | 8,3 | 17,5 |
| | B95 | MFH_H | 550 | 78,0 | MFH_H | 869 | 10,4 | 9,5 |
| | B97 | EFH_H | 140 | 17,1 | EFH_H | 2106 | 14,5 | 32,0 |
| | B98 | TH_J | 650 | 37,4 | EFH_K | 2629 | 25,7 | 70,9 |
| | B99 | EFH_E | 170 | 41,3 | TH_K | 1855 | 48,6 | 94,6 |
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| Non-resi- | B10 | School | 768 | 42,9 | Kindergarten | 1534 | 40,8 | 65,7 |

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|---|---|---|---|---|---|---|---|---|
| | B112 | School | 1.183 | 82,2 | Kindergarten | 1837 | 38,4 | 74,1 |
| | B115 | General use | 5.820 | 285,6 | Building for public use | 2242 | 467,3 | 1100,1 |
| | B120 | General use | 154 | 8,7 | Building for business or trade | 1519 | 33,3 | 53,2 |
| | B125 | General use | 7.656 | 94,5 | Not specified | 1665 | 335,4 | 586,4 |
| | B126 | General use | 6.576 | 14,3 | Not specified | 2017 | 91,0 | 192,8 |
| | B127 | General use | 4.349 | 160,1 | Not specified | 2172 | 94,9 | 216,4 |
| | B128 | General use | 1.654 | 88,1 | Not specified | 1770 | 367,4 | 682,9 |
| | B129 | General use | 648 | 40,3 | Not specified | 1888 | 36,7 | 72,8 |
| | B130 | General use | 335 | 17,8 | Building for business or trade | 2286 | 38,2 | 91,7 |
| | B131 | General use | 28.835 | 335,0 | Building for business or trade | 1441 | 772,8 | 1169,4 |
| | B133 | General use | 601 | 19,5 | Building for business or trade | 858 | 27,4 | 24,7 |

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|---|---|---|---|---|---|---|---|---|
| | B135 | General use | 4.566 | 80,6 | Building for business or trade | 2057 | 133,4 | 288,3 |
| | B137 | General use | 2.083 | 40,7 | Not specified | 1971 | 49,2 | 101,9 |
| | B139 | General use | 1.546 | 77,0 | Not specified | 1104 | 77,1 | 89,3 |
| | B142 | General use | 932 | 29,6 | Not specified | 1984 | 29,3 | 61,0 |
| | B143 | General use | 13.646 | 292,9 | Building for business or trade | 1058 | 778,6 | 865,3 |
| | B145 | General use | 56.709 | 424,3 | Building for business or trade | 1301 | 572,4 | 781,9 |
| | B146 | General use | 23.304 | 585,5 | Not specified | 2213 | 3529,8 | 8200,8 |
| | B147 | General use | 18.875 | 119,8 | Building for business or trade | 1276 | 366,6 | 491,2 |
| | B148 | University | 8.184 | 350,1 | Building for education and research | 2141 | 107,2 | 241,0 |
| | B149 | University | 11.655 | 607,2 | Building for education and research | 2507 | 583,0 | 1534,6 |

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|---|---|---|---|---|---|---|---|---|
| | B150 | University | 6.531 | 426,7 | Building for education and research | 1753 | 319,4 | 587,9 |
| | B151 | University | 16.891 | 738,2 | Building for education and research | 614 | 2080,7 | 1340,5 |
| | B152 | General use | 3.735 | 63,8 | Not specified | 1796 | 71,6 | 135,1 |
| | B18 | University | 15.933 | 776,7 | Building for education and research | 1478 | 383,6 | 595,2 |
| | B24 | General use | 298 | 12,4 | Building for business or trade | 2245 | 28,1 | 66,2 |
| | B26 | University | 15.893 | 578,2 | Building for education and research | 2710 | 371,2 | 1056,4 |
| | B37 | University | 5.378 | 262,9 | Building for education and research | 2179 | 208,5 | 477,0 |
| | B38 | School | 603 | 46,5 | Kindergarten | 2662 | 34,1 | 95,4 |
| | B4 | General use | 2.210 | 137,4 | Building for public use | 3736 | 59,0 | 231,6 |
| | B54 | School | 2.089 | 120,8 | Kindergarten | 1814 | 60,0 | 114,3 |
| | B67 | University | 4.220 | 74,9 | Building for education and research | 931 | 222,9 | 217,9 |

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|---|---|---|---|---|---|---|---|---|
| | B75 | School | 462 | 41,3 | Kindergarten | 2688 | 16,6 | 46,7 |
| | B80 | University | 35.618 | 516,6 | Building for education and research | 1519 | 1392,5 | 2221,2 |
| | B96 | General use | 6.331 | 121,571 | Building for business or trade | 1925 | 293,3 | 592,8 |