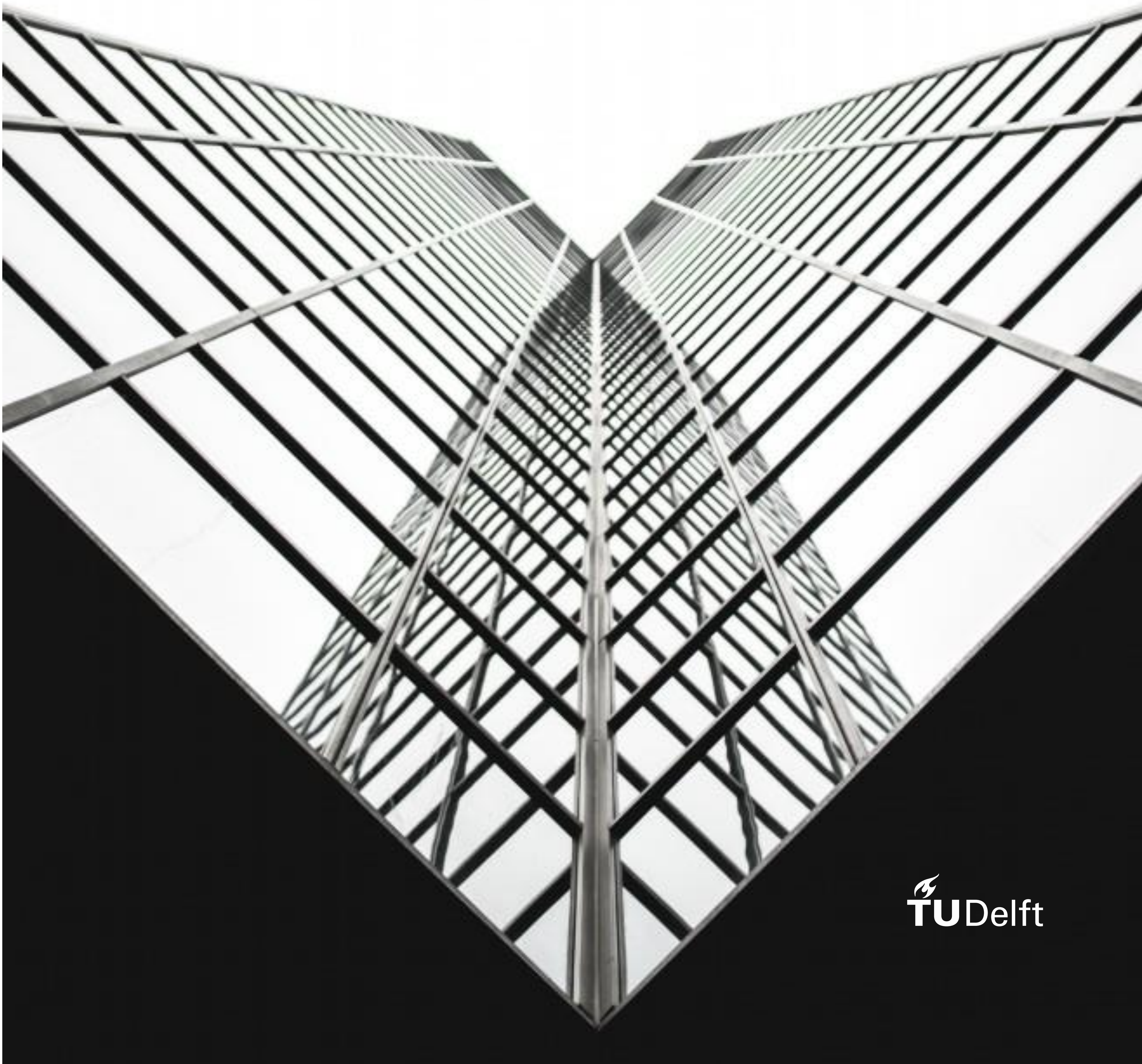
Can TALL be SUSTAINABLE ?

The potential of Energy Synergy towards a zero-energy mixed-use high-rise building in the Netherlands.

Georgios Germanos



Can tall be sustainable?

The potential of Energy Synergy towards a zero-energy mixed-use high-rise building in the Netherlands.

By

Georgios Germanos
4624653

in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering | Track Building Engineering

at the Delft University of Technology,

To be defended publicly on June 14, 2019

Thesis committee:

Chairman:	Prof. dr. ir. Rob Nijsse	TU Delft
Daily supervisor:	Assist. Prof. dr. ir. W.H. van der Spoel	TU Delft
Co-supervisor:	Dr. ir. P.J.W. van den Engel	TU Delft

TU Delft

Abstract

The sustainability of high-rise buildings is always a point of debate and doubt in current research and literature. Several studies have been performed about the zero-energy potential for skyscrapers, however taking into consideration single functions, particularly office and housing buildings. Realistic and modern tall building design however always involves a combination of uses (offices, accommodation, commercial and retail) for the project to be economically viable. On the basis of the Trias Energetica, the primary goal of the early design for sustainable buildings must be to minimize the demand for energy (heating, cooling, hot water, electricity) by means of active or passive techniques. This translates into design guidelines for the shape, orientation, building envelope and climate properties, parameters that have been already widely investigated by researchers and designers in practice. However, an important feature in order to improve the sustainable profile of a building is to employ circular techniques that aim to avoid wasting energy and re-use / re-purpose it. The main objective of this graduation research is to determine the zero-energy potential for high-rise buildings by taking advantage of a mixed-use scheme and examining the possibilities for energy exchange and cooperation between different functions by means of storing energy in the form of warm and cold-water tanks. This research aims to determine which synergetic combinations between functions can be performed, what type of building systems and technology can be used and, by establishing a complete energy simulation, conclude on what are the energy benefits for the building on a yearly basis . The results will be an important addition to the sustainable design for “MEGA” scale projects, according to the forthcoming Dutch regulation that after 2020 all newly built buildings must comply with the nearly zero energy guidelines.

Preface

Since the acceptance of climate change and its effects during the early 90's, the concept of sustainability has evolved from a luxury and innovative approach, to a standard approach and absolute necessity nowadays. The introduction of technological innovation for building design and the large benefits of Building Information modelling have made the calculation processes faster, accurate and thus more reliable. Consequently, buildings have been rendered highly sustainable, with proved rankings and internationally acknowledged qualifications such as LEED or BREEAM certificates.

The idea to apply sustainable concepts on a high-rise scale, resulted to me after completing my contribution as a façade designer, during the multidisciplinary studio "MEGA", during Q4 of my first year as Building Engineering student in TU Delft. Our Team's concept and vision was to create a highly sustainable design, by employing several climate techniques and features for the envelope, while promoting as well a concept of "wild" mixing of functions in both a vertical and horizontal way in the building, closer to the approach of a "vertical city". The principal comment from the committee of judges was significantly that "if you want to make a building sustainable, not at all means build it tall and big".

My specific interest for sustainability has led me from an early stage to follow the Annotation for Technology in Sustainable Development. It was within the annotation curriculum, that I became familiar with many sustainable concepts, materials, techniques and standards. The most important was my work on the Circular Economy that really proved highly enlightening for me. As most circular principles for buildings are focused on materials, and detailing for disassembly and re-use, an effort to save and recycle energy within a building in a circular approach because a very attractive idea for me. On this basis, I embarked to investigate the potential for energy re-use, or "synergy", the Greek word that expresses cooperation ('syn" = together, in a group, "ergia "= produce work, perform together). The concept of energy synergy can be a useful addition to the sustainable techniques, that contribute to adding value to an existing approach and general energy saving strategy for a building. It is of course important, that during concept stage an early development, building and envelope characteristics are designed in a manner that is energy saving. Synergy can contribute a secondary effect of managing the remaining energy demand in a more smart and sensible manner. The combination of passive measures, synergetic energy storage and exchange and renewable energy production on site, is the most viable approach towards a zero-energy building of every scale, from shed to skyscraper. However, what makes the element of synergy very interesting is the prerequisite of abnormalities within the building, different uses or functions that create non uniform patterns. It is thorough variation then, that "waste" from one function (including energy) can be used as source material for another. Tackling this subject was a very educating experience for me, allowing me to expand my knowledge in energy modelling and mechanical engineering principles, that were very out my current skillset when I first started forming my proposal.

I would thus, like to first of all thank my daily supervisor, assistant professor Mr. Willem van der Spoel, for providing me with endless insight on my ideas. His creative comments while forming the proposal and valuable contribution with modelling issues were the cornerstones for developing this project, that would otherwise not have been possible. His easy going and relaxed demeanour was very encouraging during "sticky" points and stressful periods as well and made meetings and discussions with him very enjoyable. Secondly, I would like to thank my co-supervisor dr. Ing. Peter van Engel, for providing me with specialist insight whenever required. His experience with climate and energy concepts, allowed me to contemplate deeper and re-asses certain points that were not obvious from an early stage. Finally, I would like to express my gratitude to the committee Chairman, Professor dr. Ing. Rob Nijsse, who kept a close grip on my performance and time-management as well as providing his creative comments and insight throughout the process.

Embarking on my 2-year educational journey was a highly stressful and challenging but also rewarding and character shaping experience for me. I would not have made this possible, without the help of my family, who were always believing in me, and supporting every choice that I made both materially and mentally with all means possible. The culmination of this project is their achievement as well, and there are no words to express my deepest gratitude to them. My mother Vaya, for encouraging me to start a master programme and "go back to school" after 2 full years of professional activity and providing for me during my first busy year of courses, my sister Kleopatra and brother Vasilios, for their endless support and for setting the example with their achievements, and always my late father Aggelos, who never got to know about my experiences in Netherlands, but I am most certain that he would approve and support every step as well.

My gratitude goes as well to all the friends, colleagues and tutors that I had the pleasure to meet along the way, that helped me to broaden my horizons, learn about different cultures and become a more versatile, tolerant and sociable person. Special thanks to all my Greek friends that never let me feel homesick and were my "family overseas".

Georgios Germanos, May 2019

Table of Contents

1. Introduction 15
1.1. Introduction 17
1.2. State-of-the-art / Literature Review 17
1.3. Research question, objectives and sub-goals 18
1.4. Research approach and strategy 19
1.5. Analysis and presentation of research results 21
2. The upcoming demand for Nearly Zero Energy Buildings 23
2.1. Introduction 25
2.2. Current energy policy and standards in the Netherlands and the European Union 25
  2.2.1. The Building Decree / Bouwbesluit 25
  2.2.2. Thermal comfort guideline for the Netherlands 27
  2.2.3. The European EPB Standard- EN52000 29
2.3. The vision – From 2020 to 2050 31
2.4. The adapted Trias Energetica – a circular concept 33
2.5. Case Studies of synergetic nZEB in the Netherlands 34
  2.5.1. The Maas Tower (Maastoren) 34
  2.5.2. De Rotterdam 36
3. The concept of Energy Synergy 39
3.1. Introduction 41
3.2. Thermal energy Storage and Exchange 41
  3.2.1. Sensible heat storage 43
  3.2.2. Latent heat storage 45
  3.2.3. Chemical Energy Storage 46
3.3. Heat Pumps 47
  3.3.1. Principle and components 47
  3.3.2. Air-source heat pumps 48
  3.3.3. Ground-source heat pumps 49
3.4. Efficiency and performance of heat pumps 50
4. Problem Context
The "MEGA" building 51
4.1. Introduction 53
4.2. Description and location 53
4.3. Program and functional requirements 54
  4.3.1. International House of Justice and Ancillary Spaces 54
  4.3.2. Hotel with conference rooms 54
  4.3.3. Offices 55
  4.3.4. Housing 55
  4.3.5. General Services 55
4.4. Building design and characteristics 55
  4.4.1. Geometry and layout 56
  4.4.2. Envelope design 59
  4.4.3. Climate design 60
5. Calculating the energy demand 63
5.1. Introduction 65
5.2. The Dutch Reference Climate 65
5.3. Comfort requirements 68
5.4. User occupancies and schedules 68
5.5. Calculating the heat balances 71
  5.5.1. Internal heat gains 71

5.5.2. External heat gains ... 72
5.5.3. Ventilation ... 72
5.5.4. Transmission ... 72
5.6. Simulation and modelling ... 73
5.7. Energy Demand Profiles ... 73
5.8. Building specific energy scatter for mixed functions ... 75
6. From function to installation ... 77
6.1. Interpreting the energy demand scatter diagram ... 79
6.2. Sensitivity analysis ... 81
6.2.1. The effects of comfort requirements ... 81
6.2.2. The effects of Domestic Hot Water requirements ... 82
6.3. Investigation of additional cases for energy scatter profiles ... 83
6.3.1. Case 1 - 100% Residential function ... 84
6.3.2. Case 2 - 25% Residential function + 75% Offices function ... 85
6.3.3. Case 3 - 50% Residential function + 50% Offices function ... 86
6.3.4. Case 4 - 75% Residential function + 25% Offices function ... 87
6.3.5. Case 5 - 100% Offices function ... 88
7. Synergetic Installation concept ... 89
7.1. Introduction ... 91
7.2. Heating and cooling scheme ... 91
7.3. Modelling and simulation ... 92
7.3.1. System Mode 1 – Simultaneous Heating and cooling demand ... 92
7.3.2. System Mode 2 – Heating Mode ... 93
7.3.3. System Mode 3 – Cooling Mode ... 93
7.3.4. System Mode 4 – Neutral Mode ... 94
7.4. Calculating the energy savings ... 94
7.5. Overview of maximum electricity savings ... 101
8. Conclusions and Discussion ... 103
8.1. Overview of the research methodology and results ... 105
8.2. Overview of energy savings ... 105
8.3. Research questions and goals ... 106
8.4. Conclusions and Recommendations for further research ... 108
9. Appendices ... 109
9.1. APENDIX 1: Manual calculation of monthly and hourly thermal balances ... 111
9.2. APPENDIX 2: Design Builder Simulation ... 118
9.3. APPENDIX 3 – Additional cases of energy demand distribution ... 123
9.4. APPENDIX 4: MATLAB / SIMULINK Model ... 127
10. References ... 133

List of figures

Figure 1 – EPC policy from 1995 up to 2020 for the residential sector (source: Agentschap NL, 2013) 26
Figure 2 - EPC policy from 1995 up to 2020 for the non- residential sector (source: Agentschap NL, 2013) 27
Figure 3 – Adaptive temperature limits (ATG) (source: Boerstra et al., 2014) 28
Figure 4 – Principles for sustainable nZEB in the EU (source: BPIE) 31
Figure 5 - Sustainable vision 2050 (source: Energy Agenda,2017) 32
Figure 6 - 5 step system (Adapted Trias Energetica) 33
Figure 7 – The Maas Tower 34
Figure 8 - Energy installation for the Maas Tower (source: Beerda, 2008) 35
Figure 9 - De Rooterdam (source: OMA Architects) 36
Figure 10 - Functional program and stacking for De Rotterdam (source: Zeiler, 2017) 36
Figure 11- Energy concept scheme for De Rotterdam (source:Zeiler, 2017) 37
Figure 12 - Under-floor pipe system for heating and cooling (source: Zeiler, 2017) 37
Figure 13 – Schematic representation of an aquifer thermal energy storage system in heating and cooling season (source: iftechnology.nl) 44
Figure 14 – Categorisation of PCMs according to their natural origin (source: Sharma et al., 2009) 45
Figure 15 – Categorisation of PCM according to the transition temperature (Source: Ge et al, 2013) 46
Figure 16 – Heating and cooling cycle of a common heat pump arrangement (source: energyeducation.ca) 47
Figure 17 – Heating mode of an ai-to-air heat pump (source: Canada Office of Energy Efficiency) 48
Figure 18 – Cooling mode of an ai-to-air heat pump (source: Canada Office of Energy Efficiency) 49
Figure 19 – Operation of a ground-source heat pump in heating mode (Canada Office of Energy Efficiency) 50
Figure 20 – Location of the conceptual MEGA building 53
Figure 21 - Functional diagram of the conceptual MEGA building 56
Figure 22 – Building outline and dimensions 56
Figure 23 – Building overview (stacking) and vertical section 57
Figure 24 – Typical arrangement for the courthouse function 57
Figure 25 – Typical floor arrangement for hotel + housing functions 58
Figure 26 – Typical floor arrangement for housing + office functions 58
Figure 27 – Façade general appearance 59
Figure 28 – Original façade arrangement and function 59
Figure 29 – Overview of the original ventilation concept of the MEGA building 61
Figure 30 – Overview of heating and cooling installations for the original MEGA building 61
Figure 31 – Floor section showing position of services in the MEGA building 62
Figure 32 . - Orientation and sun path at the location of the MEGA Building 65
Figure 33 – Climate data for the city of The Hague 65
Figure 34 - Rendered aspect of a sample floor including the building envelope 73
Figure 35 - Design Builder model of the main building functions 73
Figure 36 - Monthly energy demand for the whole building (manual calculation) 74
Figure 37 - Monthly energy demand profile for the whole building (DB simulation) 74
Figure 38 - Energy demand scatter for the MEGA building using daily intervals 75
Figure 39- Energy demand distribution for the MEGA building using hourly intervals 76
Figure 40 – Peak demands for heating and cooling (highlighted in red) as represented in a energy demand scatter diagram 79
Figure 41 – Cloud of time steps when simultaneous heating and cooling is required. 80
Figure 42 – Example of an unbalanced energy demand scatter as calculated for the case study of the MEGA building. 80
Figure 43 – Energy demand scatter of comfort sensitivity analysis 82
Figure 44 – Energy demand distribution including DHW 83
Figure 45 – Daily energy demand distribution for 100% Residential Function 84
Figure 46 – Hourly energy demand distribution for 100% Residential Function 84
Figure 47 – Daily energy demand for Case 2 of additional building cases 85
Figure 48 - Hourly energy demand for Case 2 of additional building cases 85
Figure 49 - Daily energy demand for Case 3 of additional building cases 86
Figure 50 - Hourly energy demand for Case 3 of additional building cases 86
Figure 51 - Daily energy demand for Case 4 of additional building cases 87
Figure 52 - Hourly energy demand for Case 4 of additional building cases 87
Figure 53 - Daily energy demand for Case 5 of additional building cases 88
Figure 54 - Hourly energy demand for Case 5 of additional building cases 88
Figure 55 – Schematic representation for System Mode 1 of the synergetic installation system 92
Figure 56 - Schematic representation for System Mode 2 of the synergetic installation system 93
Figure 57 - Schematic representation for System Mode 3 of the synergetic installation system 93
Figure 58 - Schematic representation for System Mode 4 of the synergetic installation system 94
Figure 59 – Percentage of energy savings compared to the reference case for the MEGA building – Variable buffering capacity 95
Figure 60 – Percentage of energy savings compared to the reference case for the MEGA building – Variable heat pump power 95
Figure 61 – Percentage of energy savings compared to the reference case for 100% Residential function – Variable heat pump power 96

Figure 62 – Percentage of energy savings compared to the reference case for 100% Residential function – Variable buffering capacity........ 96
Figure 63 – Percentage of energy savings compared to the reference case for 25% Residential + 75% Office function – Variable heat pump power........ 97
Figure 64 – Percentage of energy savings compared to the reference case for 25% Residential + 75% Office function – Variable buffering capacity........ 97
Figure 65 – Percentage of energy savings compared to the reference case for 50% Residential + 50% Office function – Variable heat pump power........ 98
Figure 66 – Percentage of energy savings compared to the reference case for 50% Residential + 50% Office function – Variable buffering capacity........ 98
Figure 67 – Percentage of energy savings compared to the reference case for 75% Residential + 25% Office function – Variable heat pump power........ 99
Figure 68 – Percentage of energy savings compared to the reference case for 75% Residential + 25% Office function – Variable buffering capacity........ 99
Figure 69 – Percentage of energy savings compared to the reference case for 100% Office function – Variable heat pump power........ 100
Figure 70 – Percentage of energy savings compared to the reference case for 100% Office function – Variable buffering capacity........ 100
Figure 71 – Overview of maximum energy savings for the investigated cases........ 101
Figure 72 - Overview of maximum energy savings for the investigated cases........ 105

List of Tables

Table 1- Timeline of reforms for the energy performance of buildings in the Netherlands (source:Agentschap NL, 2013) 26
Table 2 – Current and suture EPC values for the Netherlands (source: de Bont at al., 2016) 26
Table 3 – Description of the comfort classification levels (Source: Olesen 2007, EN15251) 29
Table 4 – Content of the different modules included in the EN52000 series of standards (source: epb.center) 30
Table 5 – Operational properties of thermal storage methods based on the storage medium (adapted from Hauer, 2011) 42
Table 6 – Properties of various materials used for sensible heat storage (source: Ayappan et al. 2016, Tian et al. 2013, adapted from Sarbu and Sebarchievici, 2018) 43
Table 7 – Chemical reactions for thermal energy storage (source: Garg et al.,2013, adapted from Sarbu and Sebarchievici, 2018) 47
Table 8 – Average total hourly solar radiation for different orientations according to NEN 7120 66
Table 9 – Average monthly outdoor temperatures according to NEN 7120 66
Table 10 – Hourly reference temperatures for January and July (source: KNMI) 66
Table 11 – Hourly total irradiance for January (source: BK Wiki – Zon Bouwfysica) 67
Table 12 – Hourly total irradiance for July (Source: BK WIKi – Zon Bouwfysica) 67
Table 13 – Assumed comfort parameters for the different functions within the MEGA building 68
Table 14 - Occupancy and internal gains for the residential function (source: EN16798-1) 69
Table 15 - Occupancy and internal gains for the office function (source: EN16798-1) 69
Table 16- Occupancy and internal gains for the conference / meeting room function (source: EN16798-1) 70
Table 17 - Occupancy and internal gains for the restaurant function (source: EN16798-1) 70
Table 18 – Internal heat gains 71
Table 19 – Case 1 of comfort sensitivity analysis. 81
Table 20 – Operational temperatures for the hot and cold storage tanks 92

1. Introduction

The Red Apple” – Rotterdam

source: Flickr)

1.1. Introduction

Due to the constantly developing climate change and the depletion of fossil fuel reserves, modern building requirements for energy efficiency and sustainability are in transition from a trend to a requirement. By 2020, the directive is that all newly constructed buildings in Netherlands will be required to comply with the nZEB guidelines and have an EPC=0.

Rapid urbanization and shortage of appropriate building space is currently projected to the future compared with the emerging needs for housing in the Netherlands. The supply and demand problems are expected to lead to an increase in the development of high-rise buildings. The potential for sustainability for high-rise development has been a point of debate in recent research and literature. Extensive studies have been conducted regarding design parameters that can lead to more sustainable high-rise in the cases of housing or offices, that led to certain design guidelines about the shape, orientations, envelope characteristics that can result to substantial energy savings.

The case in practice, however, is that most high-rise developments are designed for mixed-uses (housing, office, retail etc.) in a single building, that leads to greater complexity because of different requirements for different functions and different demands in energy. This complexity is the grey point in the development of such projects, as accomplishing to accommodate for all functions is what makes the project economically viable, but usually shifts the focus for energy efficiency to lower priority.

For this reason, trying to analyze the energy design requirements for a mixed-use high-rise would be an interesting point of view from both an academic and building industry point of view. The theme of “synergy” (co-operation, co-existing) is inspired from the first step of the “Trias Energetica” concept. This states that the primary goal of zero energy design is to reduce the energy demand by smart design and avoiding waste of energy. Synergy is also aligned with the emerging concept of circular economy, avoiding waste with any means and re-using/recycling materials and services.

The focus of this project is thus to examine the potential for a nZEB scheme of a mixed-use high-rise building in the Netherlands, based on the possibilities for energy exchange/cooperation between different functions, the most common being office and housing spaces. The research is not irrelevant to market needs and is actually an engineering challenge, as all newly developed buildings (including high-rise) will be required by law to be energy neutral in the coming years.

In the following pages, the research goals of the project will be presented in detail and the strategy to achieve the required results will be analyzed. The expected results and their organization as well as the project management/planning will be organized based on the current expectations.

1.2. State-of-the-art / Literature Review

The concept of zero-energy buildings is not new. The effort and design to create viable and sustainable buildings begun in circa 1997 with the rise of “environmental consciousness” as soon as the phenomenon of climate change and its causes were widely examined and analyzed by scientists and researchers. Energy efficient design in buildings however is a multi-variable task and can expands through different knowledge areas, being architecture, environmental engineering, mechanical and energy engineering as well as material science and computational mechanics.

Current research is focused on 3 levels: the first level is early stage design parameters based on the location and particular climate of the building site, meaning design decisions such as the orientation of the building, envelope characteristics and area and position of openings (windows) in order to achieve better energy performance without the need of intricate energy systems. The second level involves techniques for energy production in buildings such as integrated photovoltaics, wind turbines, algae or systems for passive/heating cooling. Inspiration is many drawn from nature or vernacular techniques of past builders, creating a particular field of bioclimatic/biomimetic architecture. The third level focuses on next generation technology and mechanical systems (heating, cooling, HVAC, lighting) that are smart and enable better performance, efficiency, user involvement and comfort in a lower cost and without having an impact on the environment.

The energy performance of high-rise buildings is relatively new, considered their first appearance in USA in 1880s and their increasing popularity until the 1970s. The different techniques in tall building design and their implications in energy performance are presented in a very organized manner by *Oldfield et al. (2009)*. The different types of skyscrapers are organized in 5 generations, from early voluptuous office buildings in Chicago, to modern glazed curtain wall towers and present time sustainable oriented buildings that employ environmental techniques and high-end systems and material for energy production and savings.

Generalova et al. (2018) , analyzes the concept and emerging trends in mixed-use high-rise development. The complexity of this type of projects is showcased and case studies around the world are compared. The conclusion is that the trending concept of the “vertical city” will be the norm of the future and current efforts have to be focused on one hand, to integrate these buildings in the urban context and create livable and prosperous spaces for human living and development. On the other hand, comfort in those buildings is very important, a factor that also concerns the current research project. Energy efficiency is of course a vital factor but always assuring an appropriate living environment for building inhabitants.

Energy efficiency translated into building design was investigated by *Raji et al. (2016)*. While this paper is not directly connected to synergetic energy design, the early stage design recommendations that are presented, are important in order to create a relatively optimal reference building where energy exchange techniques can be properly tested. This implies that envelope characteristics have to be appropriate and according to regulations so that no errors are later presented in the energy consumption of different functions.

The innovative theme of energy exchange was first tackled in the graduation project of *Sillem (2011),* where different techniques for energy exchange and storage are presented and analyzed. The graduation also involved a design case where the theme is applied in a compound of buildings with different functions. The primary results show that while energy cooperation is viable, it strongly depends on the types of different buildings that co-exist. The theme is expanded in the graduation research of *Ten Caat (2018),* where the term of “energetic circularity” is used to better describe the design concept. Energetic circularity is design for a cooperation between a greenhouse, a supermarket building and nearby dwellings so that a zero-energy chain is created.

Based on the mentioned literature, this research project is aiming to combine past knowledge in order to solve a modern problem. The use of energy exchange within the same building with space limitations, against the previous efforts applied on different buildings is the uncharted territory that the project will explore. Hopefully, the results can be a useful addition to the body of knowledge for sustainable buildings and circular energy systems, as well as a primary design manual for professionals that want to use innovative techniques in their projects.

1.3. Research question, objectives and sub-goals

As mentioned in the introduction, the project revolves around the subject of zero energy design in buildings with application to mixed-use high-rise buildings and the research focus will be placed on the theme of energy exchange and storage between different functions within the same building. This concept was chosen first of all to stress the importance of energy efficiency in buildings.

Most importantly, the choice to investigate the potential for energy cooperation between functions is aimed to stress the importance of firstly investing in passive techniques. Recycling of energy in building and applying circular concepts rather than only paying attention to renewable sources of production (wind energy, photovoltaics) can considerably reduce costs and improve efficiency.

In this context, the main research goal of the project can be expressed by paraphrasing the first step in “Trias Energetica”:

Main question:

“How can energy demand in a mixed-use high-rise building be reduced by means of energy exchange between different functions?”

The main question is the basis for forming the required sub-questions. By analyzing the keywords contained in the sentence against the relevant literature, the required steps in order to produce useful results can be listed.

1. **“Energy Demand” –** This term usually involves energy used for heating and cooling during the year, which are the most common indicators used in energy efficient building design. However, in order to increase the accuracy of the final results, approximation for the electricity used for lighting and services should be included in the calculations.

2. **“Mixed-use” –** The mixed-use concept is the special feature that creates the necessary complexity for an original/innovative research project, but at the same time is the required basis to examine the “synergy” concept. A mixed-use building requires different comfort levels for each function and influences the energy demand. This is because different functions have different requirements for heating/cooling/electricity within the same day or season. As a result, the energy demand profiles for each function can show the daily/monthly/seasonal patterns that will be used to determine combinations for energy exchange.

3. **“High-rise” –** High-rise buildings are a very special category in building design as they require substantial amounts of energy to operate, but at the same time have limited space for energy systems and installations. The case of high-rise buildings was chosen from one part, because it is the most complex case for zero-energy design and from the other part, to differentiate this project from existing research. Similar circular concepts

have been investigated for city districts and between buildings in the same district but not entirely for a single building with limited available space.

4. **“Energy exchange” –** Energy exchange involves the patterns that can be established to create energy loops between different functions. This requires the identification of energy sources and sinks within the high-rise building and based on the energy profiles and functions, energy surpluses and deficits in time and quantity that can be exchanged. On a second level, the term involves the proper design and dimensioning of energy systems that can allow transport and storage of energy between within the chosen cooperation loops.

Based on this analysis, a set of sub-questions can be derived, that express the different steps of the research approach.

Sub-questions:

1. What is the influence of mixed-uses for the energy design of the building?
2. What are the potential energy benefits from a mixed-use scheme?
3. Which technical solutions/systems can be used?
4. What are the general design guidelines for synergetic systems that can be derived from the analysis?

These questions express the project goals as well and are used to formulate the research approach and strategy in order to produce the required results.

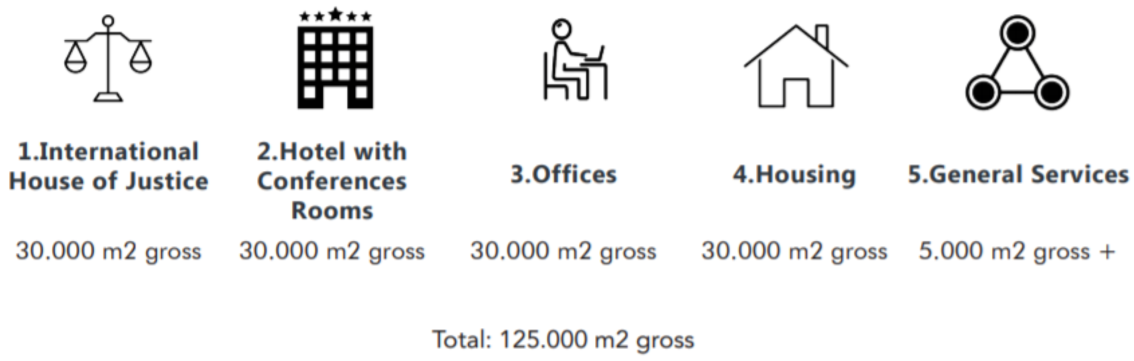
1.4. Research approach and strategy

Based on the research questions that were mentioned in the previous part, the project can be characterized as a design case with a specific research focus. This means that although the energy synergy theme has research value, it must be calculated and applied within a specific design case. Thus, the most appropriate research method is a quantitative analysis of the energy behavior based on a modelled version of the reference building. The modelling results can be expanded at a second point using supplementary software or approximations/calculations to derive results about costs or the dimensions/efficiency of chosen energy systems.

The design case that will be used as a realistic case for this research project is the program of the course AR0026 MEGA, as it was presented during the academic year 2016/2017. The course involved the design of a mixed-use high-rise building at least 120 m high, located in Den Haag, Netherlands, with specific program requirements. The project accommodates for office spaces (the new International Court of Justice), a hotel and conference center as well as residential units and commercial spaces. The program is representative of a modern mixed-use skyscraper and serves as an appropriate case study to investigate energy efficiency. In this manner, there are sufficient and realistic data, dimensions, requirements and restrictions that can serve as input for the research part. Next to that, the results can be quantitative and comparable to existing or similar future buildings with similar functions based on the number of floors, total gross floor area etc.

The research strategy can be organized in 6 individual steps, that include a main volume of calculations and aim to produce a set of results that can be also considered milestones for the project. This means that the project cannot progress forward in a proper way if the individual result set are not produced or produced with mistakes.

Step 1	Analyze the building program of MEGA 2017
Objective 1	Identify energy sources and sinks



By analyzing the program requirements of MEGA 2017, the different functions and their characteristics can be identified and organized. This will serve to identify functions that behave as energy sources and functions that behave as energy sinks within the building. By establishing the comfort requirements and temperatures for all functions, the basis for calculating their energy demand is laid and also important conclusions are produced about the manner that mixed-use influences the energy demand in the building, the content of the first sub-question.

Step 2	Determine the comfort requirements for each function
Objective 2	Set acceptable and realistic comfort levels for sample spaces

This step is important in order to create a comfortable indoor environment for all functions that can serve as the basis for calculating the energy balances in a later step. The correct choice of temperature ranges will influence the energy demand for the building. An extensive sensitivity analysis of the temperature ranges will also help to indicate if certain energy reductions can be achieved by just creating lower (but still acceptable according to regulations) comfort levels within the building.

Step 3	Calculate the energy balances for sample functions
Objective 3	Determine monthly/seasonal energy demand profiles for every function

This step focuses on modelling and calculations in order to determine the patterns of energy demand for different functions within the building. Based on the patterns, energy surplus and deficit can be identified, an indication for appropriate energy exchange loops between building spaces. The profiles will be summarized in a form of energy demand scatter which will be used to determine the eligibility and potential of the mixed-use building for energy synergy by storage and exchange.

Step 4	Analyze patterns/scatteer – identify surplus and deficit
Objective 4	Translate into appropriate exchange loops between the right spaces Translate into algorithmic steps for the interpretation of the demand scatter

The analysis of patterns is what will decide which are the most appropriate functions that can cooperate and exchange energy. This step will produce quantitative results on the amount of energy that is needed/is in excess at any time during the operation of the building. The results will influence the exchange rates (daily/monthly/seasonal) and the potential or requirement for storage, that consequently influences the choice of equipment at a later stage.

Step 5	Determine and calculate the required energy systems
Objective 5	Final detailed energy exchange diagrams

This step is important in order to translate the theoretical results into an actual design of building energy systems and services. The choice and dimension of equipment will influence the final levels of efficiency and energy reductions.

Step 6	Conclusions
Objective 6	Quantitative energy savings, minimum EPC, cost versus benefit

The final step will actually answer the set of individual sub-questions and the main research questions. The assessment of results will show the actual potential of energy savings and the possibility or not for a zero-energy building with or without the contribution of energy production. An approximation of the cost of the chosen equipment versus the final energy saving, is an indicator of feasibility for the circular energy approach within high-rise buildings.

An alternative approach to the chosen research strategy would be to choose an existing building with the appropriate characteristics within Netherlands. In this case, the project would focus on comparing the existing design of energy systems and a scheme for energy cooperation according to the research goals set.

The advantage of this approach is that final results can be directly comparable based on the current energy behavior of the existing building, while with the approach mentioned before, a conceptual building is designed with no realistic data that can be compared in order to assess the level of energy savings. However, there are very few buildings in Netherlands that can fulfill the criteria and access to the design information would be an issue. Further to that, existing buildings designed in past years might conform to outdated regulations, a factor than can influence the results. For example, buildings with insufficient insulation or a building envelope that does not enable energy saving, would be inappropriate to study because its energy level would not only rely on energy systems but also design parameters including orientation, window to wall ratios and provision for shading/ventilation etc.

In the case of the concept building, an assumption is made that all non-mechanical or energy related parameters (insulation, window to wall ratio and shading) are optimal based on current regulations and current literature. Of course, zero-energy design is a holistic approach, but the assumption enables the results to focus merely on the potential of energy exchange, irrelevant of other parameters, always subject to the time and complexity limitations of a master graduation project.

1.5. Analysis and presentation of research results

The project involves both qualitative and quantitative results, so different forms of analysis and representation will be used. The expected results of the project can be organized in the following categories:

- **Energy demand profiles for sample functions**
  The profiles are a representation of the building's energy behavior through time and are important in order to determine the energy exchange plan. These profiles are organized as graphs of energy units (kWh) against time, which can be hours of a day, months or a seasonal average. The energy scatter profile will showcase the demand for both heating and cooling within the same day or season, and the quantitative aspect of this demand that will determine the design of the systems used.

- **Patterns for appropriate energy cooperation**
  The patterns express a synergetic relation between functions, for example excess heat from office spaces can be used for housing, or a conference center can be cooled down in cooperation with the pool are or restaurant within the building. These qualitative results are expressed in figures and graphics and can serve as samples for building designers.

- **Quantitative annual energy savings**
  Based on calculations, the energy that will be able to be exchanged between functions, will result as a save for new energy from the grid. These savings will be organized in a graph showing the % in savings compared to the seasonal or monthly needs without a synergetic scheme, as well as a total annual percentage of energy savings based on the yearly demand of the building.

- **Description and dimensions of chosen energy systems**
  These schemes will be organized in graphic that present the chosen energy loops, and their dimensions such as efficiency, operational temperature levels and position in the building. For example, these schemes can present the position of heat pumps or exchangers, transport systems and storage points within the building, together with the temperature requirements for each step in the loop.

2. The upcoming demand for Nearly Zero Energy Buildings

“De Rotterdam” – Rotterdam

(source: flickrhivemind.com)

2.2. Introduction

Modern time living and requirements has render substantial changes on the built environment. Modern building in the developed world, consume approximately 40% of the energy produced worldwide, while being responsible for emitting 36% of the total CO_2 emissions. Research and studies have shown that the effects of climate change, if no regulating measures are to be taken will be, will be severe. The answer to the challenge of climate change was answered by the signing of the Paris Agreement in 2016, among 195 countries of the world. The plan is to regulate energy production and use in order to limit global warming below the threshold of 2 degrees Celsius within the coming years (Dutch Energy Agenda,2015).

The Netherlands, among the signees has already established a plan to manage factors affecting climate change with the short- and long-term future. Regarding the building sector, a national plan was introduced by the Dutch government in 2012, with aim to implement strict nZEB guidelines. The requirement was that within the horizon of 8 years, the energy performance for residential and commercial buildings must improve with stricter limits. The main target is that all newly built buildings should be nearly energy neutral by 2020 (Dutch Energy Agenda, 2015).

"Nearly Zero Energy Building: Technical and reasonably achievable national energy use of > 0 kWh/(m²a) but no more than a national limit value of non-renewable primary energy, achieved with a combination of best practice energy efficiency measures and renewable energy technologies which may or may not be cost optimal."

The definition shows that the basic characteristic of a nearly zero energy building is the total consumption that should be equal to zero. However, it is important that the primary energy source is partly or in its entirety renewable. A large point of debate lies in the economic viability of nZEB project. Whereas the main target is to achieve the best possible energy performance, the feasibility and cost efficiency throughout the total life cycle of the building, are important parameters in order to establish energy neutral buildings as a proven concept.

2.3. Current energy policy and standards in the Netherlands and the European Union

2.3.1. The Building Decree / Bouwbesluit

The Dutch Building Act 2003 or "Bouwbesluit 2003" was the first decree in The Netherlands related to the building industry. It contains provisions on the building and demolition of buildings, the state and the use of existing buildings, yards and open fields and on safety measures during construction and demolition. It sets rules relating to the construction of structures in terms of safety, health, usability, energy efficiency and environment. These are the requirements to ensure the minimum necessary quality of the buildings.

The Dutch Building Decree, has undergone revisions in 2012 and is divided in five chapters relating to safety, health, usefulness, energy-saving and environmental performance. Especially, chapter 5 (NEN 7120:2011) has significant importance because it contains the guidelines and the building regulations in the Netherlands in order to design and assess the energy performance of buildings. According to NEN7120, the energy performance is expressed by the **EPC** or ***"energy performance coefficient"***.

The Bouwbesluit, provided early stage guidance for building design and regulates the basic characteristics for building envelopes. The Decree also contains some provisions related to the building's internal heat productions: lighting, people and equipment.

The current recommended values for the thermal resistance of building components is:

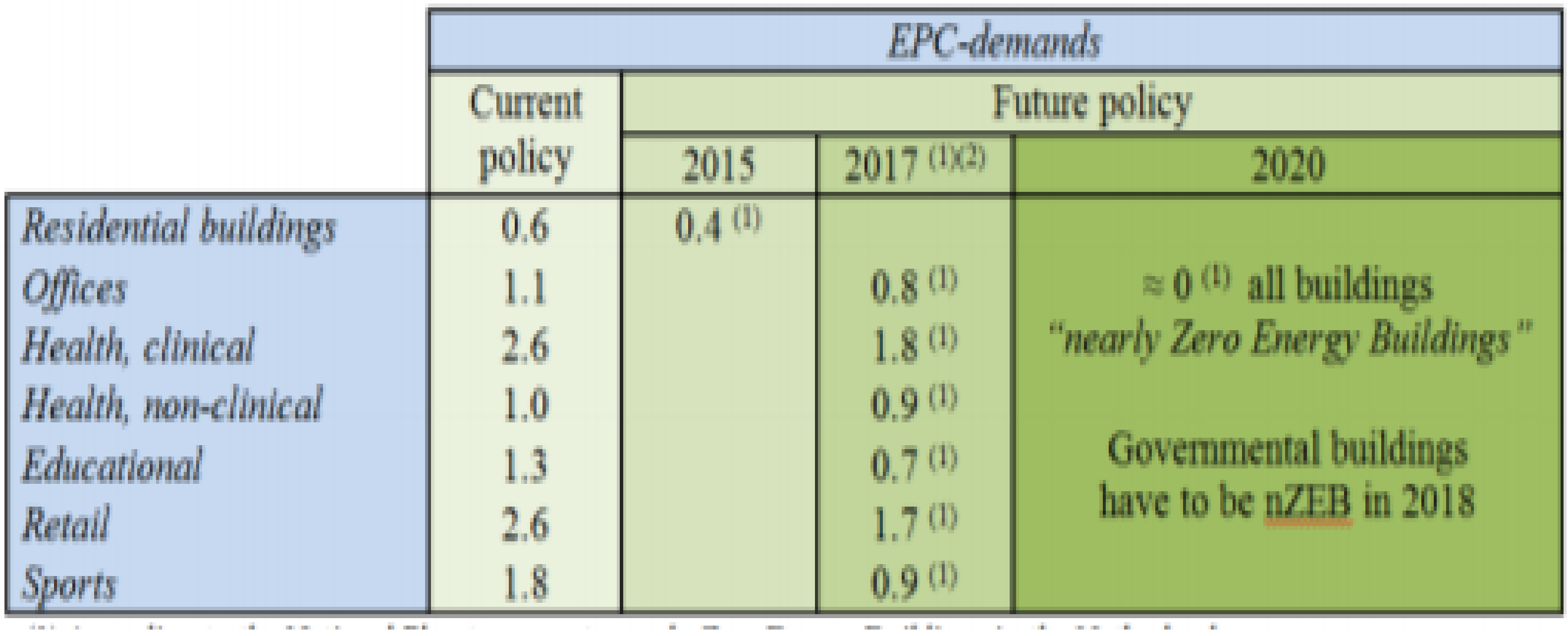
- Roofs – 6.0 m^2.K/W
- Walls / façade s– 4.5 m^2.K/W
- Floors – 3.5 m^2.K/W
- Windows – 0.16 to 0.7 m^2.K/W

In the Netherlands building energy performance is expressed in an EPC score, which includes energy performance of installations (heating, cooling, hot tap water, ventilation, and lighting) and levels of insulation (roof, walls, floor, and windows). The EPC for has been introduced in 1995 and been tightened onwards. Building companies have agreed with the Dutch government on further tightening of the requirements in the near future, in order to move towards nZEBs. The EPC requirement for the residential sector was decrease to 0.4 in 2015 (Figure 1). For the non-residential sector, EPC requirements were lessened by 50% in 2017 compared to the requirements of 2007 as shown in Figure 2 (National Agency, 2013).

The timeline for reforms regarding the energy performance of buildings can be seen bellow:

1978- 1988	National Insulation Program Requirements thermal insulation in Building code for new buildings.
1990-1994	EP determination methods were introduced in the Dutch standards
1995	EP requirements in Building legislation
2000 -2003	EP Advice and subsidy program
2003-2006	EPBD development tools (EU directive)
2006	Implementation Energy Label

Table 1- Timeline of reforms for the energy performance of buildings in the Netherlands (source:Agentschap NL, 2013)



	EPC-demands			
	Current policy	Future policy		
		2015	2017 (1)(2)	2020
Residential buildings	0.6	0.4 (1)		≈ 0 (1) all buildings *"nearly Zero Energy Buildings"* Governmental buildings have to be nZEB in 2018
Offices	1.1		0.8 (1)	
Health, clinical	2.6		1.8 (1)	
Health, non-clinical	1.0		0.9 (1)	
Educational	1.3		0.7 (1)	
Retail	2.6		1.7 (1)	
Sports	1.8		0.9 (1)	

Table 2 – Current and suture EPC values for the Netherlands (source: de Bont at al., 2016)

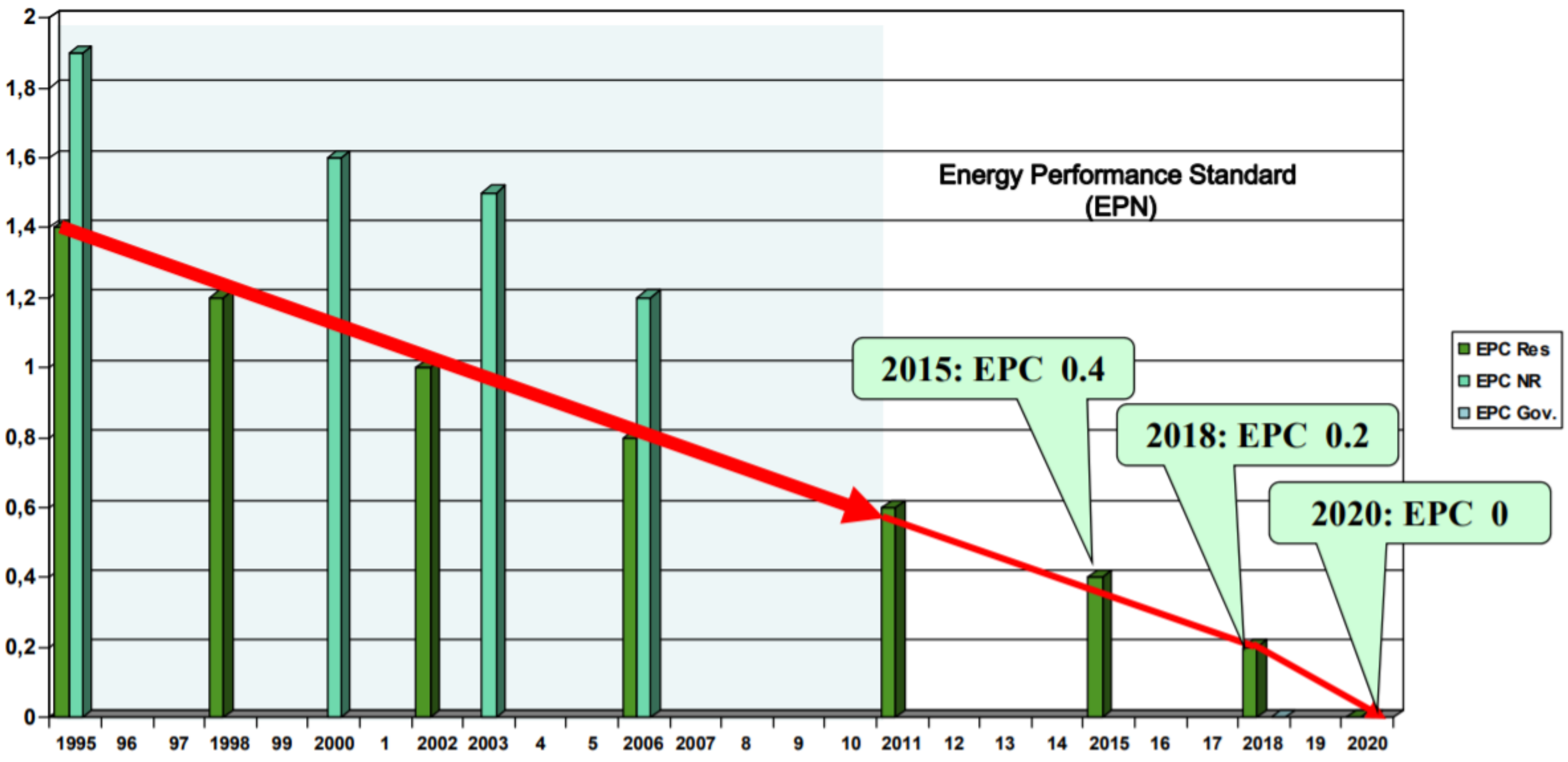


Figure 1 – EPC policy from 1995 up to 2020 for the residential sector (source: Agentschap NL, 2013)

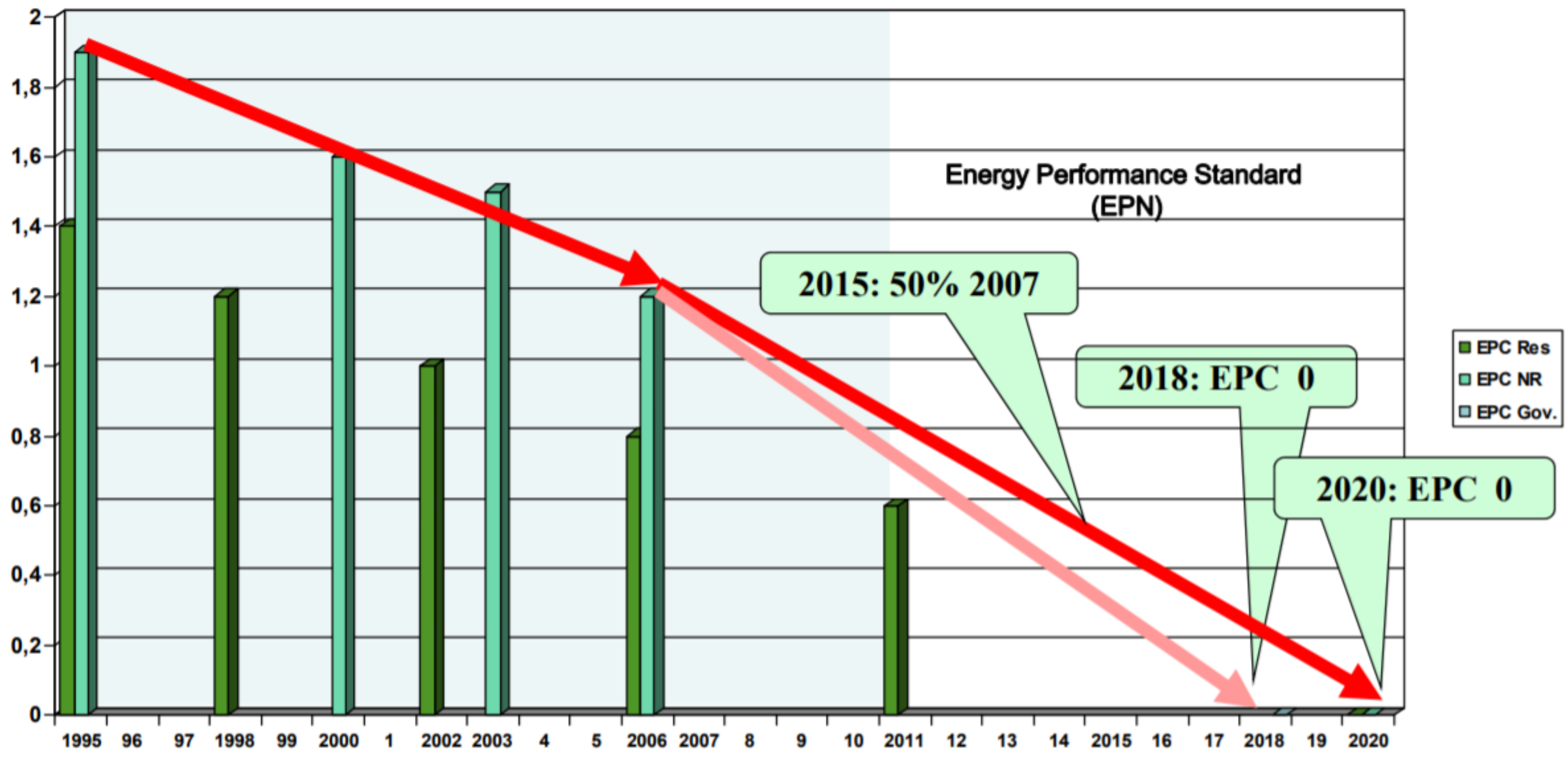


Figure 2 - EPC policy from 1995 up to 2020 for the non- residential sector (source: Agentschap NL, 2013)

2.3.2. Thermal comfort guideline for the Netherlands

In the mid-70s, Netherlands started to develop the first guidelines and strategies relative to thermal comfort in buildings. They were primarily based on the PMV-PPD model developed by P.O. Fanger and later on ISO-EN 7730. Both presented a theory to predict whether a particular circumstance experienced by building users will be perceived as “cold”, “neutral” or “hot”. Over the years, the Netherlands adopted three consecutive methods to assess thermal comfort for the design and simulation of buildings, and they respectively are:

- Overheating Hours (TO)
- Weighted Overheating Hours (GTO)
- Adaptive Temperature Limits (ATG)

PMV was developed to be used in steady-state conditions. Then, it is important to take into account that only TO performance indicator is suitable for these cases only. Consequently, for naturally ventilated spaces, which often have high levels of air movement, were developed empirical methods of thermal comfort, such as GTO and ATG. The Overheating Hours (TO) method was first presented in 1979 by the Netherlands government. It is the simple and quickest technique to evaluate a certain indoor environment in terms of comfort for its occupants. The standard ISO 7730 establishes that for a space to present “good” conditions of thermal comfort must comply with the limits of $0.5<PMV<0.5$ and no more than 10% of its occupants may feel uncomfortable. TO defines that the number of hours at which temperature levels are superior to 25ºC and 28 ºC, should not exceed 100 and 10 to 20 hours, respectively, during the course of a full year. However, one disadvantage of this indicator is that does not provide information about how long the overheating hours last and it does not take into consideration other aspects than temperature.

Afterwards, the TO method evolved into the so-called Weighted Overheating Hours (GTO) method and was initially introduced in the Guidelines for Governmental Buildings in 1989. The GTO is supported by the theory developed by Fanger. This performance index relates the hours in which a predicted mean vote (PMV) exceeds +0.5 or -0.5 the comfort boundaries with weighting criteria proportional to PPD values. The sum of these hourly factors over the year result in the GTO. In case the system is improperly sized, the number of weighted overheating hours can be seen to be rather high, in some cases even higher than the number of operation hours. When the number of weighted overheating hours remain below 150 hours per year, the indoor conditions are considered to be in an acceptable range.

This method however, has some important drawbacks. To begin with, thermal comfort results obtained through this method are not intuitive, and therefore it may be difficult to present them to people untrained on this subject. Secondly, as the GTO is based on the occupants’ thermal comfort perception, this method may not be suitable for buildings in which occupants take different actions, in order to adapt themselves to the changing thermal environment. For buildings with degree of adaptive opportunity the TO and GTO thermal comfort models were found to have major obstacles.

Following this, in 2004 a new method to access thermal comfort was adopted, in which a distinction between sealed centrally air-conditioned buildings and buildings with free running conditions and possibility to control room temperature is made. In an effort to overcome these complications the terms Alpha and Beta, were introduced to characterize the different climate/building types.

The Adaptive Temperature Limits (ATG) thermal comfort model, described in detail in ISSO 74, is -occupant as being able to adapt himself to different temperatures during the seasons of the year. The maximum indoor temperature is higher for Alpha buildings rather than for Beta buildings, though the minimal values are equal in both building types. Alpha buildings are categorised by the existence of natural ventilation, free-running conditions or climate control conditions by the user himself in terms of having at least one operable window and/or temperature adjustment. In opposition, Beta buildings are characterized for having a closed façade and air conditioning with centrally regulated climate.

The main advantage of this method is that allows the distinction between two types of buildings. ATG method tolerates a wider temperature range for natural ventilated buildings and simultaneously, facilitates the communication with the client about the thermal comfort assessment. One should take in mind, that the comfort perceived by occupants differs, when comparing office buildings to dwellings. When one is at home, usually, wears a more comfortable clothing to relax, whereas at work the main requirement is to feel comfortable, in order to be productive. Moreover, office buildings distinguish from dwellings in terms of occupancy times. With this method, the occupant's thermal comfort can be easily determined by means of a simple, clear and objective chart. In addition, the ATG method also takes into account the different building configurations, operational approaches, inside and outside temperatures and people behaviour, unlike the other methods.

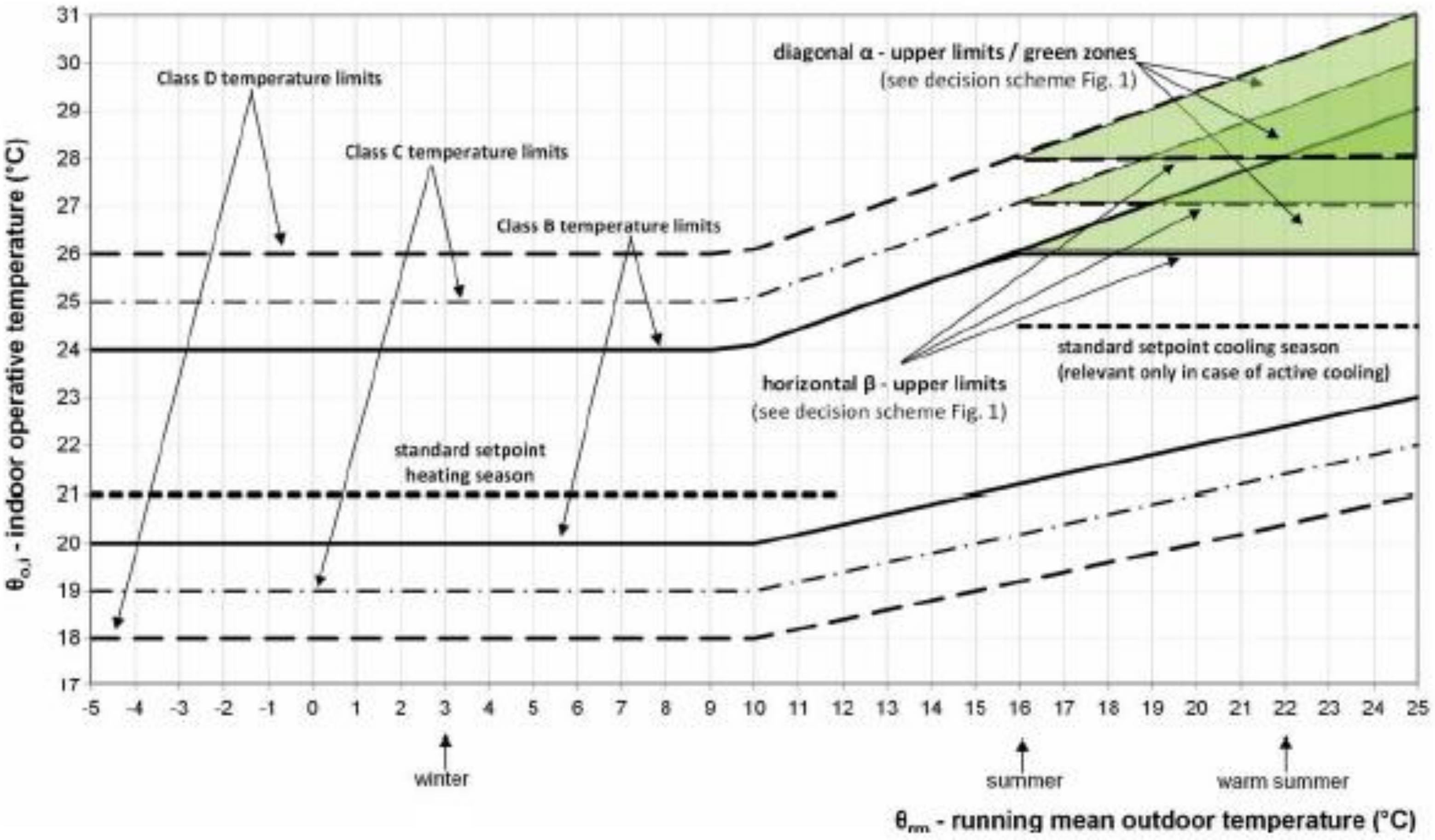


Figure 3 – Adaptive temperature limits (ATG) (source: Boerstra et al., 2014)

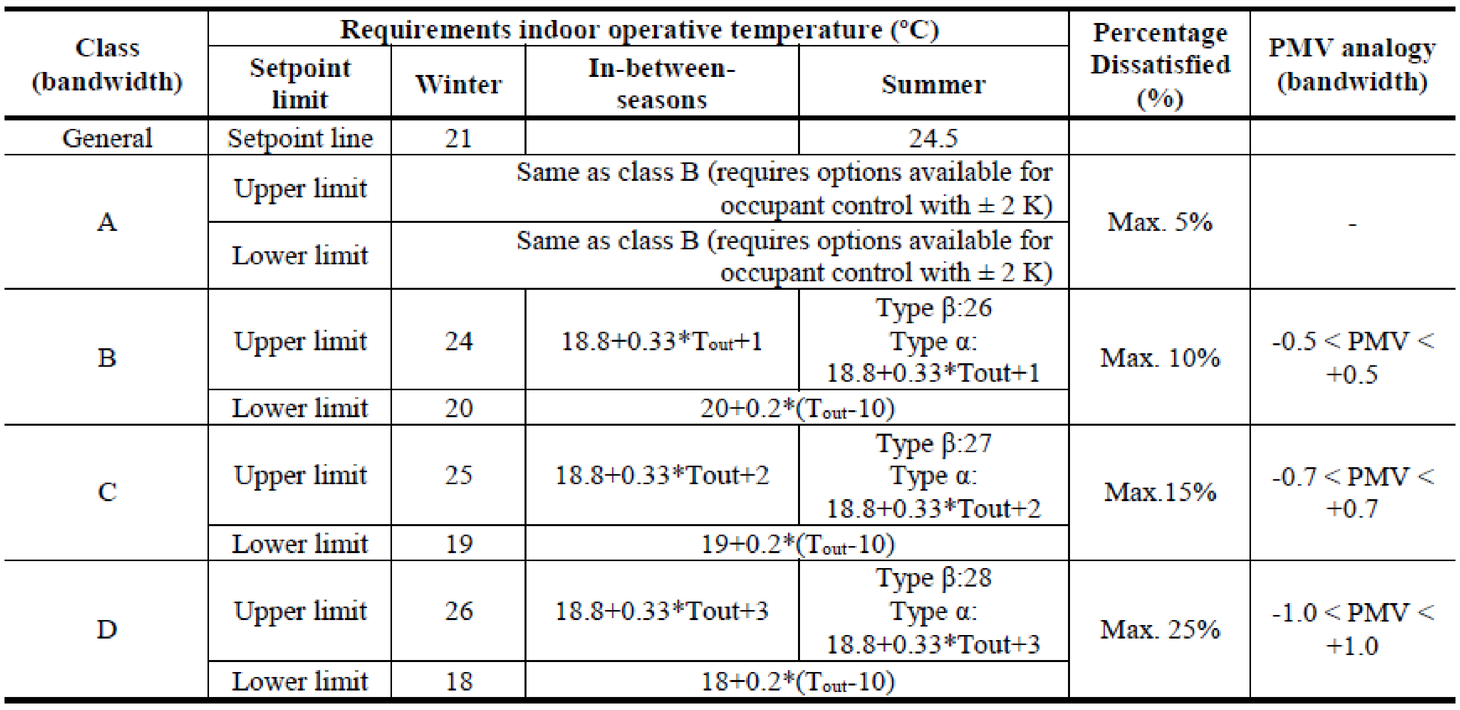
In 2014, a new version was elaborated of the ISSO 74:2004 guideline, making it the current Dutch Adaptive Thermal Comfort Guideline used when designing a new or refurbishing a building. To determine the limits that one must use for the operative temperature, two very important features must be examined initially for every building:

- Whether the situation is type α or a type β (room or building);
- The classification level pretended (Class A, B, C or D).

For cases where the building or room is in free-running conditions during summer, with operable windows and other adaptive opportunities for the occupants, the operative temperature limits are type α. Whereas, type β refers to situations where the operative temperature limits to consider are based on a building or room that depends on centrally-controlled cooling.

After determining what type of building it matches, the known temperature limits should be used as a threshold value, so that measurements can be made or can be ascertained by a computer simulation to estimate the inside operative temperatures. Every time that is made a reference to operative temperatures, this implies that also radiant temperature effects are taken into consideration.

The classification level should be applied given the situation intended. Class A is projected when exists a high level of expectation. This category is a reference when designing spaces for people with limited load capacity (extra sensitive people namely ill people) or when extra luxury is asked for. Class B is the most common level of expectation; it is a reference when designing or measuring new buildings or in case of extensive renovations. When measuring older existing buildings, the most common anticipated thermal comfort class is C. For a low level of thermal comfort, the classification level is D, normally can be used as a reference in the case of temporarily buildings or with limited use. The temperature boundaries are presented in Table 2.



Class (bandwidth)	Requirements indoor operative temperature (°C)				Percentage Dissatisfied (%)	PMV analogy (bandwidth)
	Setpoint limit	Winter	In-between-seasons	Summer		
General	Setpoint line	21		24.5		
A	Upper limit	Same as class B (requires options available for occupant control with ± 2 K)			Max. 5%	-
	Lower limit	Same as class B (requires options available for occupant control with ± 2 K)				
B	Upper limit	24	18.8+0.33*T_{out}+1	Type β:26 Type α: 18.8+0.33*Tout+1	Max. 10%	-0.5 < PMV < +0.5
	Lower limit	20	20+0.2*(T_{out}-10)			
C	Upper limit	25	18.8+0.33*Tout+2	Type β:27 Type α: 18.8+0.33*Tout+2	Max.15%	-0.7 < PMV < +0.7
	Lower limit	19	19+0.2*(T_{out}-10)			
D	Upper limit	26	18.8+0.33*Tout+3	Type β:28 Type α: 18.8+0.33*Tout+3	Max. 25%	-1.0 < PMV < +1.0
	Lower limit	18	18+0.2*(T_{out}-10)			

Table 3 – Description of the comfort classification levels (Source: Olesen 2007, EN15251)

2.3.3. The European EPB Standard- EN52000

The set of standards and accompanying technical reports on the energy performance of buildings (set of EPB standards) have been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association (Mandate M/480), to support the EPBD (EPB Center B.V.).

The EPBD, the European Directive 2010/31/EU recasting the Directive 2002/91/EC on energy performance of buildings promotes the improvement of the energy performance of buildings within the European Union, taking into account all types of energy uses (heating, domestic hot water, lighting, cooling, air conditioning, ventilation) and outdoor climatic and local conditions, as well as indoor climate requirements and cost effectiveness.

The mandate M/480 was issued as the recast of the EPBD raised the need to revisit already existing standards and reformulate and add standards so that they become on the one hand unambiguous and compatible, and on the other hand a clear and explicit overview of the choices, boundary conditions and input data that need to be defined at national or regional level. Such national or regional choices remain necessary, due to differences in climate, culture & building tradition, policy and legal frameworks.

The development of the set of EPB standards was not restricted to Europe. For instance the main EPB standard, the EPB overarching standard EN ISO 52000-1, and the subset of EPB standards on building energy needs and building elements is done at global level, in a cooperation between CEN (Europe) and ISO (worldwide).

In general, the set of EPB standards were developed in five CEN Technical Committees (Europe), in two ISO Technical Committees (worldwide), each covering a specific expertise. The mandate M/480 project (2011-2016) enabled the required effective central coordination via the CTL (expert group of CEN core Team Leaders) of CEN/TC371 to obtain and secure consistency of the overall approach and of the technical details.

The set of EPB standards is modular and flexible, making it the perfect basis for future developments like innovations, new insights and new market demands. The contents of the modules are analysed below as well as presented in Table 3.

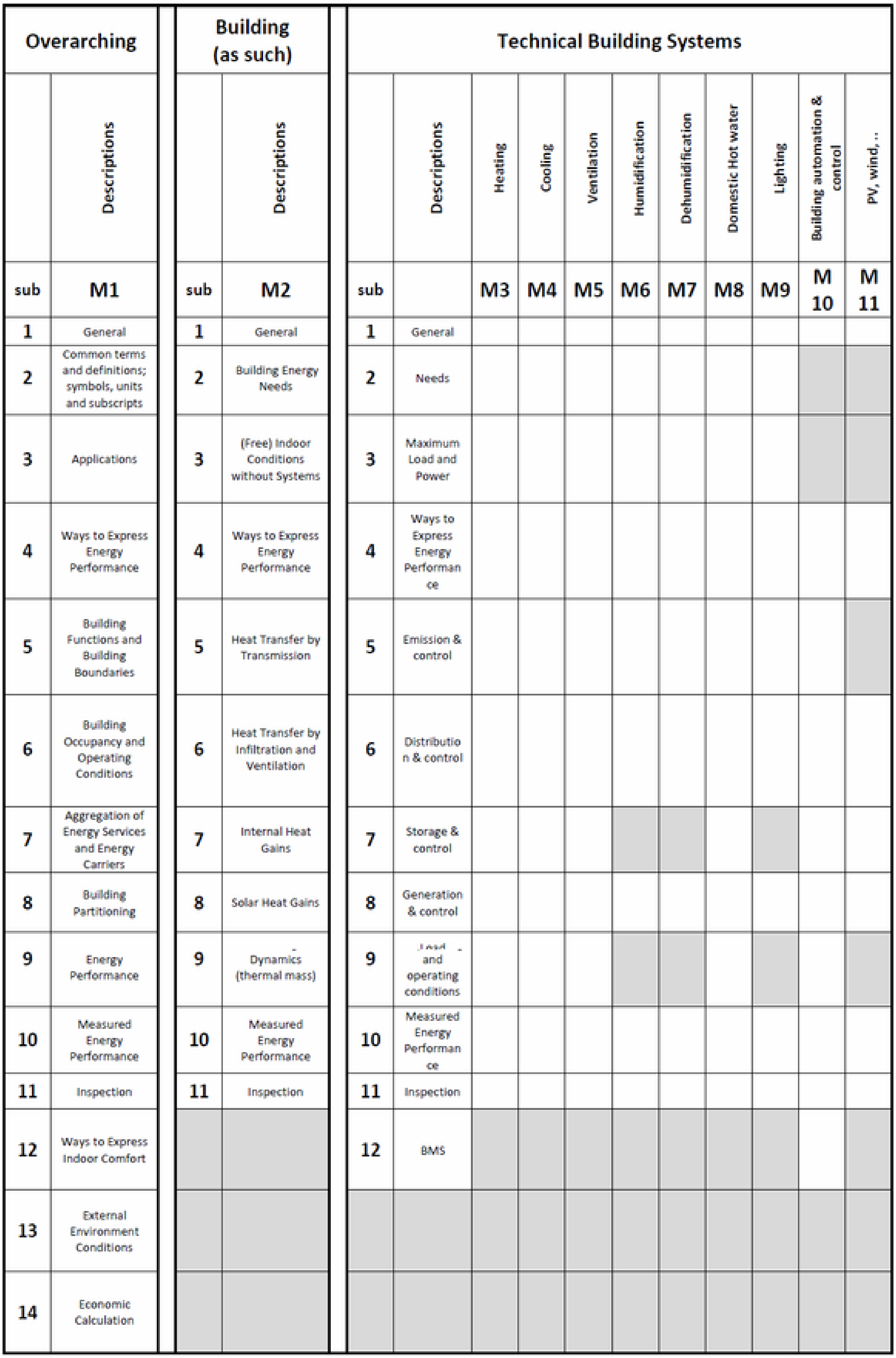
An overarching reference modular structure is used to identify:

- all required parts of the assessment procedure and provide an overview;
- the modules covered by the EPB standards and to support specifications given to standard writers of the EPB modules;
- the connection between the EPB standards (e.g.: calculation, expression of the energy performance).

The over-arching modular structure has the following four main areas:

- M1 Overarching standards

- M2 Building (as such)
- M3 - M11 Technical Building Systems under EPB
- M12 - M13 Other systems or appliances (non-EPB)



Overarching		Building (as such)		Technical Building Systems										
	Descriptions		Descriptions		Descriptions	Heating	Cooling	Ventilation	Humidification	Dehumidification	Domestic Hot water	Lighting	Building automation & control	PV, wind, ..
sub	M1	sub	M2	sub		M3	M4	M5	M6	M7	M8	M9	M 10	M 11
1	General	1	General	1	General									
2	Common terms and definitions; symbols, units and subscripts	2	Building Energy Needs	2	Needs								▨	▨
3	Applications	3	(Free) Indoor Conditions without Systems	3	Maximum Load and Power								▨	▨
4	Ways to Express Energy Performance	4	Ways to Express Energy Performance	4	Ways to Express Energy Performance									
5	Building Functions and Building Boundaries	5	Heat Transfer by Transmission	5	Emission & control									▨
6	Building Occupancy and Operating Conditions	6	Heat Transfer by Infiltration and Ventilation	6	Distribution & control									
7	Aggregation of Energy Services and Energy Carriers	7	Internal Heat Gains	7	Storage & control				▨	▨		▨		
8	Building Partitioning	8	Solar Heat Gains	8	Generation & control									
9	Energy Performance	9	Dynamics (thermal mass)	9	Load and operating conditions				▨	▨		▨		▨
10	Measured Energy Performance	10	Measured Energy Performance	10	Measured Energy Performance									
11	Inspection	11	Inspection	11	Inspection									
12	Ways to Express Indoor Comfort	▨	▨	12	BMS	▨	▨	▨	▨	▨	▨	▨		▨
13	External Environment Conditions	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
14	Economic Calculation	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Table 4 – Content of the different modules included in the EN52000 series of standards (source: epb.center)

2.4. The vision – From 2020 to 2050

The main features of future energy policy for the period to 2050 were outlined in the Energy Report. These features were discussed in detail in the Energy Dialogue, the outcomes of which have been building blocks for the Energy Agenda. The Dutch government intends using this agenda to outline a clear, ambitious perspective towards 2030 and 2050. (Energy Agenda, 2017)

In 2010 the European Commission launched the EPBDrecast (Energy Performance on Building Directive) with the main targets to reduce CO_2 emissions with 90% by 2050 compared to CO_2 levels in 1990. The EPBD requires all newly built buildings to be nZEB in 2020 for different building functions. Existing buildings will also have to comply with this regulation towards 2050. (Zeiler et al, 2015). The main strategies to fulfil the vision towards 2050, are presented in Figure 4. The main theme focuses as mentioned before on the ***Trias Energetica***.

In 2012 the Dutch government presented a plan to implement nZEB regulation for the coming years. Between 2015 to 2017, the building performance requirements became stricter for residential buildings and non-residential buildings. In 2020 all newly build buildings must comply to the nZEB regulation with an EPC close to zero. (Zeiler et al., 2015)

By 2050, Dutch central government aims to reduce the Netherlands' emissions of greenhouse gases (like carbon dioxide to zero. It plans to make 16% of all energy used in the Netherlands sustainable by 2023. This is outlined in the Energy Agreement for Sustainable Growth that the government made with 40 groups, including employers, trade unions and environmental organisations. (Rijksoverheid)

The switch to sustainable energy will take place in stages:

- 14% sustainable energy by 2020
- 16% sustainable energy by 2023
- Almost 100% sustainable energy by 2050. CO_2 emissions should be 80% to 95% lower than in 1990.

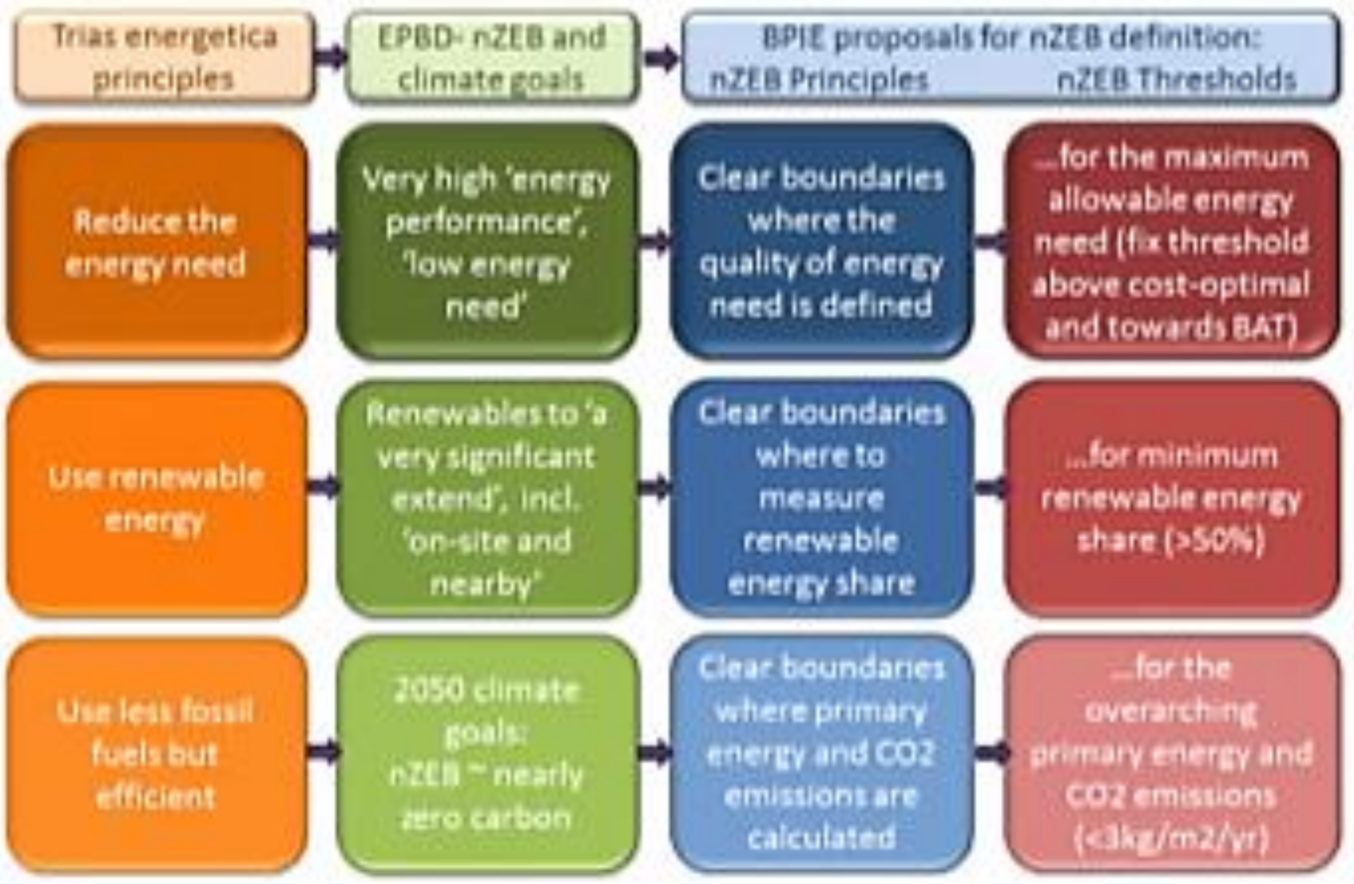


Figure 4 – Principles for sustainable nZEB in the EU (source: BPIE)

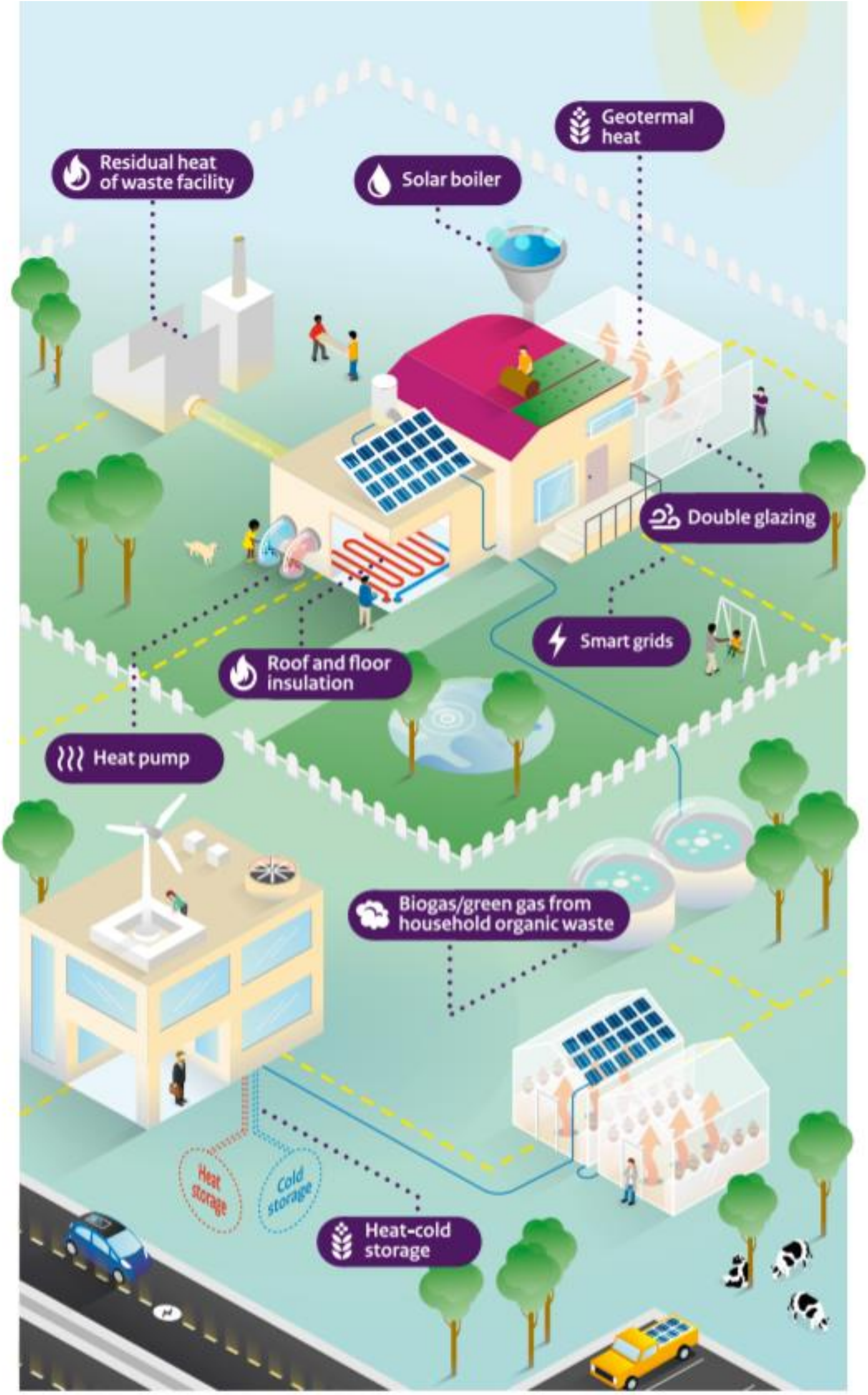


Figure 5 - Sustainable vision 2050 (source: Energy Agenda,2017)

2.5. The adapted Trias Energetica – a circular concept

As mentioned previously, in the Netherlands building energy performance is expressed in an EPC score, which includes energy performance of installations (heating, cooling, hot tap water, ventilation, and lighting) and levels of insulation (roof, walls, floor, and windows). While this method is effective in order to calculate the energy performance coefficient, no attention is given on the origins of the energy, or the effective management of waste energy surplus.

An adapted version of the Trias Energetica method could be used in the future adding the integration of user behavior as well as energy exchange and storage systems (smart grids), see figure 6. Especially these possibilities become crucially important for nZEB because of the intermittent characteristics of most renewable energy sources. Energy exchange has great potential for reducing energy demand, especially when buildings with a specific heat or cold demand are combined (e.g. nursing homes, ICT data centers, swimming pools or other sports facilities like ice rinks). (Gvozdenovic et al., 2015)

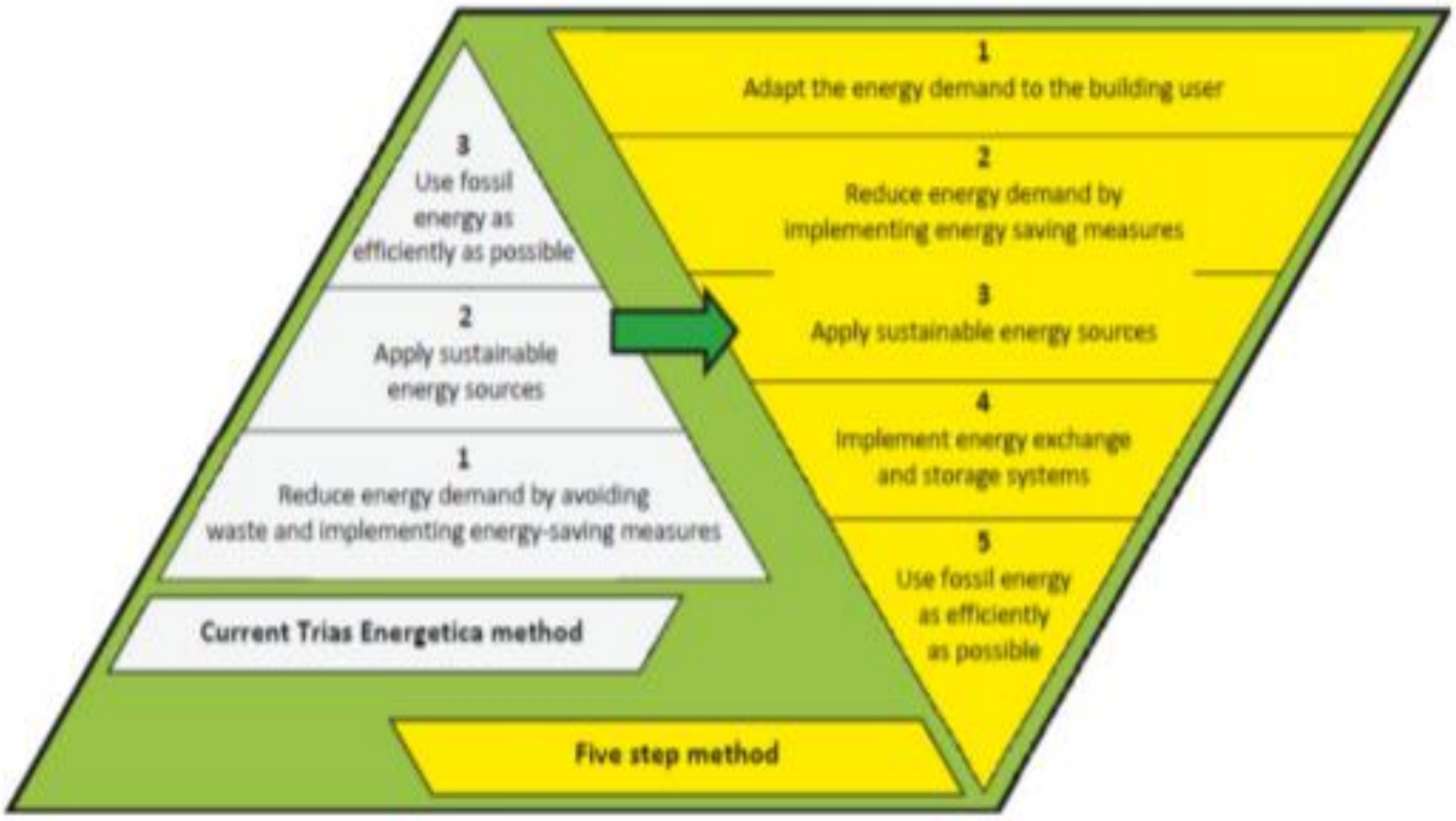


Figure 6 - 5 step system (Adapted Trias Energetica)

2.6. Case Studies of synergetic nZEB in the Netherlands

2.6.1. The Maas Tower (Maastoren)

The Maas Tower (Maastoren) is a high-rise office building located at the prestigious central area of the Erasmus bridge in the city of Rotterdam. The tower has a total height of 165 m, spanning 44 floors above the ground level. Odile Decq Benoit was the project architect and the building was constructed from 2006 to 2009.

The Maas Tower is currently the tallest building in the Netherlands, but its iconic status is extended beyond that, as it was also the field of introduction for many innovations towards sustainability with respect to the local context and environment. The design of the HVAC system and the energy savings scheme was performed by Techniplan Adviseurs, resulting to the award for Innovation from the Society of Consulting Engineers in the Netherlands.

Figure 7 – The Maas Tower

(source: skyscrapercenter.com)

The system consists of a heat pump installation, combined with an Aquifer Thermal Energy Storage system that operates using water from the nearby Maas river. The main function of the ATES system is to store energy in the form of warm or cold water underground. The storage is performed in two deep storage wells that are located at a depth of 150 meter and at specific distances from each other. The system as described by Zeiler (2017), perform in 2 distinctive cycles, summer and winter cycle that are also controlled by the weather conditions of the indoor and outdoor environment. An overview of the system function can be seen in Figure

The summer cycle (cooling period)

During the warm summer months, the water from the river Maas is used as the main source for cooling energy, as it maintains a relatively cool temperature, at least during the first part of the cooling period. In the case where the river water temperature reaches an upper limit, the cold water stored in the cold well is employed in order to cool the building. The circulation water is then heated from the storage temperature of 8^{O}C up to a temperature of 16 ^{O}C, and it is subsequently stored in the warm well.

The winter cycle (heating period)

During the early autumn months, the river water still maintains a relative temperature of 20 ^{O}C, cased by industrial residual waste heat. The water is driven through a heat exchanger and is circulating in the building with the help of the central air conditioning system. During winter months

The warm water is extracted from the well with a temperature of 14 ^{O}C and is used to heat the building. A heat pump is used to extract the heat from the warm water, and the feedback water after heating, with a temperature of about 6 ^{O}C is again used to charge the cold aquifer well.

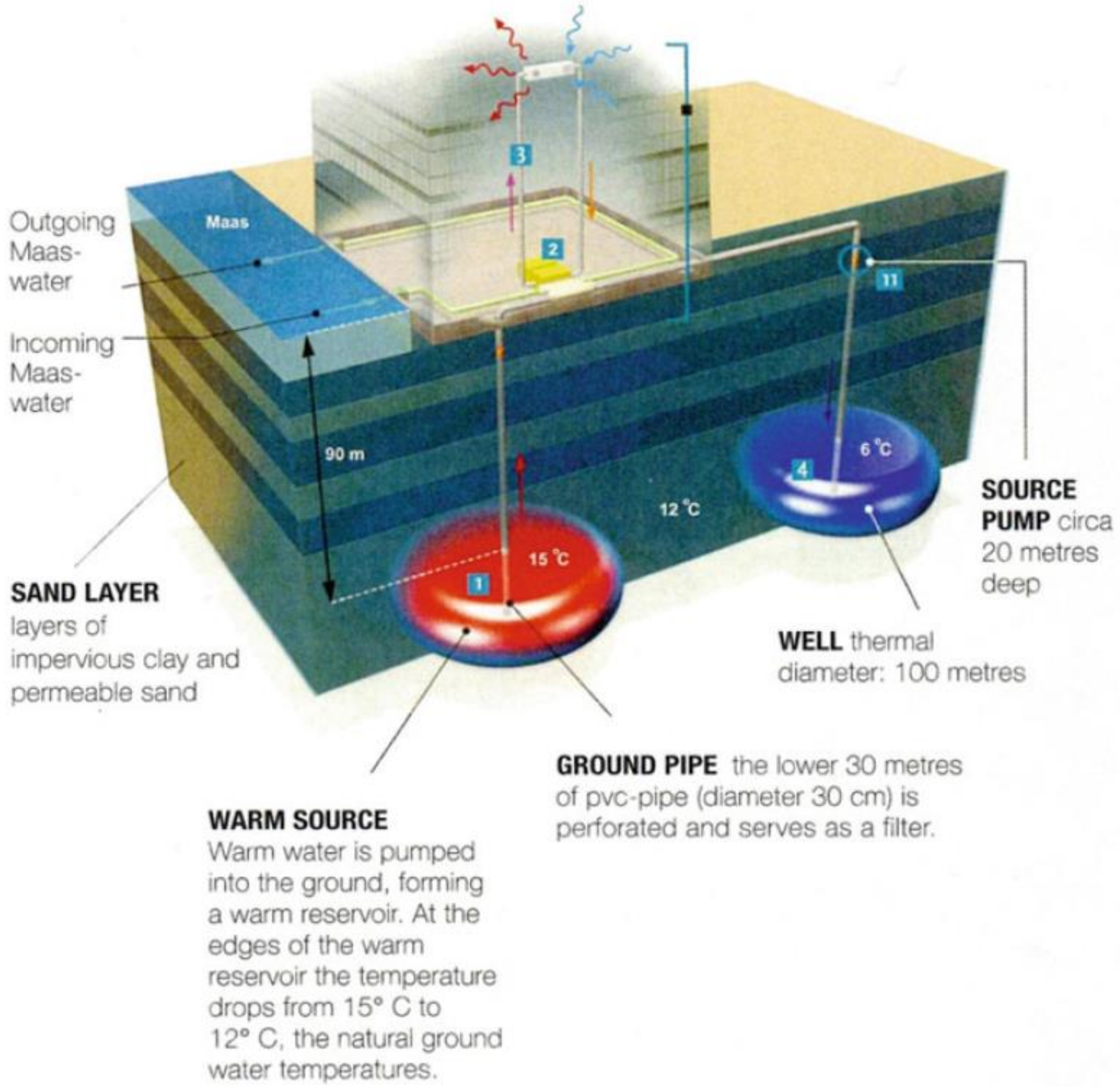


Figure 8 - Energy installation for the Maas Tower (source: Beerda, 2008)

The use of this innovative system resulted in a 55% reduction of the primary energy utilized by the tower as well as a 50% reduction of the total CO$_2$ emissions. As stated by Zeiler (2017), the function of the energy system was supported by in-field measurements that were performed and discussed by Molenaar (2011).

The measurements showed that the combined use of the heat pump arrangement and the underground storage resulted in an Annual Performance Factor of 5.0, and a Seasonal Performance Factor of 47 for cooling and 3.8 for heating.

Molenaar (2011) also explained the substantial advantages that the combination of the heat pump – ATES system offered to the overall performance of the tower:

1. The use of the river water resulted in a substantial reduction of the demand for extracted heating and cooling from the cold / warm wells. Maas water offered a saving of approximately 3,300 hours per year for heating and 1,900 hours per year for cooling.
2. The temperature of the Maas water can be used to increase the maximum temperature of the warm and cold wells. This potential resulted in 3.5% savings in electricity use.
3. The use of the river water can serve both as a source for heating and cooling, as well as backup auxiliary thermal source during maintenance or failure of the main system, It was calculated that the Maas water can be used for approximately 5440 hours per year without any contribution from the water stored underground.

2.6.2. De Rotterdam

De Rotterdam is a building that solidifies the concept of a MEGA structure in its literal sense. Currently being the largest building in the Netherlands, it has a total height of 149 meters and a gross floor area of 162.000 m^2, divided in 44 floors.

The building is also one of the most formidable examples of the concept of the “vertical city”. Rem Koolhas as the project architect, applied the philosophy of creating a district within a very limited space. Thus, the whole district of different functions, namely residential apartments, hotel, office spaces and leisure/commercial activities are “stacked” on top of each other, in a thoughtful and organized manner.

Figure 9 - De Rooterdam (source: OMA Architects)

The sustainability concept for De Rotterdam, as described by Zeiler (2017), is similar to the one of the Maas Tower, taking advantage of the nearby available water source of the Maas river. The system comprises of a combination of a heat pump installation combined with Aquifer Thermal Energy Storage. The special feature is that heating / cooling is performed by means of under-floor heating. Pipes are integrated in the concrete floors, and the large available floor area enables high temperature cooling during the summer season and low temperature heating during the winter season. By means of the concrete floor activation, cooling can be performed utilizing cold water from the Maas river.

Figure 10 - Functional program and stacking for De Rotterdam (source: Zeiler, 2017)

The overall system utilizes smart control thermostats in every room in order to regulate the internal temperature for living and working spaces. Sustainable techniques are also integrated in the building envelope, where reflective glazing and ventilation openings are integrated in order to reduce the heat load on the building. Finally, any remaining energy demand is produced and supplied by a biofuel-based system.

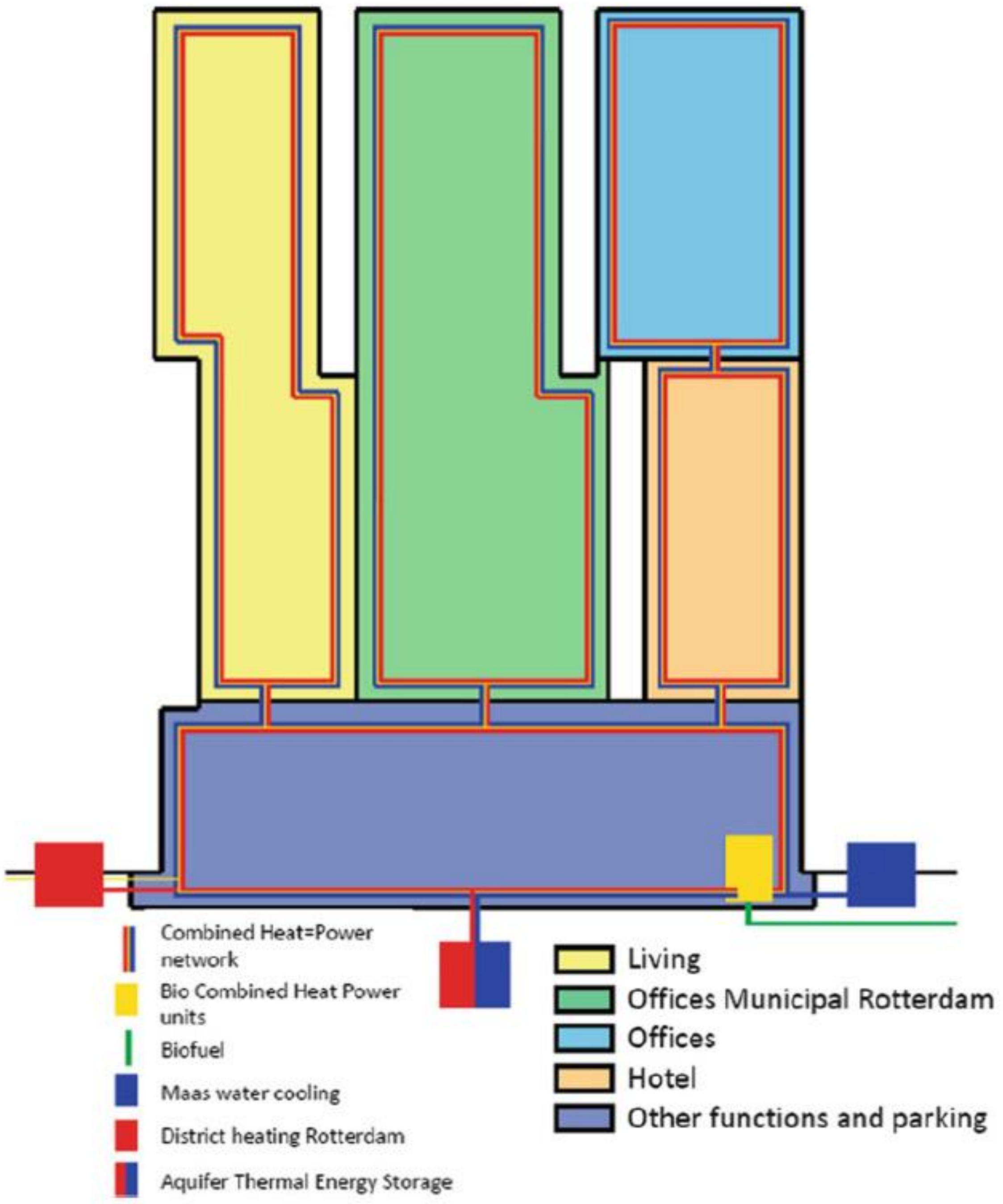


Figure 11- Energy concept scheme for De Rotterdam (source:Zeiler, 2017)

Figure 12 - Under-floor pipe system for heating and cooling (source: Zeiler, 2017)

3. The concept of Energy Synergy

“De Rabotoren” – Utrecht

(source: SkyscraperCity)

3.1. Introduction

The modern built environment is considered the primary source of energy consumption and emission of pollutants within the developed world. Modern buildings in the European Union, account for 40% of total primary energy consumption, while the total production of CO_2 emissions is estimated to 36%, compared to the other economic sectors. (European Commission, 2019). As mentioned in Chapter 2, the renovation of the current building stock in the EU and the investment in sustainable solutions has evolved from a market innovation to an absolute necessity. It is evident, that this approach has an enormous potential for fighting the scarcity of energy sources and the effects of climate change, while also resulting in considerable economic benefits for the construction sector. An organized plan in order to achieve considerable results within the near future is already drawn by the European legislative authorities. The introduction of the European Energy Performance of Buildings Directive has set strict regulations and targets in order to assure an energy neutral future until the year 2050.

The quality of the built environment in the Netherlands is also a reflection of the current building stock in the European Union. Zeiler (2017), explains that the building stock in the Netherlands was highly influenced by geographic and demographic factors. The small geographic area in combination with a rapidly growing population resulted in a shortage of available construction areas. Massive urbanization has created large urban centers, where the majority of economic and administrative activities take place. Increased efficiency and quality of the urban environment is valued, so effort is put in order to maintain a high performance on urban development and economic growth, however creating stress on material use and energy consumption. The concept of the vertical city is gaining popularity, as proven concept to increase available residential and business space in large economic centers, but also creating considerable impact on the environment and quality of living,

Sustainable building design is thus the approach that can bridge the gap between maintaining a prosperous and continuous urban and economic growth, without compromising quality of living for inhabitants, and abuse of resources. The *Trias Energetica*, is a valuable tool in order to balance function and environmental consciousness in the built environment, while its adapted form as presented in Chapter 2, also emphasizes on the benefits of a Circular approach. The concept of Energy Storage and Exchange in its different forms directly applies to the aforementioned principles. The early stage design of a building (shape, envelope, materials, passive measures) is of course deciding for its energy consumption. The concept of Synergy focuses on the part of building services as a support to the initial design, in order to achieve an energy efficient and successful maintaining of comfort, carefully designed heating and cooling installations need to be designed.

In the case of mixed-use development, the potential for synergetic building services is higher, as different functions create unusual demands for heating and cooling within certain time periods. In this chapter, the basic theoretic principles of energy storage and exchange are explained, in order for the designer to have a sufficient understanding of the concept. In the following pages, the principles and use of heat pumps in the built environment is also explained, as the combination of the 2 systems is the basis to create synergetic heating and cooling concepts for different types of buildings.

3.2. Thermal energy Storage and Exchange

Thermal energy is the physical term that expresses the energy contained in a system, that influences its temperature level**.** It can thus be derived that a system with high thermal energy will have a larger temperature than a system with lower thermal energy. Heat is the term referring to the amount of energy flowing from one system to another. Based on physical principles, heat is transferred from a system with higher thermal energy (referred to as a “warm system”) to a system with lower thermal energy (referred to as a “cold system”). In a building context, thermal energy is linked to all activities inside the building that result in an increase of temperature. These are commonly the solar gains through transparent and non-transparent openings, thermal gains through the building envelope, internal activity of people and equipment and thermal gains or losses through air flows within the building, or from the interior to the exterior and vice versa. In this context, flow of thermal energy is an active phenomenon that takes place in real time between a warmer and colder system, and by traditional means can be “delayed” but not “postponed” for a different and distinct moment in time after a warmer and colder system are in contact.

Thermal energy storage can be referred to as a “*technology that stocks thermal energy by heating or cooling a storage medium, so that the stored energy can be used at a later and distinct point in time, for heating and cooling applications or power generation*.” (Sarbu and Sebarchievici, 2018)

The process of thermal energy storage is a concept that is used in buildings or industrial and manufacturing processes. The characterization of thermal energy storage technologies can be performed according to 3 main parameters.

1. **Temperature level**
   Based on the temperature level, a thermal energy storage system can be used for “hot” storage (high temperature) or “cold” storage (low temperature).

2. **Time Frame**
   According to the period of time that elapses between the moment of thermal energy generation or storage to the point in time that the thermal energy is re-used or transformed to a different type of energy, thermal energy storage can be characterized as hourly, daily, monthly, bi-monthly, seasonal or yearly.

3. **Physical properties of the storage medium**
   According to the physical behavior of the storage medium, three methods of thermal energy storage can be listed, sensible heat storage mainly using water or other materials with a high thermal capacity, latent heat storage associated with Phase Change Materials and thermo-chemical heat storage that is performed after certain chemical reactions take place. Different operational parameters for the storage medium alternatives can be seen in Table 5.

Storage System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period	Cost (€/kWh)
Sensible	10-50	0.001-10	50-90	days/months	0.1-10
Latent	50-150	0.001-1	75-90	Hours/months	10-50
Chemical	120-250	0.01-1	75-100	Hours/days	8-100

Table 5 – Operational properties of thermal storage methods based on the storage medium (adapted from Hauer, 2011)

The operation of thermal energy storage systems is influenced by many technical parameters that can be summarized as follows: (Sarbu and Sebarchievici, 2018)

1. **Capacity**
   The capacity for storage expresses the amount of thermal energy that can be stored and the sizing of the installations.

2. **Power**
   The system power expresses the ability of the system to provide the stored energy for discharge faster, also the ability of the charging mechanism to restore stock thermal energy in the same rate.

3. **Efficiency**
   The efficiency of the system expresses the ratio between input energy for charging the storage system, to beneficial energy that is provided to the end user.

4. **Storage period**
   Expresses the time frame that elapses between the charge/discharge time point in other terms the total time that thermal energy remains in stock. Storage period can vary from several hours to several months for the case of seasonal storage.

5. **Charge/Discharge time**
   Expresses the operational time that is required to store energy in the system and discharge energy for end use.

6. **Cost**
   The total cost of a thermal storage energy system is constituted by early/capital costs for the installation and runtime/operational costs during the entire life cycle of the system. It can be expressed in capacity cost (€/kWh) or power cost (€/kW).

3.2.1. Sensible heat storage

Sensible heat storage uses the property of thermal capacity that most physical materials possess. The principle of sensible heat cooling is that, thermal energy is stored in a medium, once it is heated or cooled. Most common storage medium are water, being the most abundant and cost-effective material, sand and gravel or other forms of aggregate and different types of salts in molten form. Sensible heat storage in water tanks is the most common and cheap method that can be used for both small- and large-scale projects, with an added benefit that no hazardous materials are used in the process.

The principle of sensible heat storage is based on the physical property of heat capacity of materials. The energy provided to the medium results in a rise of temperature that is directly proportionate to the total mass and specific heat capacity of the medium. The calculation of the total thermal energy stored is performed according to equation 1.

$$Q_s = \int_{t1}^{t2} m \cdot c_p \cdot dt = m \cdot c_p \cdot (t_2 - t_1) \quad (1)$$

Where:

Q_s is the total thermal energy stored expressed in Joules

m is the total mass of the storage material expressed in kg

c_p is the specific heat capacity of the storage material in J/(kg deg)

t_1,t_2 are the storage and discharge moment temperatures respectively in degrees Celsius

The properties of different materials that can be used as sensible heat storage mediums can be seen in Table 6 .

Material	Density (kg / m^3)	Specific Heat (KJ /kg K)
Sand	1555	0.8
Rock	2560	0.879
Brick	1600	0.84
Concrete	2240	0.88
Granite	2640	0.82
Aluminium	2707	0.896
Cast Iron	7900	0.837
Water	1000	4.19
Calorie HT43	867	2.2
Engine Oil	888	1.88
Ethanol	790	2.4
Propane	800	2.5
Butane	809	2.4
Isotunaol	808	3
Isopetanol	831	2.2
Octane	704	2.4
Sand rock mineral	1700	1.3
Reinforced concrete	2200	0.85
Cast iron	7200	0.56
Natrium Chloride	2160	0.85
Cast steel	7800	0.6
Silica fire bricks	1820	1
Magnesia fire bricks	3000	1.15

Table 6 – Properties of various materials used for sensible heat storage (source: Ayappan et al. 2016, Tian et al. 2013, adapted from Sarbu and Sebarchievici, 2018)

There are various technologies that utilize the principle of sensible heat in order to enable thermal energy storage in construction or industrial projects. These methods can be summarized below.

1. **Water Tank storage**
   The most commonly used technology for energy storage in buildings is based on the large specific heat of water and the ability to store large amounts of thermal energy with relatively low temperatures. Water tanks used in building projects are usually combined with a solar thermal collector for heating purposes. Proper insulation of the storage tanks is required in order to minimize heat loss to the external environment. Modern research is focused on a type of stratified water tanks in order to accommodate for different temperature levels and lower thermal loss of the system.

2. **Underground storage**
   Underground thermal energy storage is also a widely used storage technology, which makes use of the ground (e.g., the soil, sand, rocks, and clay) as a storage medium for both heat and cold storage. Means must be provided to add energy to and remove it from the medium. This is done by pumping heat transfer fluids (HTFs) through pipe arrays in the ground. The pipes may be vertical U-tubes inserted in wells (boreholes) that are spaced at appropriate intervals in the storage field or they may be horizontal pipes buried in trenches. The rates of charging and discharging are limited by the area of the pipe arrays and the rates of heat transfer through the ground surrounding the pipes. If the storage medium is porous, energy transport may occur by evaporation and condensation and by the movement of water through the medium, and a complete analysis of such a store must include consideration of both heat and mass transfer. These storage systems are usually not insulated, although insulation may be provided at the ground surface.

3. **Aquifer storage**
   Aquifer storage is closely related to ground storage, except that the primary storage medium is water, which flows at low rates through the ground. Water is pumped out of and into the ground to heat it and extract energy from it. Water flow also provides a mechanism for heat exchange with the ground itself. As a practical matter, aquifers cannot be insulated. Only aquifers that have low natural flow rates through the storage field can be used. A further limitation may be in chemical reactions of heated water with the ground materials. Aquifers, as with ground storage, operate over smaller temperature ranges than water stores. Most applications deal with the storage of winter cold to be used for the cooling of large office buildings and industrial processes in the summer.

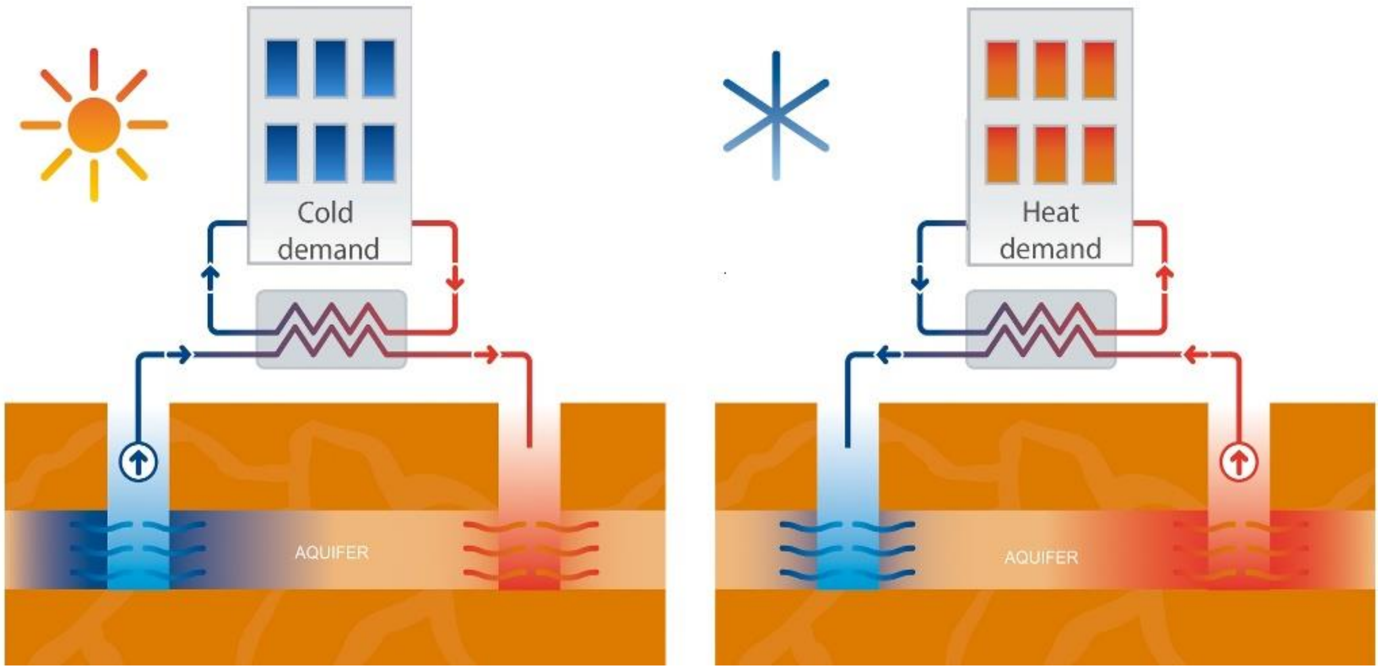


Figure 13 – Schematic representation of an aquifer thermal energy storage system in heating and cooling season (source: iftechnology.nl)

4. **Packed-bed storage**
   This method is based on the heat capacity of solid materials, sand pebble and rocks. The material is stratified in a confined space that enables the inflow, outflow and circulation of a transport fluid, most commonly air. The difference between a packed-bed storage system and water-based systems is that thermal energy cannot be added and extracted from the storage space simultaneously.

3.2.2. Latent heat storage

Latent heat storage is based on the physical intake or outflow of energy, when a certain material is transitioning from a solid to liquid phase or liquid to gas phase and vice versa. The initial transition requires a large absorption of thermal energy that is metaphorically “stored” in the resulting phase of the material, while the opposite transition results in rapid release of thermal energy that can be directly used. The controlling mechanism of the phase transition is the temperature of the material or gas in relation to time.
In this case, the advantage is that a large capacity for storage can be achieved with relatively small temperature ranges.

The physical relation that describe the amount of thermal energy that can be stored in a latent heat system utilizing phase change materials is presented in equations 2 and 3.

$$Q_s = \int_{t_i}^{t_m} m \cdot C_p \cdot dt + m \cdot f \cdot \Delta q + \int_{t_m}^{t_f} m \cdot C_p \cdot dt \quad (2)$$

$$Q_s = m \cdot [c_{ps} \cdot (t_m - t_i) + f \cdot \Delta q + \ c_{pl} \cdot \left(t_f - t_m\right) \quad (3)$$

Where:
t,m is the melting temperature of the phase change material in deg. Celsius
m is the mass of the PCM in kg
C,ps is the specific heat for the solid phase between initial and melting temperature in J/kg K
C,pl is the specific heat between melting temperature and the final temperature in J/ kg K
f is the melting fraction
Δq is the latent heat of fusion in J/kg

The choice of the appropriate phase material is very important according to the intended use and efficiency required. PCMs are classified usually according to their physical properties and transition type (solid-liquid or liquid-gas) as well as their thermal limits (high or low transition temperatures). It is important for all applications of latent energy storage system, that the suitable material performing in the appropriate temperature range is chisen, a suitable heat exchange surface and a proper container. (Sarbu and Sebarchievici, 2018)

In the following figures , the categorization of different phase change materials i presented.

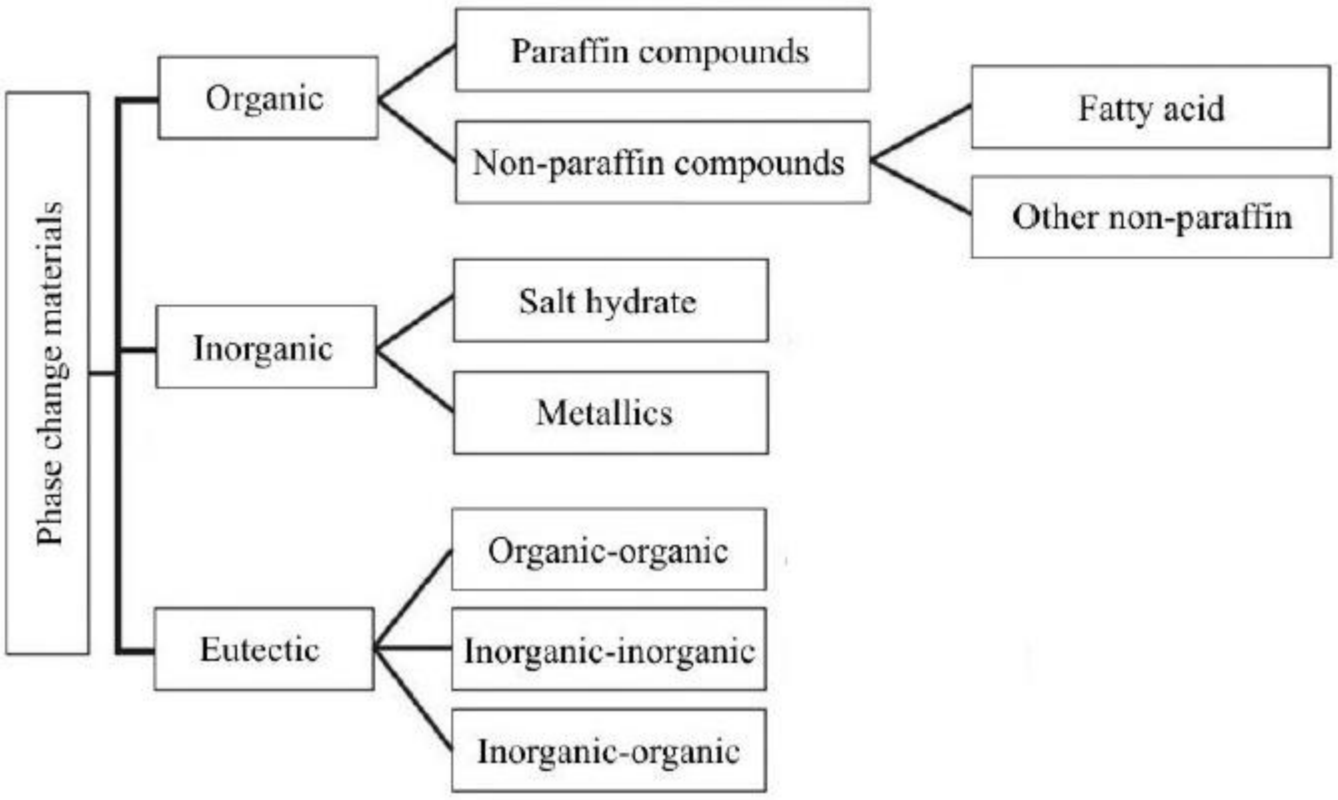


Figure 14 – Categorisation of PCMs according to their natural origin (source: Sharma et al., 2009)

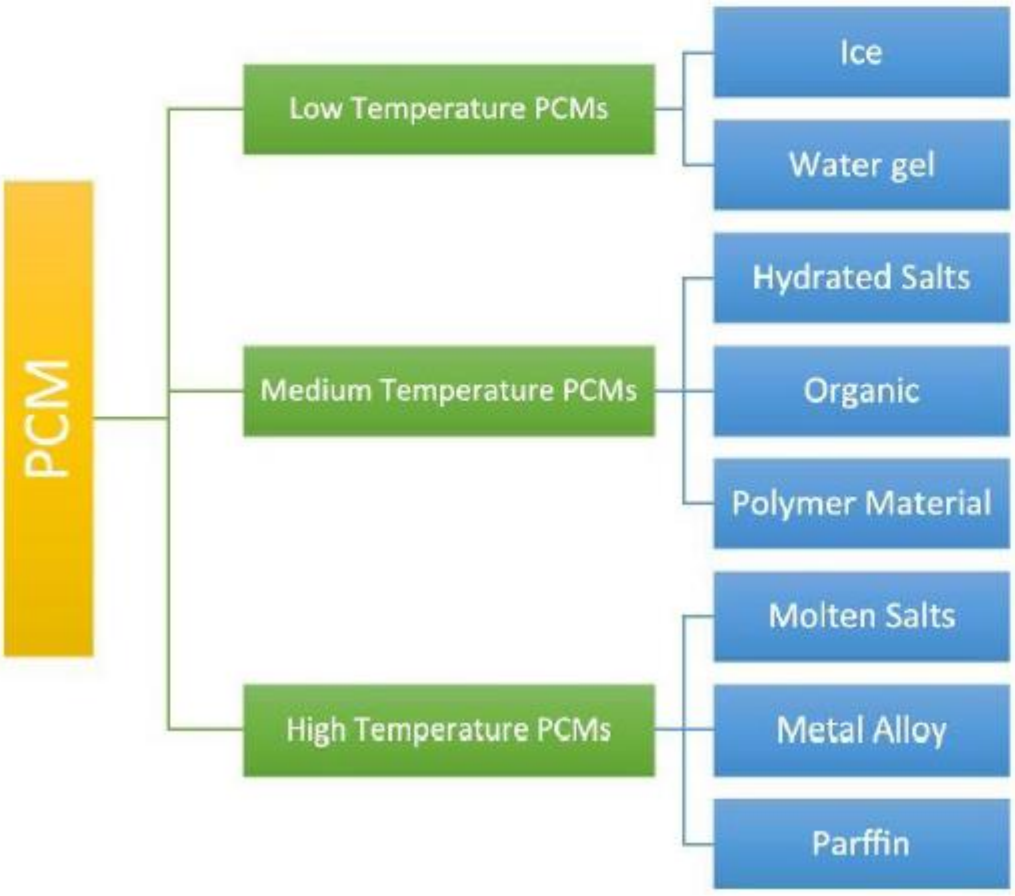


Figure 15 – Categorisation of PCM according to the transition temperature (Source: Ge et al, 2013)

In the construction industry, phase change materials are used for energy storage and re-use in active or passive solutions. Active techniques are used in order to enhance the performance of HVAC equipment or provide active heating or cooling without the requirement for mechanical installations. Passive solutions with use of PCMs, aims to maintain the required comfort levels within the building without additional contribution of HVAC systems. This is translated in changing the point in time, that thermal energy from the internal and external environment is absorbed and released at a later off-peak point. The most common use of passive PCM use in buildings, is the solar or Trombe wall. The use of PCM is intended in order to increase the thermal capacity of the Trombe wall while minimizing thermal loss to the external environment.

The advantages and disadvantages of latent over sensible heat storage can be summarized in the following points. (Chindabaram et al., 2011)

- The use of phase change materials over water can result in considerable saving of storage space, for the same amount of storage capacity. This demands however, that the latent storage system operates with small margins around the transition temperature.
- A reduction for the demand of additional chillers or heaters that support the storage system.
- The initial investment for sensible heat storage is considerably lower.
- Water is a safe and non-toxic material, while PCMs entail hazardous risks for instability or erosion of storage tanks/installations.

3.2.3. Chemical Energy Storage

Chemical energy storage is based on the endothermic or exothermic result of certain chemical reactions. This is achieved with the help of thermochemical materials, that can be analyzed in simpler chemical compounds by introducing or removing energy from the system. The reaction products can be stored separately, and the 2 cycles of the chemical reaction can be produced, when heat release or absorption is required. The most commonly used reactions are summarized in Table 7 .

Reaction		Temperature (ºC)	Energy Density (kJ/kg)
Methane steam reforming	$CH_4 + H_2O = CO + 3H_2$	480-1195	6053
Ammonia dissociation	$2NH_3 = N_2 + 3H_2$	400-500	3940
Thermal dehydrogenation of metal hydrides	$MgH_2 = Mg + H_2$	200-500	3079 (heat) 9000 (hydrogen)
Dehydration of metal hydroxides	$CA(OH)_2 = CAO + H_2O$	402-572	1415
Catalytic dissociation	$SO_3 = SO_2 + 1/2O_2$	520-960	1235

Table 7 – Chemical reactions for thermal energy storage (source: Garg et al.,2013, adapted from Sarbu and Sebarchievici, 2018)

3.3. Heat Pumps

In modern construction and industrial projects, thermal energy storage systems are commonly combined with heat pump installations. The basis of a heat pump is as described by the name a device that *extracts heat from one system (source) and transfers it to another system (sink)*.

3.3.1. Principle and components

Heat pumps transfer heat by circulating a substance called a refrigerant through a cycle of evaporation and condensation. A compressor pumps the refrigerant between two heat exchanger coils. In one coil, the refrigerant is evaporated at low pressure and absorbs heat from its surroundings. The refrigerant is then compressed en route to the other coil, where it condenses at high pressure. At this point, it releases the heat it absorbed earlier in the cycle.

Refrigerators and air conditioners are both examples of heat pumps operating only in the cooling mode. A refrigerator is essentially an insulated box with a heat pump system connected to it. The evaporator coil is located inside the box, usually in the freezer compartment. Heat is absorbed from this location and transferred outside, usually behind or underneath the unit where the condenser coil is located. Similarly, an air conditioner transfers heat from inside a house to the outdoors. The process of a heat pump refrigeration cycle can be used for both heating and cooling purposes. The refrigerant circulation can be reversed, and, in this manner, heating can be provided during the winter season and cooling during the summer season. A simple heat pump cycle in heating and cooling mode is presented in Figure 16 .

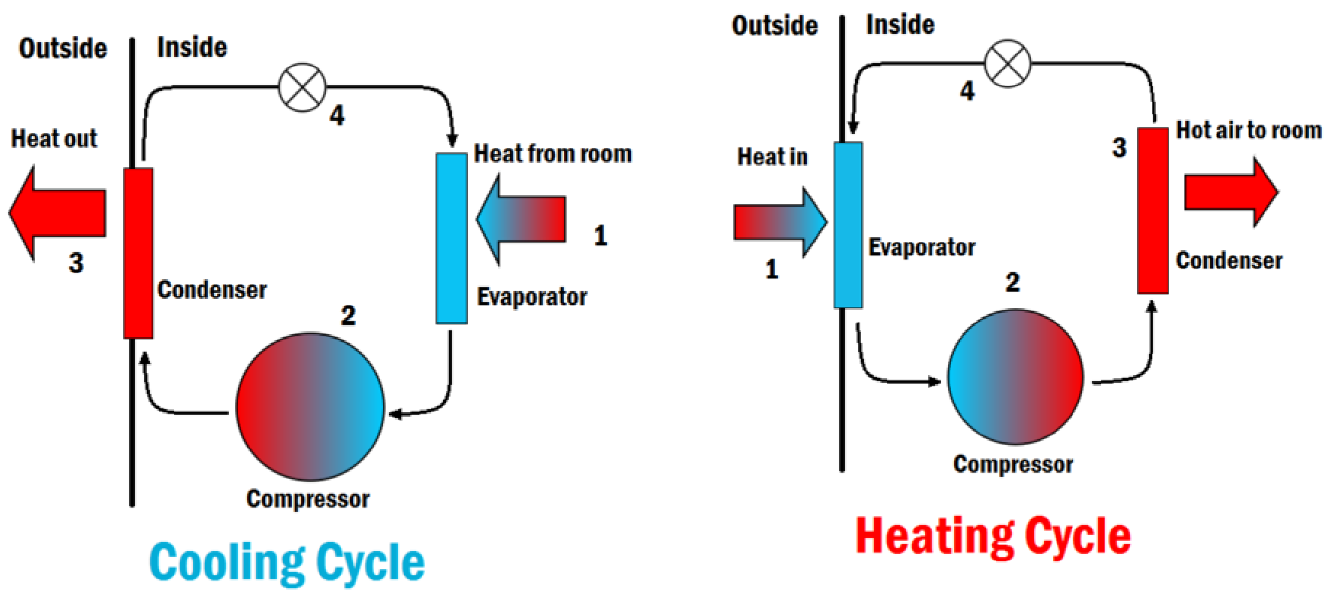


Figure 16 – Heating and cooling cycle of a common heat pump arrangement (source: energyeducation.ca)

3.3.2. Air-source heat pumps

Air-source heat pumps use the ambient outdoor air as a heat source in order to provide heating during the heating season and discharge heat from the indoor spaces during the cooling season. Air-source heat pumps are subcategorized to air-to-air heat pumps, where heat from outdoor air is transferred to the indoor environment, and air-to-water heat pumps that transfer the heat of outdoor air to the internal spaces with the aid of a water distribution system. The process during the cooling can be again reversed, with the water system extracting the thermal load to the outdoor unit. A typical air-source heat pump can perform in 3 different modes, a heating mode, a cooling mode and a defrost mode.

Heating mode

The heating mode of a common air-to-air heat pump can be summarized in the following steps and is presented in Figure .

1. First, the liquid refrigerant passes through the expansion device, changing to a low-pressure liquid/vapor mixture. It then goes to the outdoor coil, which acts as the evaporator coil. The liquid refrigerant absorbs heat from the outdoor air and boils, becoming a low temperature vapor.

2. This vapor passes through the reversing valve to the accumulator, which collects any remaining liquid before the vapor enters the compressor. The vapor is then compressed, reducing its volume and causing it to heat up.

3. Finally, the reversing valve sends the gas, which is now hot, to the indoor coil, which is the condenser. The heat from the hot gas is transferred to the indoor air, causing the refrigerant to condense into a liquid. This liquid returns to the expansion device and the cycle is repeated. The indoor coil is in the ductwork, close to the furnace.

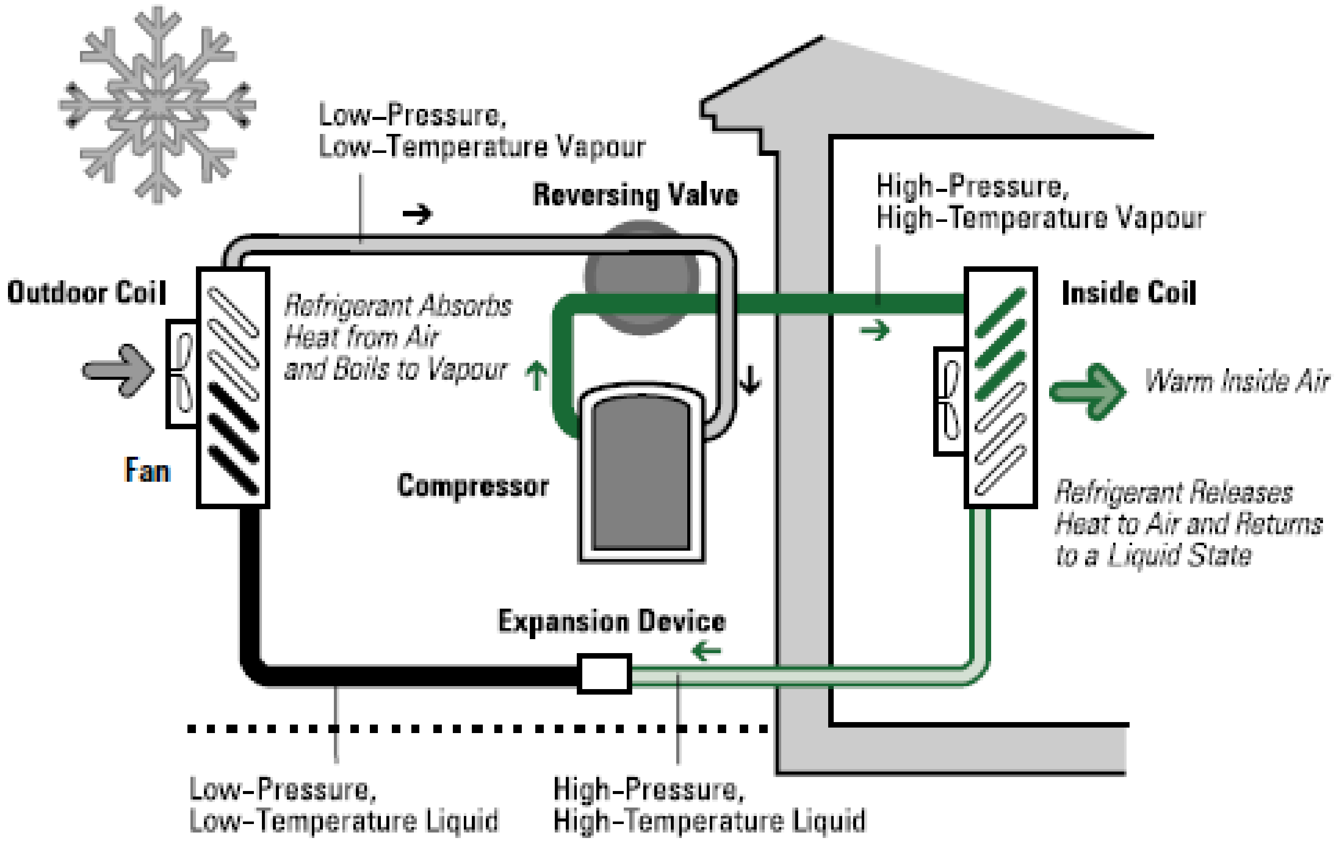


Figure 17 – Heating mode of an ai-to-air heat pump (source: Canada Office of Energy Efficiency)

Cooling mode

During the cooling mode, the refrigeration cycle is reversed, in order to extract heat from the indoor space and discharge it to the outdoor environment. The steps during the cooling cycle can be summarized below and presented in Figure 18.

1. As in the heating cycle, the liquid refrigerant passes through the expansion device, changing to a low-pressure liquid/vapor mixture. It then goes to the indoor coil, which acts as the evaporator. The liquid refrigerant absorbs heat from the indoor air and boils, becoming a low-temperature vapor.

2. This vapor passes through the reversing valve to the accumulator, which collects any remaining liquid, and then to the compressor. The vapor is then compressed, reducing its volume and causing it to heat up.

3. Finally, the gas, which is now hot, passes through the reversing valve to the outdoor coil, which acts as the condenser. The heat from the hot gas is transferred to the outdoor air, causing the refrigerant to condense into a liquid. This liquid returns to the expansion device, and the cycle is repeated.

3.3.3. Ground-source heat pumps

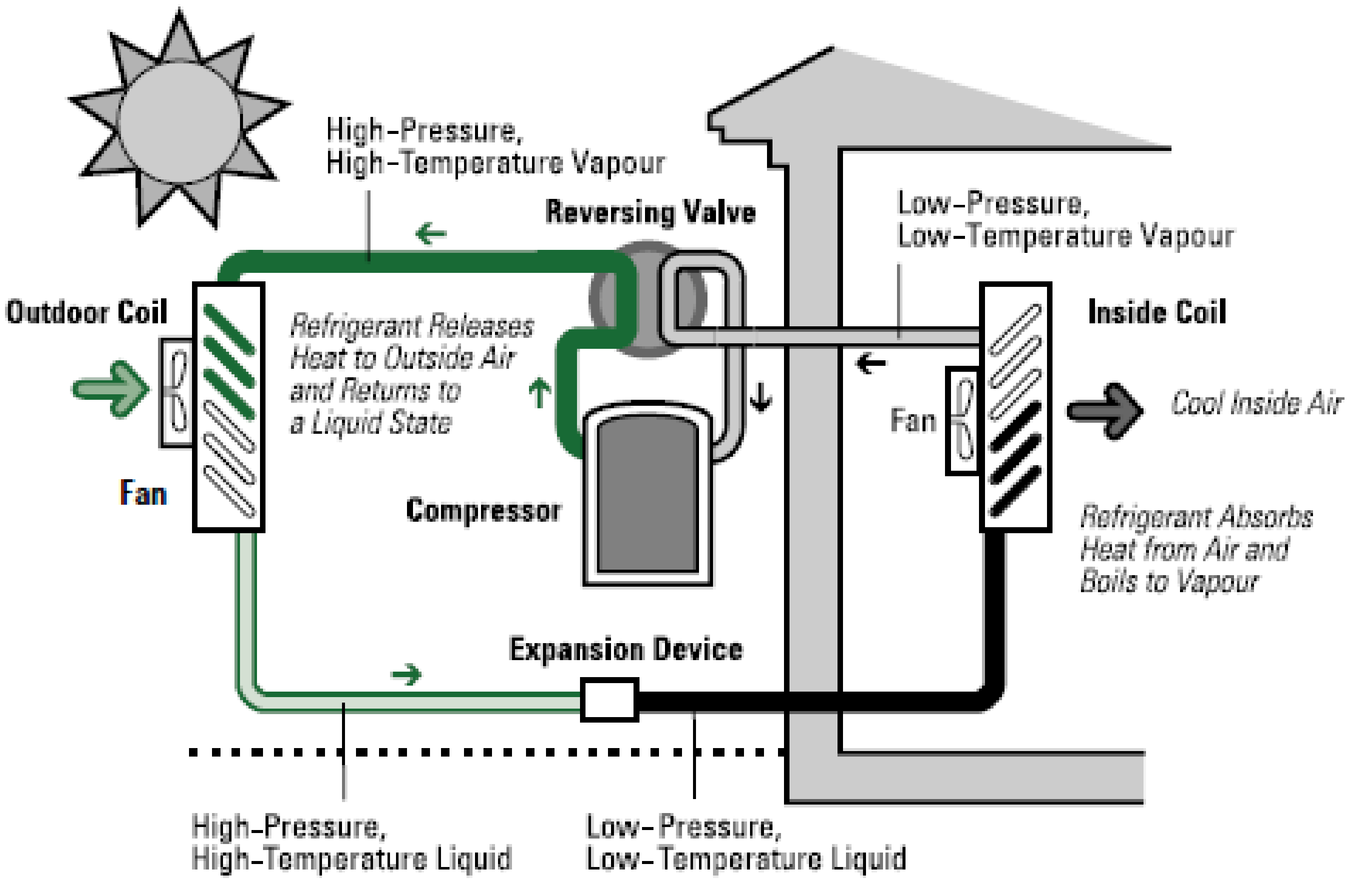


Figure 18 – Cooling mode of an ai-to-air heat pump (source: Canada Office of Energy Efficiency)

A variation of the heat pump concept substitutes the outside air as a heat source, with the heat of the ground, or underground aquifer water. The property of the ground layers to maintain a relatively constant temperature is the basis for the operation of a ground-source heat pump otherwise referred to as an earth energy system. All EESs have two parts: a circuit of underground piping outside the house, and a heat pump unit inside the house. Unlike the air-source heat pump, where one heat exchanger (and frequently the compressor) is located outside, the entire groundsource heat pump unit is located inside the house. The outdoor piping system can be either an open system or closed loop. An open system takes advantage of the heat retained in an underground body of water. The water is drawn up through a well directly to the heat exchanger, where its heat is extracted. The water is discharged either to an above-ground body of water, such as a stream or pond, or back to the same underground water body through a separate well.

Ground source heat pumps can also operate in both a heating and cooling mode. The operation of the primary refrigeration cycle is the same, with the only exception that heat absorption an discharge can be performed either with the use of an underground water circulation piping system and heat exchanger with the refrigerant circulation system, either the refrigerant can be directly circulated underground. The operation of an energy system can be seen schematically in Figure 19.

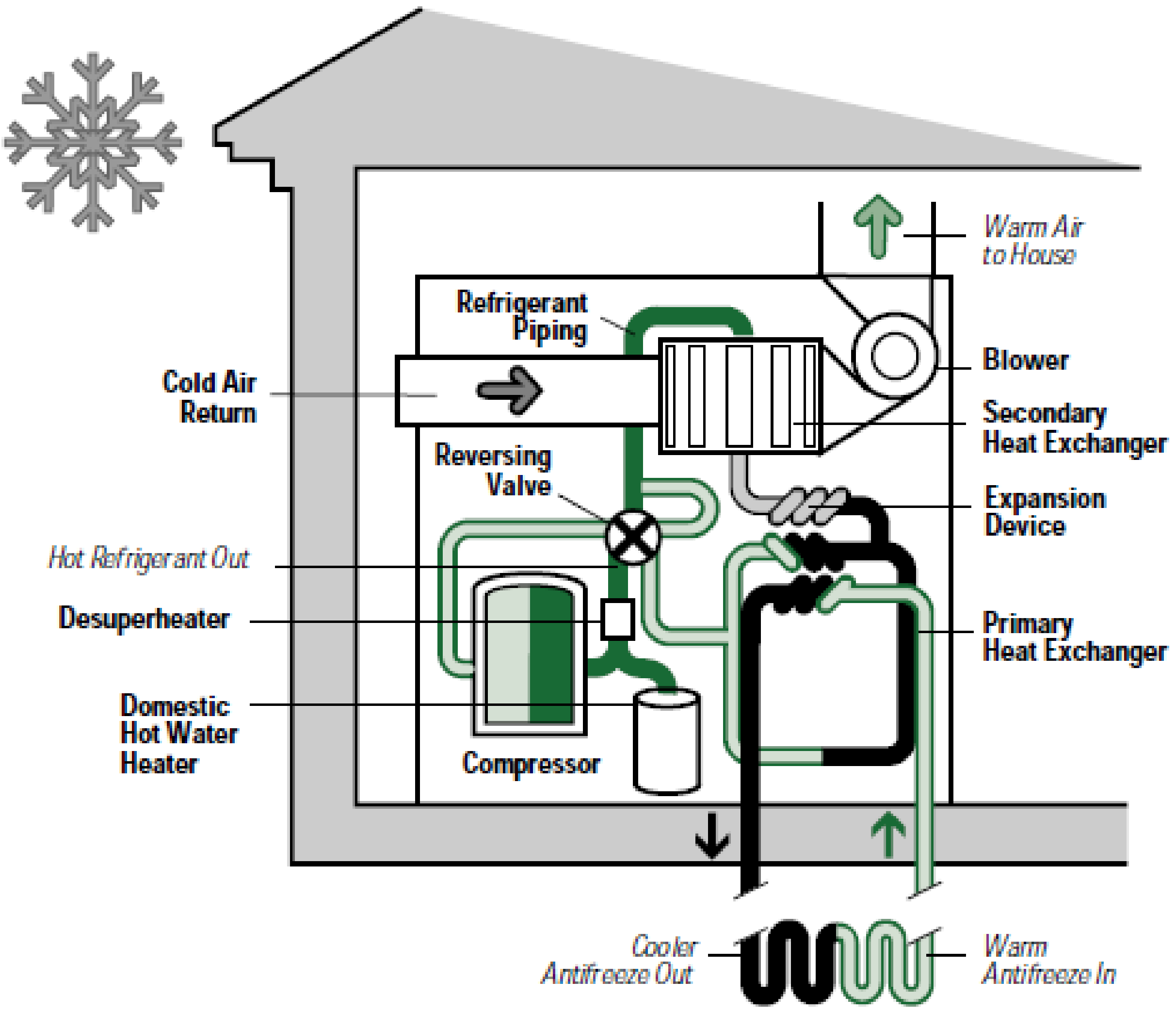


Figure 19 – Operation of a ground-source heat pump in heating mode (Canada Office of Energy Efficiency)

3.4. Efficiency and performance of heat pumps

The characteristic parameters in order to measure performance and efficiency of heat pumps is the nominal power of the heat pump system expressed in Watts, and the total or seasonal coefficient of performance (COP). A heat pump arrangement is a mechanism that contributes to synergy saving by the ability to supply simultaneous heating and cooling (Byrne et al, 2012). The output energy of a heat pump installation is as well considerably higher that its electricity input.

The performance and efficiency of the heat pump is expressed by its coefficient of performance (COP). The calculation of the COP is performed according to equation (4).This index expresses the relation between energy consumed and energy produced.(Hesaraki et al., 2015)

$$COP = n_c \cdot \left(\frac{T_{sin}(t)}{T_{sin}(t) - T_{sor}(t)} \right) \quad (4)$$

Where:
COP is the coefficient of performance
n_c is the Carnot efficiency expressing the ratio between real time efficiency and theoretical maximum possible efficiency
T,sin and T,sor are the temperatures of the heat sink and source respectively in deg. Celsius

The COP of common heat pump installations can reach in average a value up to 4. The performance coefficient is affected by many internal and external parameters, such as the the temperature gradient between the heat source and sink, the type and properties of the refrigerant and the performance of the compressor component. It can be derived from equation 4, that a high temperature heat source with a low temperature heat sink can increase considerably the efficiency of the heat pump installation.(Hesaraki et al., 2015)

4. Problem Context

The “MEGA” building

“The New Babylon” – Den Haag

(source: martijnvandernat)

4.1. Introduction

The rising population within urban centers combined with rapid urbanization has led to the increase of the so-call "high-rise development". The original concept of high-rise development started as a conventional typology of housing or office blocks that expanded to numerous floors, usually a number larger than twenty. The difference between high-rise and multi-floor buildings lies of course in the number of floors, but also on the scale of the development and gross total area.

While simple in its origins, the concept of high-rise developments has become more complex through time, directly affected by market needs, the ever-changing urban environment and rising demands for efficiency and sustainability against climate change. Single-use developments were replaced by large-scale buildings that accommodate more than one functions within the same block. The contemporary approach is evolving towards "the vertical / compact city", the reproduction of an urban block in a vertical and compact manner. Of course, such a representation ought to represent all the different interactions and co-existences within the same building shell, in a comparable manner to how a normal "living" urban block would behave.

The problem context of the current research project thus derives from an actual situation. The model building is based on the design made for TU Delft course AR0026 MEGA, based on the requirement of 2017Q4. The case study involves a multi-purpose development that has to combine both residential, office and commercial units in an extraordinary scale and height. The interesting feature was the sustainability of such a design endeavor and the overall energy performance of the building. As mentioned in Chapter 1, according to upcoming Dutch legislation, all newly built developments should be able to achieve a nearly zero-energy status. In this case, traditional techniques can be used for energy savings but adapting a circularity concept in order to reuse excess or waste energy can be a beneficial tool towards a sustainable and efficient realized building of an unusual scale.

4.2. Description and location

The concept of the MEGA building is to accommodate for 4 basic functions: housing units, office units, a hotel complex and the premises for the International Court of Justice, a fictional expansion of the already existing Court premises in the city of Hague in the Netherlands. The gross floor areas required are described within a detailed program of functional requirements.

The site that was chosen from the course team is the Koningin Julianaplein, in front of the Central Station in the city of Hague.

Figure 20 – Location of the conceptual MEGA building

4.3. Program and functional requirements

The total gross square meters of the urban planning volume is based upon the following presumption: 180 meter subdivided by an average gross floor height of 3,6 meter will give a maximum of 50 floors. 50 floors multiplied by 2500 square meter per floor averagely give a total gross floor area of 125.000 m2. The difference between 5625 m2 (= 75x75m) and 2500 m2 is an initial reservation for voids, setbacks and possible cavities on the overall volume.

4.3.1. International House of Justice and Ancillary Spaces

- 8 main court rooms of 400 m2 excluding translation booths, two retreat-rooms for the Judiciary and the defense and the waiting area for the suspects; the Judiciary, the suspects and the public enter the rooms through their own separated entrances, corridors and necessary vertical circulation.
- 8 small court rooms of 200 m2 excluding translation booths, two retreat-rooms for the Judiciary and the defense and the waiting area (holding rooms) for the suspects;
- Main Press meeting Hall with 200 seats for press and public;
- Salle des pas-perdus to enter all public spaces within the courthouse;
- 10 smaller meeting rooms of 100 m2 for inquiries and hearings;
- Main restaurant with 200 seats;
- 7.000 m2 net offices spaces for the Judiciary;
- 7.000 m2 net offices spaces for the International Prosecution;
- 1000 m2 net Secured storage of Evidence, in direct vicinity of court rooms and offices of the International Prosecution;
- Lobbies, waiting areas, reception facilities and Back of house facilities

4.3.2. Hotel with conference rooms

The hotel will be the second main tenant of the building besides the House of Justice. So all central services, like catering of the restaurant of the House of Justice, central garbage facilities and delivery, in the building will be provided by the Hotel.

The brief of the hotel consists of the following elements:

- 250 rooms of 20 m2: 40% of all units
- 150 rooms of 32 m2: 40% of all units
- 25 junior suits of 44 m2: 15 % of all units
- 20 suites deluxe 56m2: 5% of all units
- 5 presidential suits of 70 m2: not included in total number of units
- for every 50 rooms there has to be one cleaning room and intermediate storage of 15 m2 each;
- Conference area with four meeting rooms of 150 m2 each and a break-out area of equal surface;
- Two restaurant rooms
- Swimming pool and Fitness area: 1500 m2 minimum swimming pool dimensions are 12 x 25 meter
- Back of house facilities; central offices, staff rooms, waste management, garbage and luggage storage

4.3.3.Offices

The layout of the office spaces should be flexible and able to accommodate diverse contemporary office concepts. The office layout should be based on 90 cm grid and should have a flexibility based on 3,60-unit sizes. The office area should be designed in such a way that it can serve different lease concepts: one main tenant leasing the full 30.000 m2 up to multiple tenants leasing parts of the area with a minimum unit size of 3.000 m2.

4.3.4. Housing

The housing units within the building should benefit from the services and program available in the hotel like

the swimming pool and the fitness/gym area.

The building has to provide a wide range of apartments:

- Small short stay apartments of 50 m2 each, serviced by the hotel; 20% of all units
- Three rooms housing units of 85 m2: 25% of all units
- Four rooms housing units of 100 m2: 25% of all units
- Five room housing units of 120 m2: 25% of all units
- Penthouses of 250 m2 each: 5% of all units

4.3.5. General Services

The general services in the building consist of two main elements: services related to the square and the station (e.g. like cafes, shops, small retail units) and subterraneous services like parking and bicycle storage. Due to the direct vicinity of the station a large parking is not required according to the current Dutch building code, however the specific programming of the building makes a large parking garage unavoidable.

- Ground-floor related services: 5.000 m2 gross
- VIP parking: 50 places: square meters not included in the design brief;
- Secured parking for detainees and suspects: 4 small van places: square meters not included in the design brief;
- General parking 250 places: square meters not included in the design brief;
- General bicycle storage 10.000 bicycles: square meters not included in the design brief;

4.4. Building design and characteristics

The existence of more than one functions within the same building block creates a pattern of interactions between the different functions. While gross areas are calculated separately, in practice the functions will still make use of the same general services in the terms of electricity, heating and cooling and transportation etc. The interaction of functions is depicted in the following functional diagram.

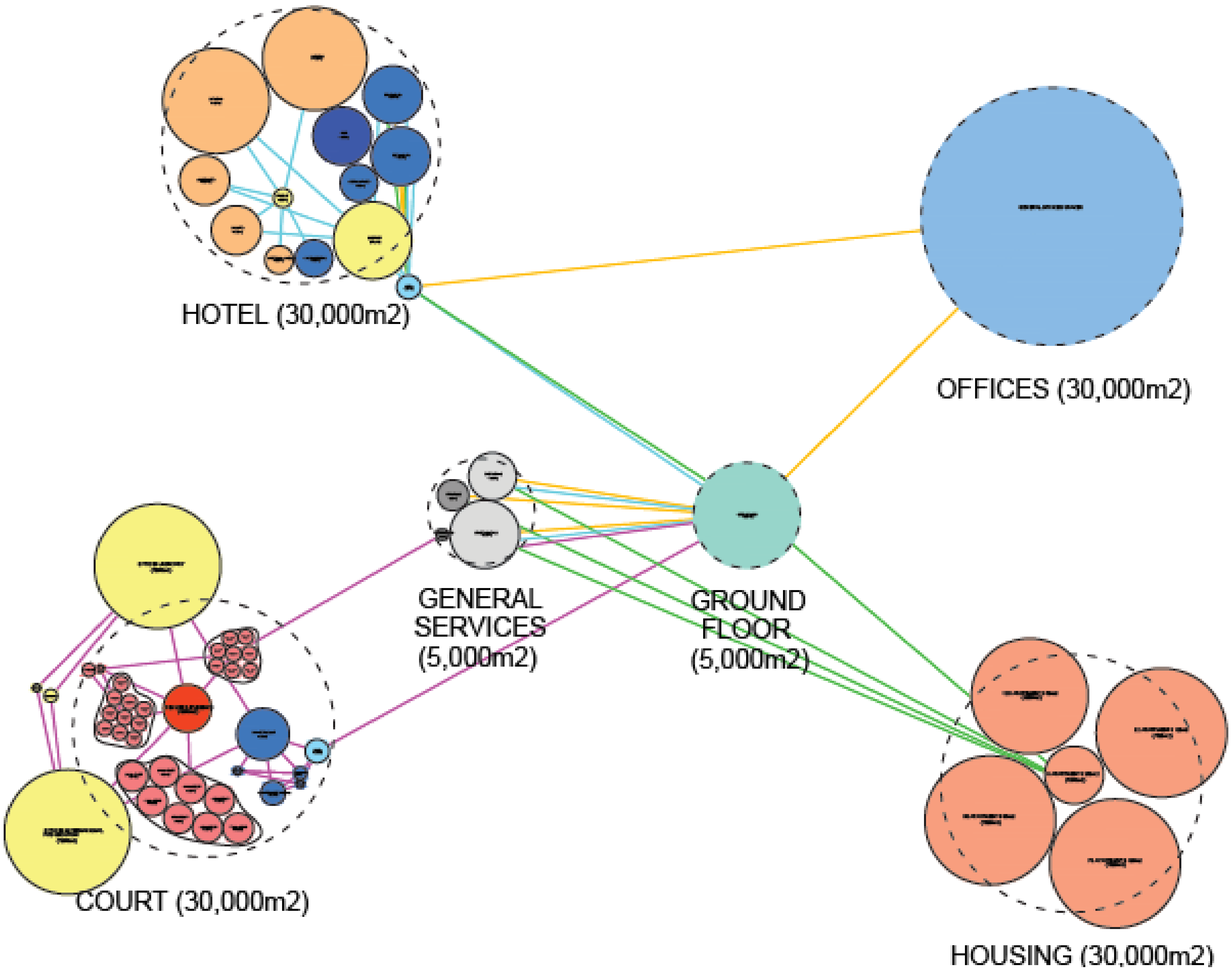


Figure 21 - Functional diagram of the conceptual MEGA building

4.4.1. Geometry and layout

The building is modeled in a simplified manner, comprising of 52 main floors of an average height of 3.0 meters. Service floors and structural floors used as location of the outrigger system are excluded and not regarded as thermal zones. The general services and storage floors are also assumed not to behave as thermal zones, but as auxiliary unheated spaces.

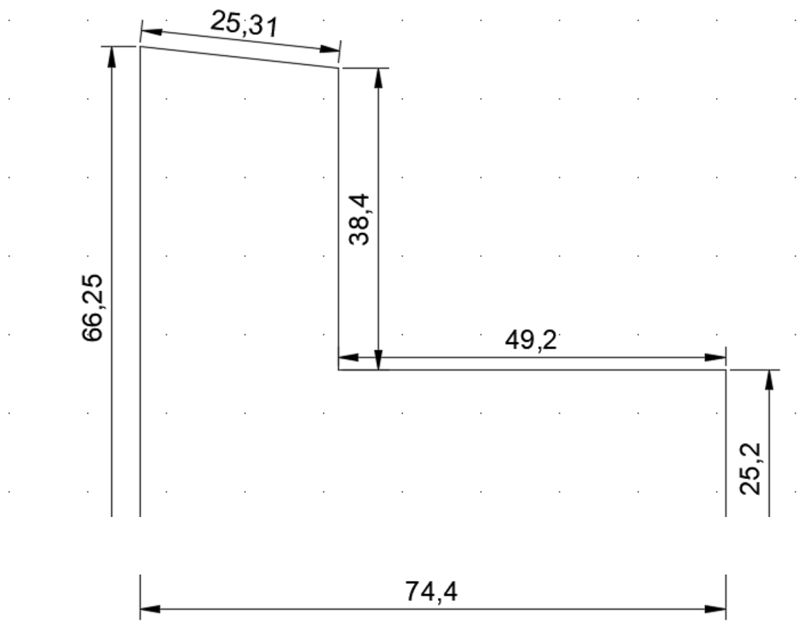


Figure 22 – Building outline and dimensions

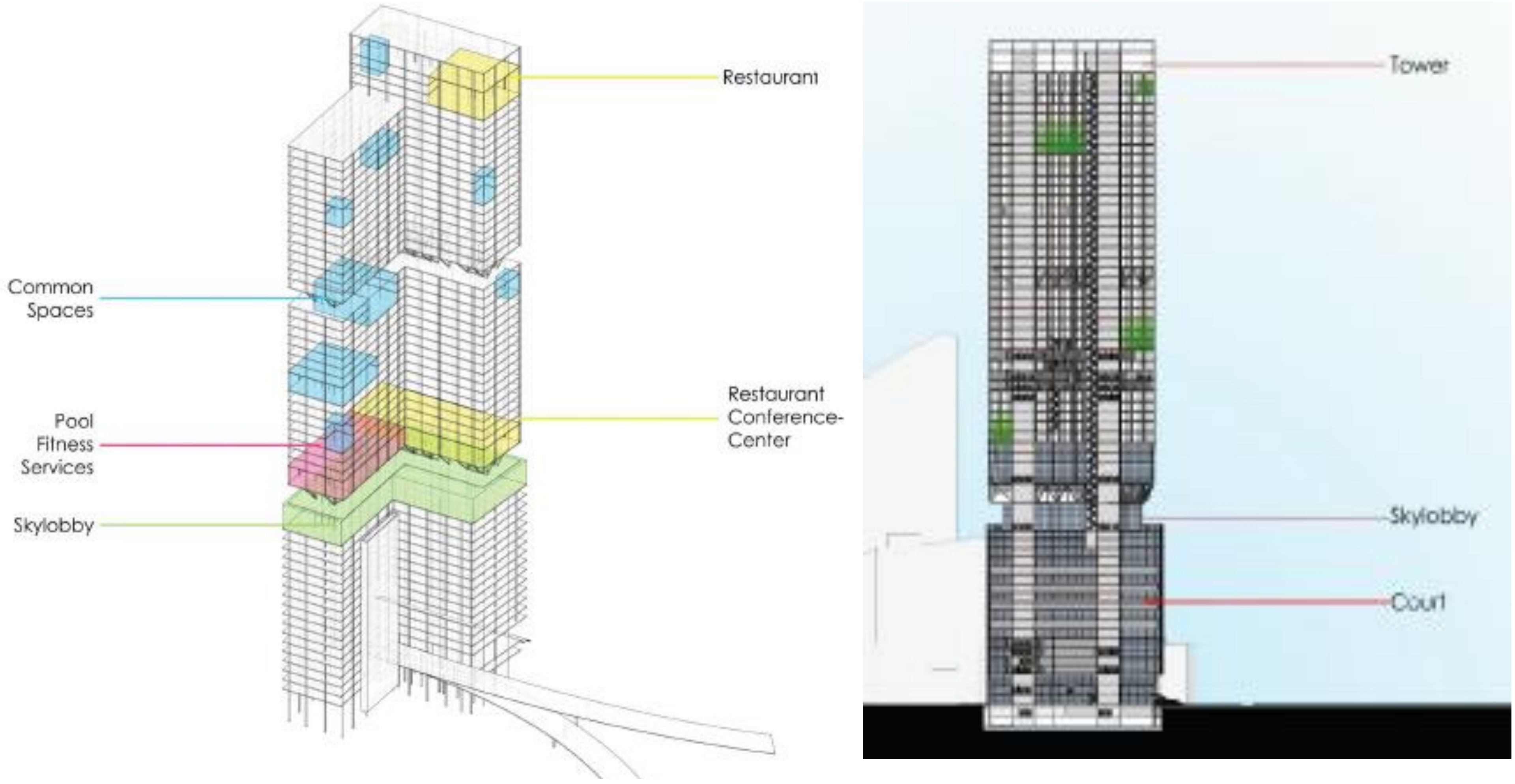


Figure 23 – Building overview (stacking) and vertical section

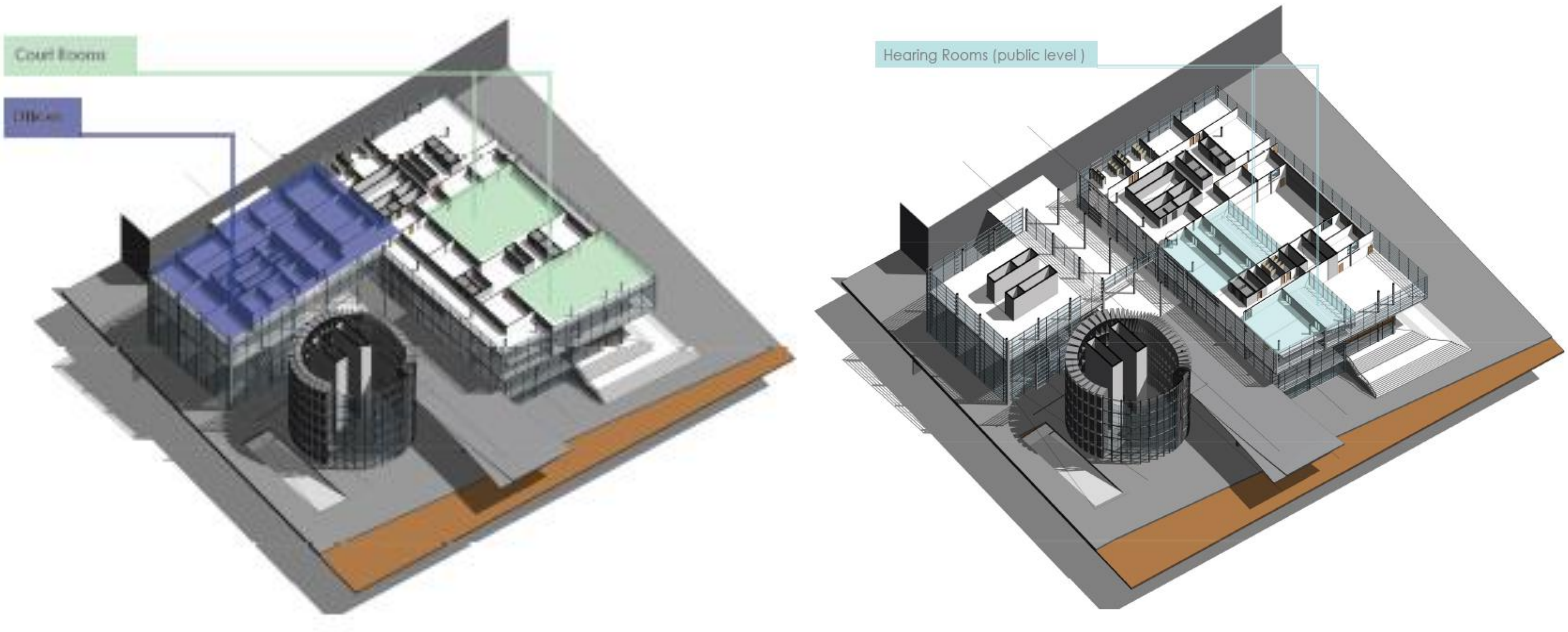


Figure 24 – Typical arrangement for the courthouse function

Figure 25 – Typical floor arrangement for hotel + housing functions

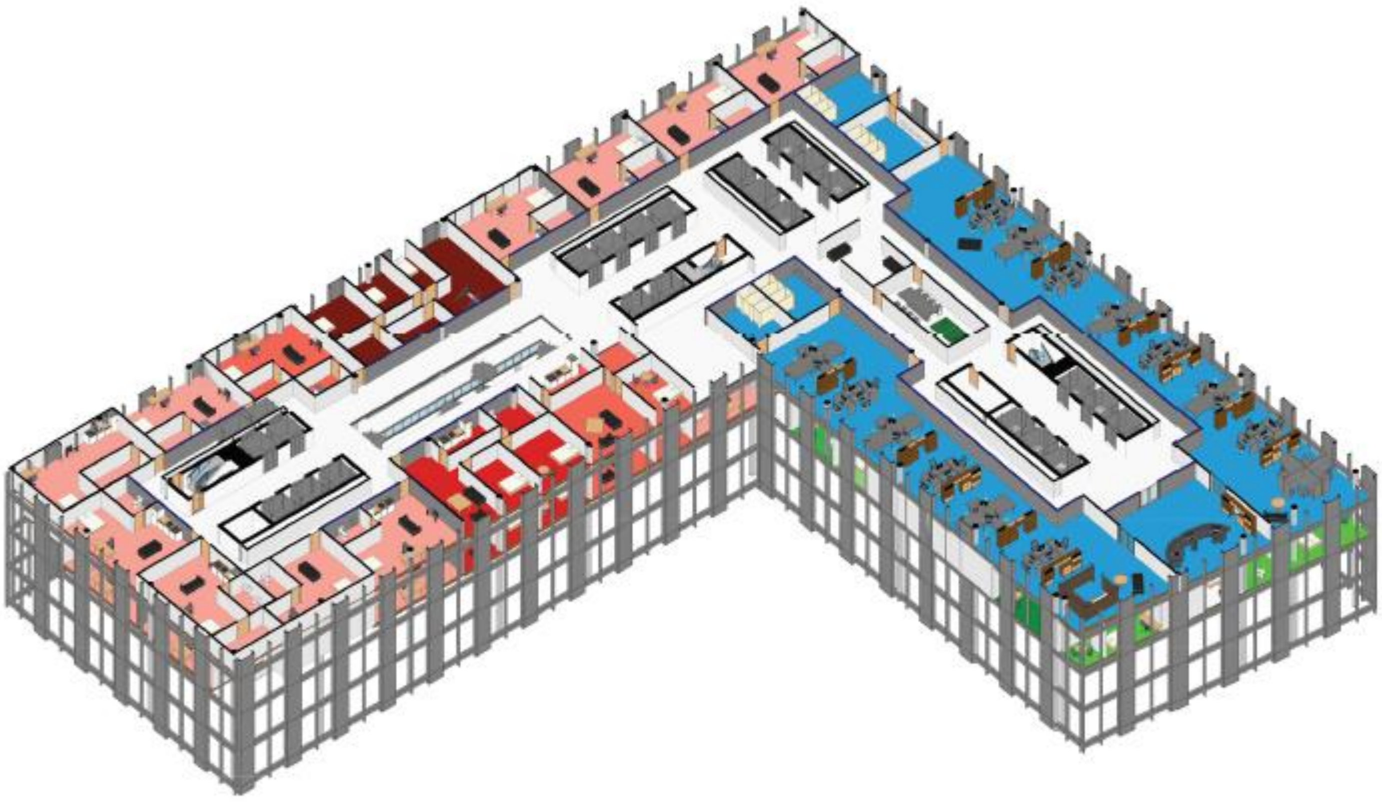


Figure 26 – Typical floor arrangement for housing + office functions

4.4.2. Envelope design

The original façade concept is based on the architectural concept of modularity and flexibility. The envelope is designed as a modular block comprised by a glazed part with a double-skin function and an insulated part that was designed as a solar chimney. The solar chimney part enables air circulation and natural ventilation for the indoor spaces.

For the purposes of the current project, the envelope characteristics will be simplified to a glazed and an opaque part, utilizing the thermal properties of the original design solution. The ratio between solid and transparent parts is 0.5, and the total window to wall ratio is 2/3 = 0.66.

Figure 27 – Façade general appearance

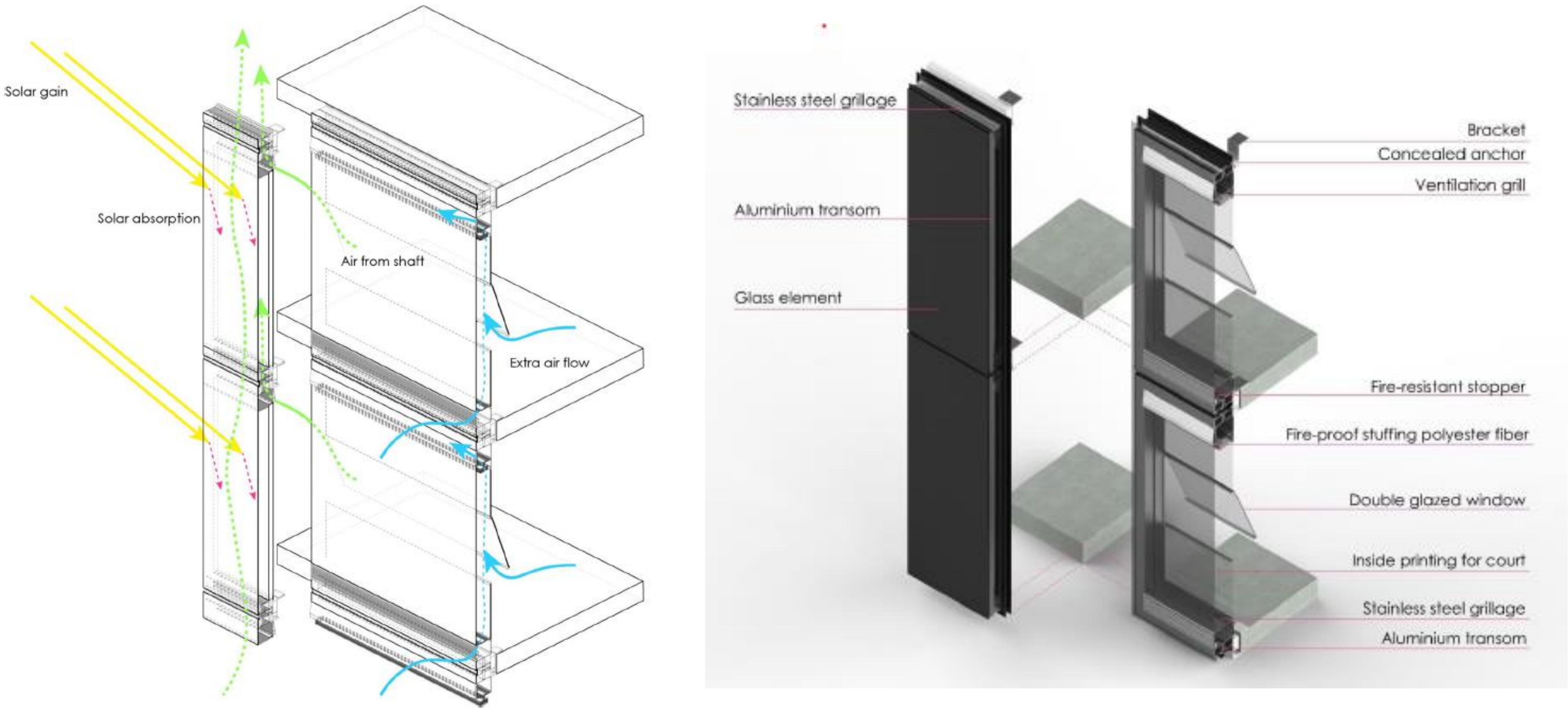


Figure 28 – Original façade arrangement and function

The characteristics of the simplified façade can be summarized below:

Total thermal resistance of opaque part:	R=4.5 m^2K/W
Total thermal resistance of glazed part:	R=1.25 m^2K/W
Solar factor glazed part:	g(%)=36
Shading coefficient glazed part:	SC=0.44
Shading mechanism:	Roller blinds operated according to solar gain control

4.4.3. Climate design

The original concept of the MEGA building was modular flexibility. In order to fully implement this concept, the building shape was restricted to a simple form. Although several climate related shapes were explored, the regular building shape was decided. Since the approach of the team's Climate Designer was to be as natural as possible, the original design accommodated for higher temperature variations accepted than with a conservative HVAC system. People might have to respond to that by slightly varying their clothing factor.

Because of the mixed functions and the concept of adaptability, a climate system that fits every use and function was investigated.

The goal was therefore to have an exposed concrete ceiling and to avoid raised floors throughout the building. Although suspended ceilings and raised floors might be acceptable or even of advantage in office or hotel spaces, that is not the case for the residential part. The Climate Designer assumed that people would not want to have a raised floor in their bedroom or living room.

Ventilation

For sustainability the Climate Designer opted for a system which operates passively to a maximum extent. By using passive means like natural ventilation, a connection to the outdoor environment was made. Therefore, we are able to work with the adaptive. The basic ventilation system relies on a solar chimney as the driving force, which is integrated in the façade and can be found all along the building. The air inlet is in the Haagse Bos, follows the earth tube and is vertically distributed in ventilation shafts connected to the core. The horizontal distribution on each floor happens via lowered ceiling in the corridors und ducts in the slabs.

Since the site is located in a densely built environment, a fresh air supply is very important. We are in the lucky situation that the Haagse Bos, a big public park, is just meters away. The air tends to be cleaner and cooler in the park compared to a normal urban environment. The idea was to connect the air supply for the high-rise building to this area by using an earth tube. This can be conceptually seen in figure xx

To keep it as passive as possible and further reduce the heating and cooling load, the supply air is preconditioned using the earth tube that levels the seasonal differences of the air temperature to a certain extent. This happens because of the inertia of the soil, which reacts slowly to temperature changes of the air. In order to additionally level diurnal differences as well, thermal mass element with a big surface area for heat exchange are placed in this shaft.

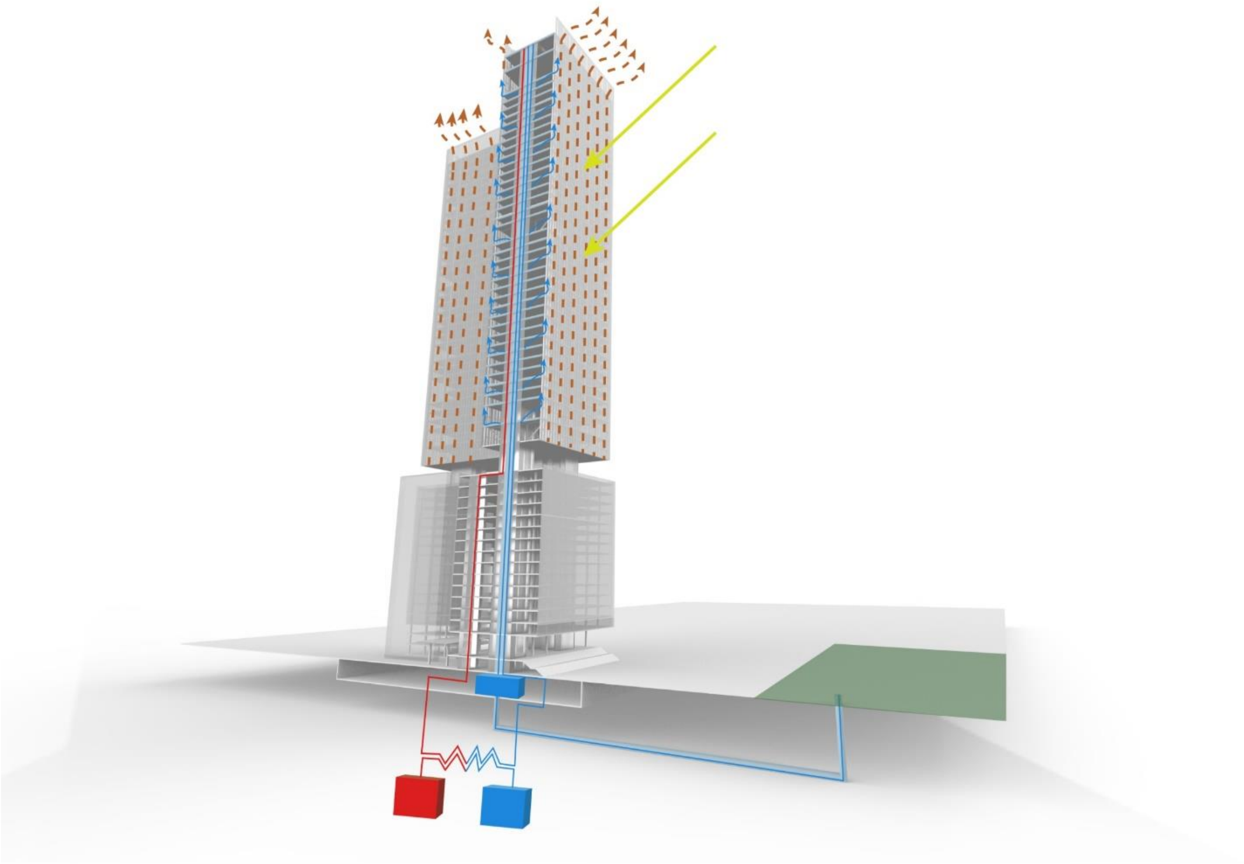


Figure 29 – Overview of the original ventilation concept of the MEGA building

.

Heating and cooling

The heating and cooling system in the original climate concept for the MEGA building is carried out by thermal activation of the concrete. Since the cooling load is expected to be higher than the heating load, it was decided to place the system in the ceiling. In that position a cooling system works more effectively and is perceived as more comfortable. As already stated before, the main idea for the climate concept was to satisfy the need for all functions in the best possible way, thus the heating and cooling system is the same all over the building. As a medium to thermally activate the slabs, water is used. This water comes from an aquifer storage and recovery system (ASR). This works by storing water seasonally in two different wells in the ground, one for hot water (about 17°) and the second one is used for cold water (about 7°). In the concrete slab, pipes of 2 cm in diameter are used every 20 cm to transfer the heat or cold to the thermal mass and activate it.

By using a heat exchanger and a heat pump, the temperature can be increased to the necessary temperature of the heating case, for instance a difference of 3 Kelvin. In case of cooling (summer), only the heat exchanger is going to be used, since the water comes with a temperature of about 7 degrees. This means the only energy used for cooling is needed to operate the pumps which leads to a very efficient COP of 12. In case of heating a heat, pump is necessary. With a COP of 5 this is still a very efficient system.

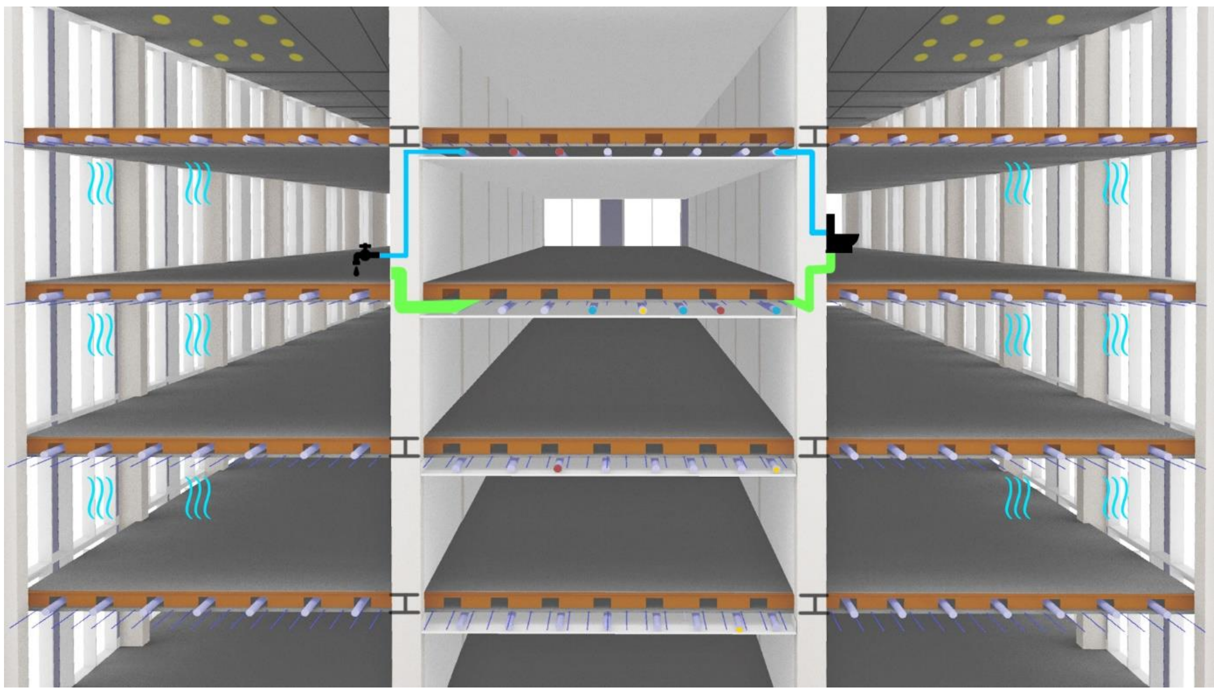


Figure 30 – Overview of heating and cooling installations for the original MEGA building

A lowered ceiling just in the corridors for horizontal distribution of the installations was introduced. The lowered ceiling connects the three cores which work as vertical distributors of the installations. In all other parts of the building, the services are placed in the concrete slab which is a slimline system. The advantage of this type of floor is that it has a cavity in between the concrete that leaves space for installations. Figure 31 shows a section of this floor together with the relevant installations.

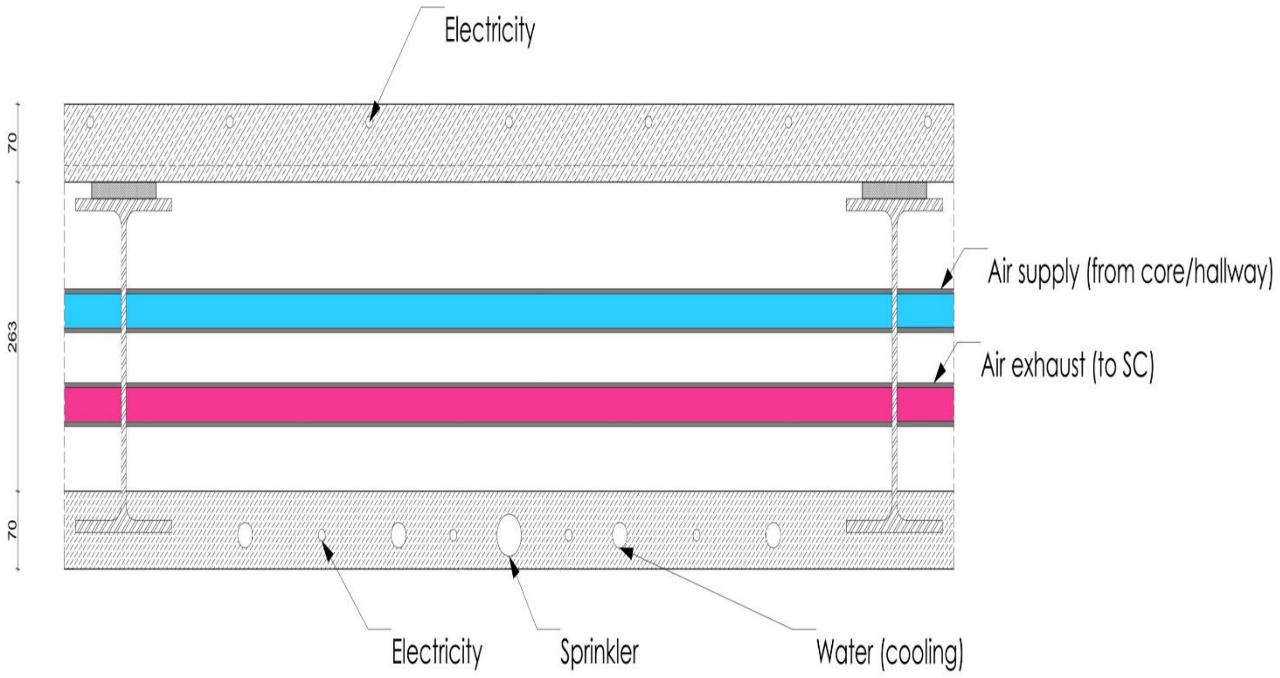
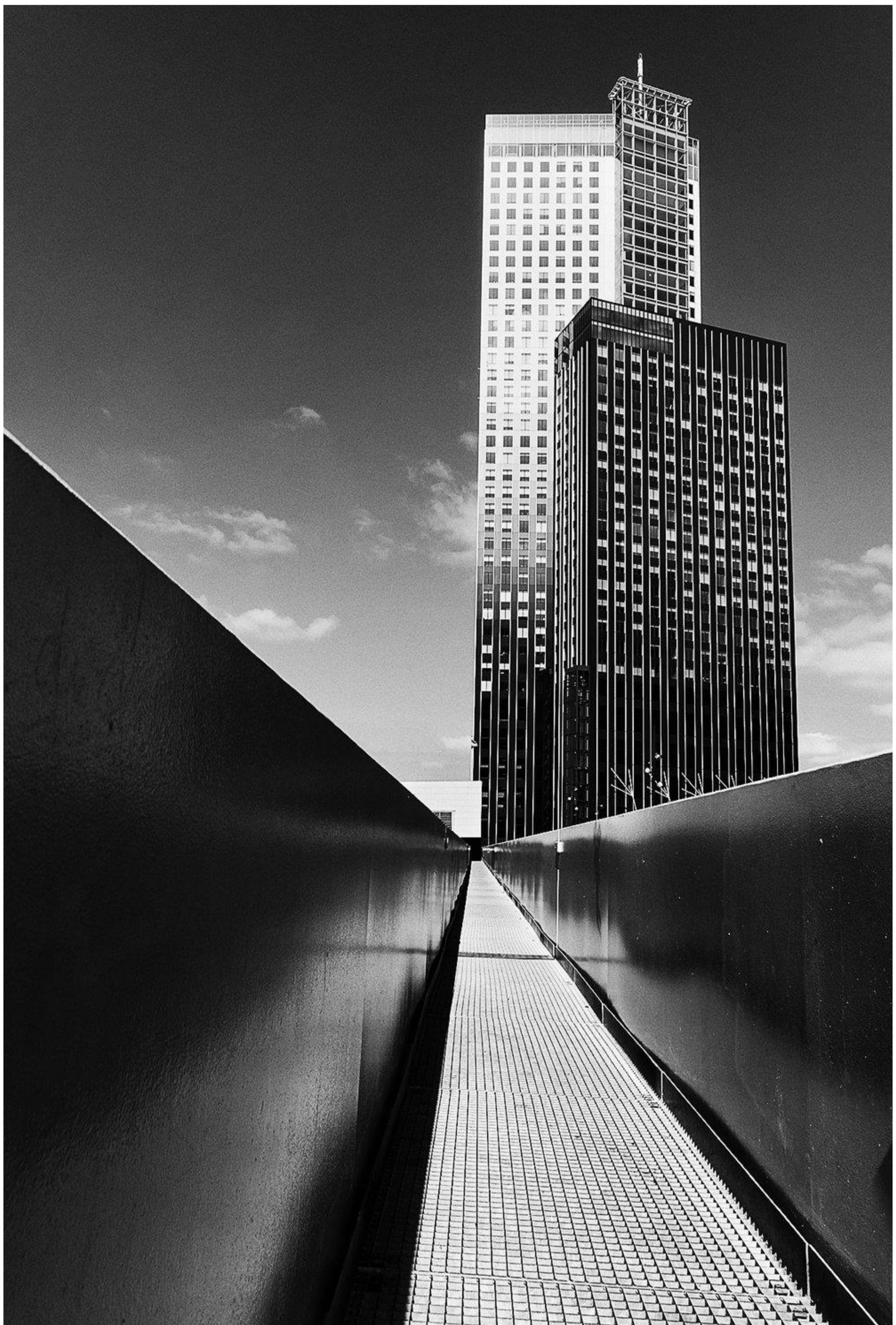


Figure 31 – Floor section showing position of services in the MEGA building

5. Calculating the energy demand



“De Maastoren” – Rotterdam

(source: O’MINE photography)

5.1. Introduction

Energy demand in the building sector is an ongoing subject of research and debate among designers, regulators and researchers. The sector is currently facing a transition, where energy demand will consequently replace design and aesthetics as the “identity” of the building ( ). The growing effects of climate change as well as the potential fossil fuel energy shortage, have rendered the excellent energy performance of buildings from a luxury to a necessity ( ).

In this context, calculating the energy demand of existing or new buildings is always the first step of determining their level and potential of sustainability. This chapter will cover the determination of parameters and assumptions, in order to calculate the energy demand of the MEGA building, based on the existing design for the building envelope and climate system. The different steps in order to set and calculate the energy balance will be explained as well as the simulation methods that were used to achieve more reliable results next to the manual calculations. Finally, the energy demand profiles of the MEGA building are presented for different time scales, in order to showcase the energy behavior of the building within a year, and how this behavior is affected by the different functions accommodated.

5.2. The Dutch Reference Climate

As mentioned in Chapter 2, the location of the concept MEGA building will be at the *Koningin Julianaplein*, in the city of The Hague. The Hague has a temperate oceanic climate with the Köppen Classification **Cfb**. Winters as well as summers are considered mild, although some extreme temperatures might occur occasionally. The prevailing wind direction is from the south west. In figure 32., the orientation and sun path in the building location be well as the surrounding context of the building site. The building has a North West orientation, with an azimuth angle of 340.5 degrees (or 19.5 degrees counterclockwise).

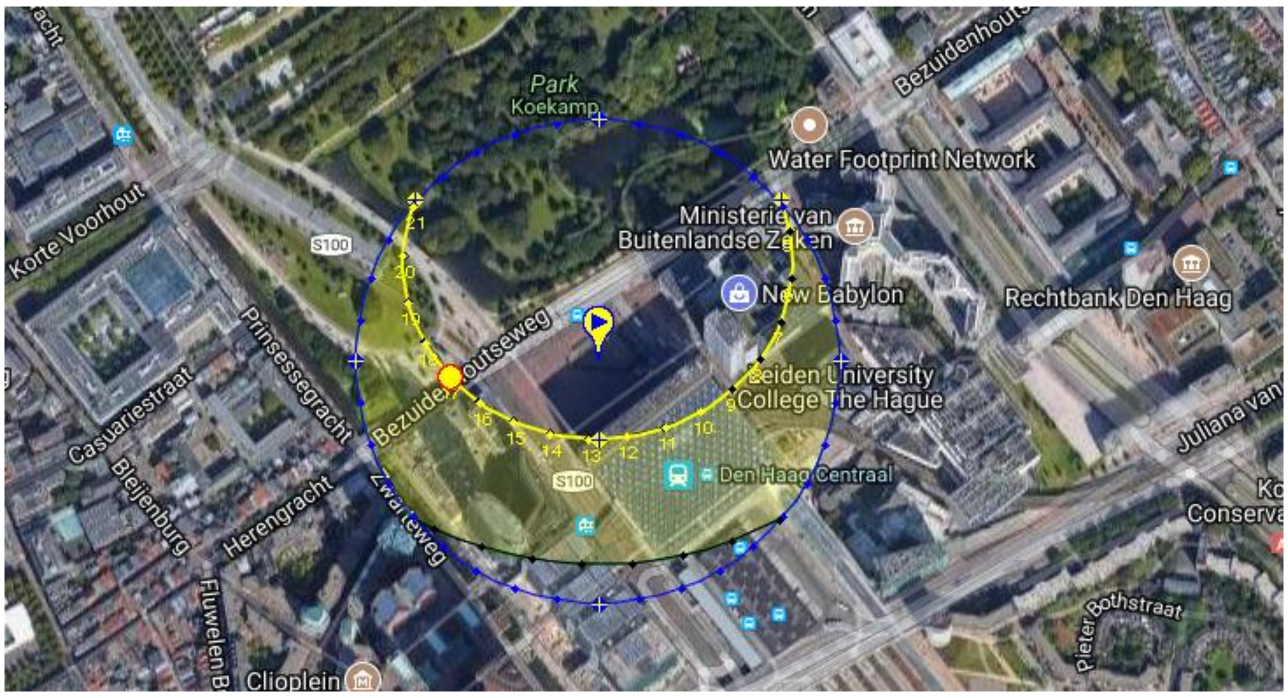


Figure 32 . - Orientation and sun path at the location of the MEGA Building

Figure 33. demonstrates the mild and temperate climate conditions in the Hague. During winter the temperatures are not severely cold and extremely hot summer days rarely exist as well. A moderate precipitation can be found all over the year.

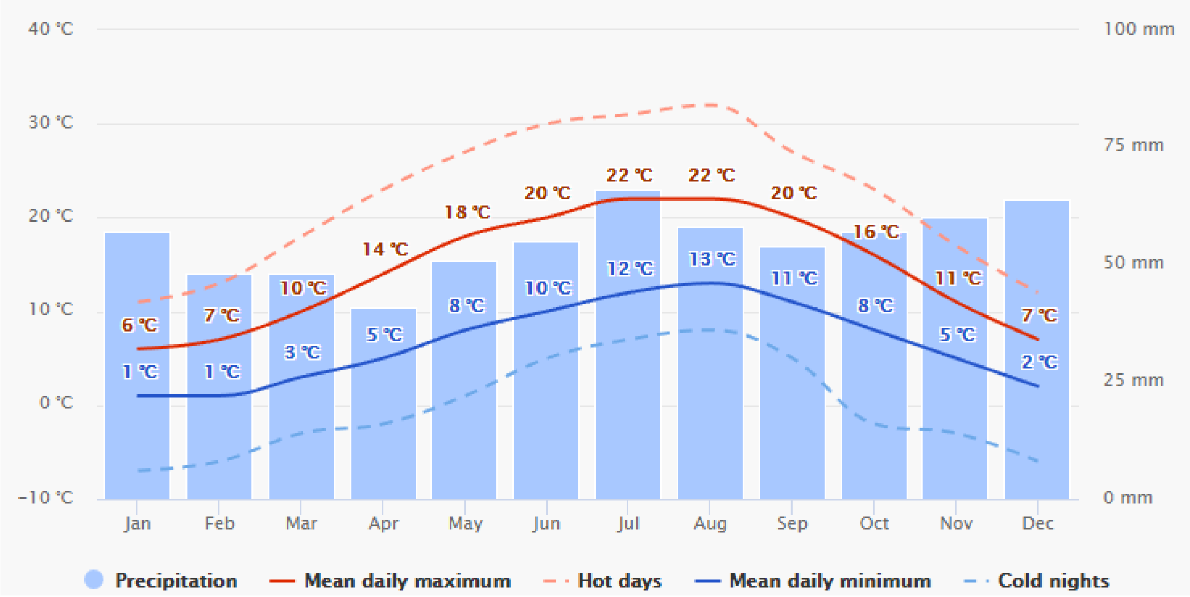


Figure 33 – Climate data for the city of The Hague

In order to perform manual calculations, different values for the temperature distribution over the year had to be determined. For manual calculations, two sets of data are used; the first data set is the average outdoor dry bulb temperature in degrees Celsius for each month and the average total hourly solar radiation in Wh/m^2. The second data set in order to determine an hourly profile within a typical day of the heating and cooling period, is the hourly distribution of temperature within the day in degrees Celsius combined with the total average solar radiation in W/m^2.

The monthly data were assumed according to the Dutch Energy Standard NEN7120 (Tables 8 and 9), while hourly temperatures were taken for the sample days of January 21st and July 21st, 2018, according to the measurements of KNMI from the weather station at De Bilt.

Month	Avg. Outdoor Temp.(o C)
January	2,6
February	5
March	6,8
April	9,3
May	13,3
June	16
July	17,4
August	17,4
Sept	14,6
Oct	11,3
Nov	7,1
Dec	4

Table 9 – Average monthly outdoor temperatures according to NEN 7120

Average total hourly solar radiation (Wh/m2)			
ZW	**ZO**	**NO**	**NW**
44,9	41,3	10,8	10,9
53	59	21,2	20,4
72,3	71,3	34,2	34,7
133,9	136,9	73,7	73,1
143,2	136,9	88,9	97,9
142,9	131,9	104	111,5
122,9	127,6	95	86,5
128,3	140,6	84,1	79,1
98,6	107	49,7	50
81,1	83,6	28,7	28,3
44,3	44,3	13,5	13,6
35,5	36,4	8,5	8,5

Table 8 – Average total hourly solar radiation for different orientations according to NEN 7120

	January	July
hour	temp	temp
1	3,6	17,6
2	3,6	16,6
3	3,9	16
4	4,2	15,9
5	4,2	16,9
6	4,1	18,4
7	4,1	20,2
8	4,4	21,6
9	4,7	22,9
10	5	23,7
11	5,8	24,7
12	5,6	25
13	5,3	26
14	5,6	25,9
15	4,8	25,8
16	4,1	25,7
17	3	25,4
18	2	24,6
19	0,5	23,3
20	-0,1	21,3
21	0,5	20,4
22	1,6	18,7
23	1,5	18,4
24	1,8	17,3

Table 10 – Hourly reference temperatures for January and July (source: KNMI)

January total irradiance								
hour	N	Z	O	W	ZW	ZO	NO	NW
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	11	77	89	11	44	83	50	11
10	33	388	303	34	211	345,5	168	33,5
11	48	607	296	50	328,5	451,5	172	49
12	56	722	174	60	391	448	115	58
13	57	739	64	122	430,5	401,5	60,5	89,5
14	51	656	53	264	460	354,5	52	157,5
15	40	471	41	319	395	256	40,5	179,5
16	20	187	20	193	190	103,5	20	106,5
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0

Table 11 – Hourly total irradiance for January (source: BK Wiki – Zon Bouwfysica)

July total irradiance								
hour	N	Z	O	W	ZW	ZO	NO	NW
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	57	0	84	11	5,5	42	70,5	34
6	195	0	441	38	19	220,5	318	116,5
7	178	0	685	63	31,5	342,5	431,5	120,5
8	97	0	786	86	43	393	441,5	91,5
9	112	77	776	107	92	426,5	444	109,5
10	126	388	678	124	256	533	402	125
11	137	607	513	137	372	560	325	137
12	144	722	308	150	436	515	226	147
13	144	739	154	233	486	446,5	149	188,5
14	141	656	141	449	552,5	398,5	141	295
15	131	471	130	630	550,5	300,5	130,5	380,5
16	117	187	113	752	469,5	150	115	434,5
17	103	0	94	795	397,5	47	98,5	449
18	150	0	71	733	366,5	35,5	110,5	441,5
19	203	0	47	540	270	23,5	125	371,5
20	124	0	20	211	105,5	10	72	167,5
21	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0

Table 12 – Hourly total irradiance for July (Source: BK WIKi – Zon Bouwfysica)

5.3. Comfort requirements

The quality of indoor living and working spaces is directly affected by the comfort level within the examined space. The different comfort requirements include acceptable temperature, air quality and illuminance levels according to the specific function for every space. While building characteristics such as material choice, level of insulation and orientation of openings and shading play a major role in the energy performance, comfort levels are also very important. The choice of comfort levels is that parameter that will determine the operational and setback temperatures during heating and cooling of the building as well as the rate of ventilation. The combination of these parameters results in creating the quantitative "energy identity" of the building, namely being the energy demand profiles for heating and cooling during a predefined time period.

There is extensive research and literature over the optimal comfort parameters for spaces with a specific function, most commonly office and housing. However, in the case of the MEGA building, the accommodation of different functions within the same building and under the same envelope characteristics creates a more complex situation.

The chosen strategy comfort strategy for the mixed-use MEGA building, is to create a uniform comfortable environment for all different functions. The temperature range for heating and cooling was chosen to accommodate for both office and housing spaces, while comfort levels for the hotel and courthouse functions are very similar and can be accommodated as well within the acceptable limits. The option in order to differentiate the needs of specific functions, was to enable different levels of ventilation. In this case, while the heating and cooling temperatures would be the same for every function, the ventilation levels can be adapted to each function in order to support and improve the function-specific comfort requirements.

The comfort levels for different functions were determined according to the suggestions and guidelines found in the European standard **EN15251** as well as the European standard **EN16798-1** that is currently under development.

The comfort requirements can be summarized as follows in Table 13.:

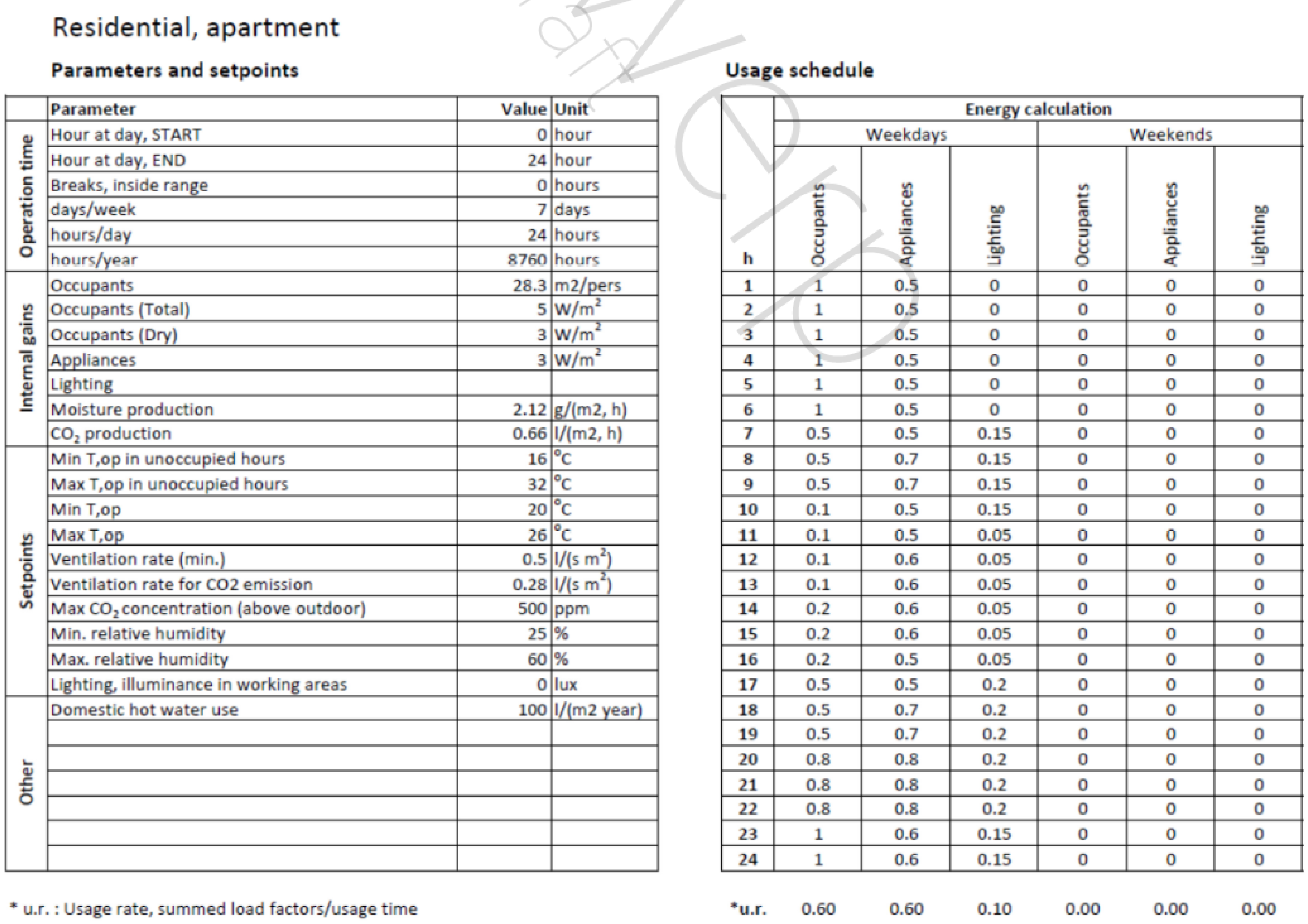
Function	Metabolism	Heating Range (^{o} C)	Cooling Range (^{o} C)	Min. Ventilation (l/sm^2)	Illuminance (lux)
Housing	1.2	20-24	23-26	0.5	500
Hotel	1 to 1.6	20-24	23-26	0.5	500
Office	1.2	20-24	23-26	0.8	500
Courthouse	1.2 to 1.6	20-24	23-26	0.8	500

Table 13 – Assumed comfort parameters for the different functions within the MEGA building

5.4. User occupancies and schedules

A very important parameter affecting the energy performance of buildings, is the behavior of its users. Usually, even if a building is designed according to strictly efficient measures, irresponsible use from the part of users and inhabitants can dramatically increase the energy use. It is therefore important, to correctly predict the user behavior as well as the distribution of people and appliances through the day. The occupancy schedules are important in order to achieve correct predictions of the energy demand profiles within a day or specific time period of building use.

Due to the complexity of the examined problem, it is complicated to determine the exact occupancy patterns for the case of the mixed-use MEGA building. The strategy to tackle this issue, is to divide the building and the different functions in smaller control blocks of a very specific activity and determine its gross area within the building surface. Based on these values and the guidelines of the European standard **EN16798-1** under development, pre-determined user schedules are used to describe the activity within the examined building.



Residential, apartment

Parameters and setpoints

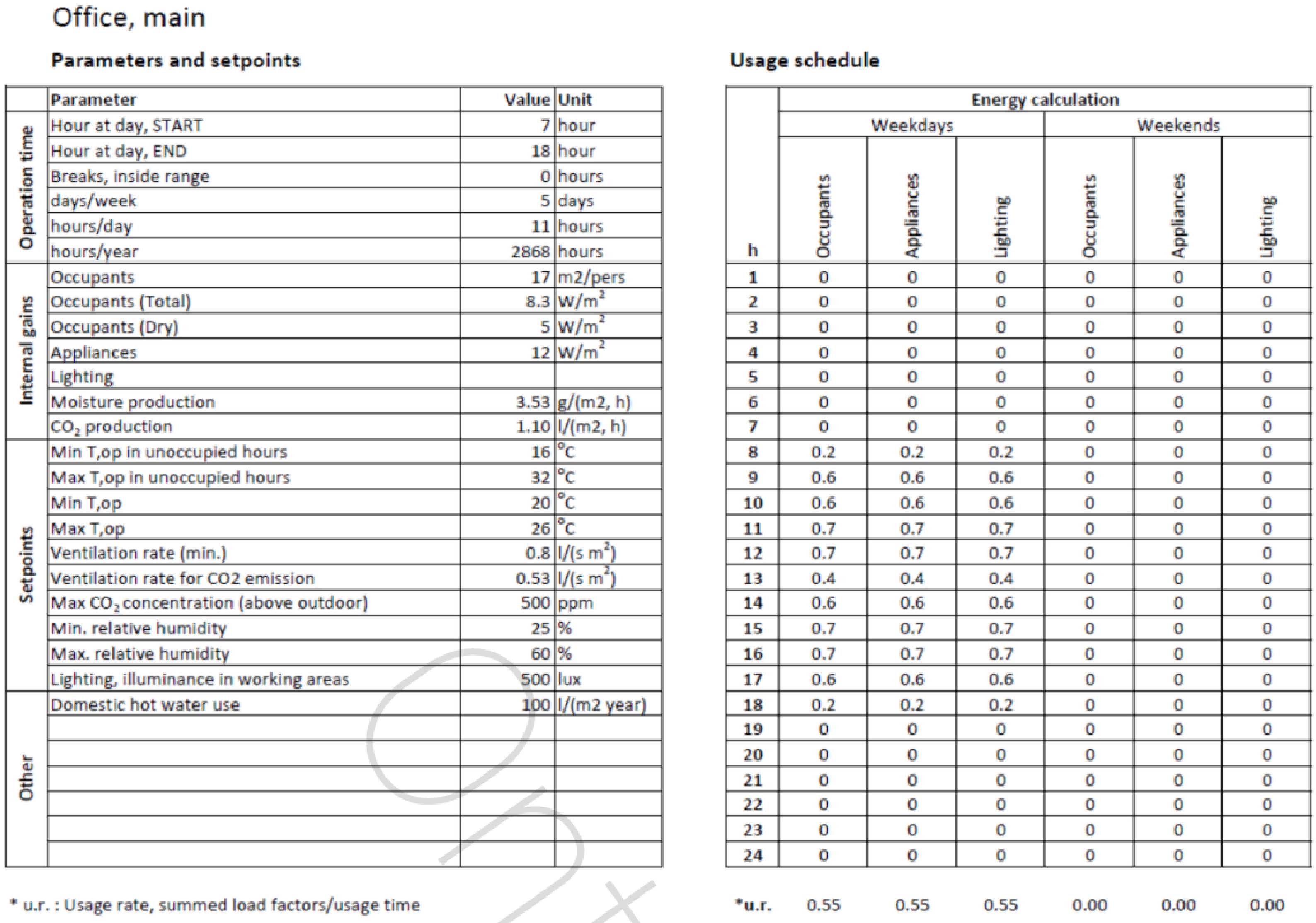
	Parameter	Value	Unit
Operation time	Hour at day, START	0	hour
	Hour at day, END	24	hour
	Breaks, inside range	0	hours
	days/week	7	days
	hours/day	24	hours
	hours/year	8760	hours
Internal gains	Occupants	28.3	m2/pers
	Occupants (Total)	5	W/m^2
	Occupants (Dry)	3	W/m^2
	Appliances	3	W/m^2
	Lighting		
	Moisture production	2.12	g/(m2, h)
	CO$_2$ production	0.66	l/(m2, h)
Setpoints	Min T,op in unoccupied hours	16	°C
	Max T,op in unoccupied hours	32	°C
	Min T,op	20	°C
	Max T,op	26	°C
	Ventilation rate (min.)	0.5	l/(s m^2)
	Ventilation rate for CO2 emission	0.28	l/(s m^2)
	Max CO$_2$ concentration (above outdoor)	500	ppm
	Min. relative humidity	25	%
	Max. relative humidity	60	%
	Lighting, illuminance in working areas	0	lux
Other	Domestic hot water use	100	l/(m2 year)

Usage schedule

h	Energy calculation					
	Weekdays			Weekends		
	Occupants	Appliances	Lighting	Occupants	Appliances	Lighting
1	1	0.5	0	0	0	0
2	1	0.5	0	0	0	0
3	1	0.5	0	0	0	0
4	1	0.5	0	0	0	0
5	1	0.5	0	0	0	0
6	1	0.5	0	0	0	0
7	0.5	0.5	0.15	0	0	0
8	0.5	0.7	0.15	0	0	0
9	0.5	0.7	0.15	0	0	0
10	0.1	0.5	0.15	0	0	0
11	0.1	0.5	0.05	0	0	0
12	0.1	0.6	0.05	0	0	0
13	0.1	0.6	0.05	0	0	0
14	0.2	0.6	0.05	0	0	0
15	0.2	0.6	0.05	0	0	0
16	0.2	0.5	0.05	0	0	0
17	0.5	0.5	0.2	0	0	0
18	0.5	0.7	0.2	0	0	0
19	0.5	0.7	0.2	0	0	0
20	0.8	0.8	0.2	0	0	0
21	0.8	0.8	0.2	0	0	0
22	0.8	0.8	0.2	0	0	0
23	1	0.6	0.15	0	0	0
24	1	0.6	0.15	0	0	0
*u.r.	0.60	0.60	0.10	0.00	0.00	0.00

* u.r. : Usage rate, summed load factors/usage time

Table 14 - Occupancy and internal gains for the residential function (source: EN16798-1)



Office, main

Parameters and setpoints

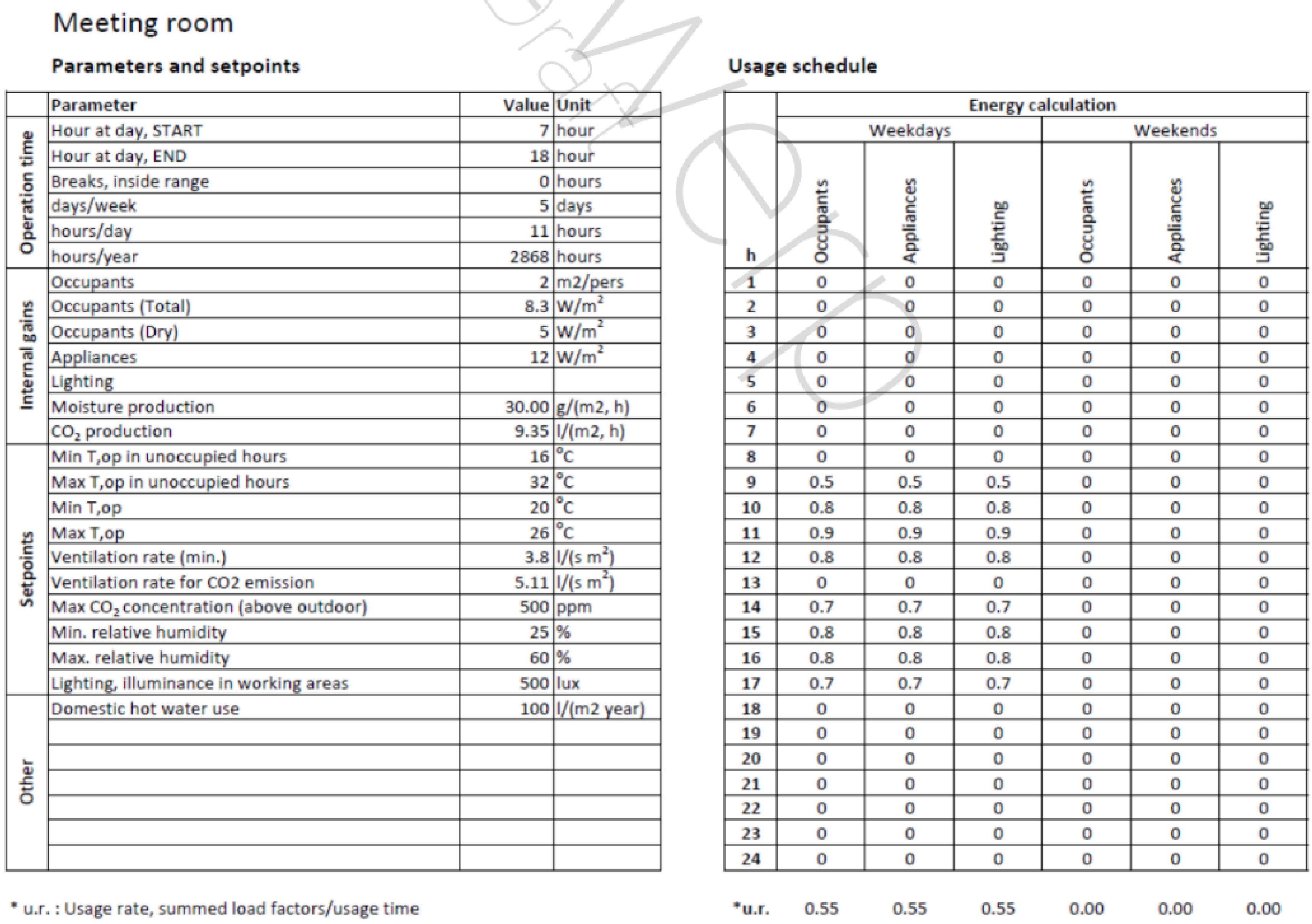
	Parameter	Value	Unit
Operation time	Hour at day, START	7	hour
	Hour at day, END	18	hour
	Breaks, inside range	0	hours
	days/week	5	days
	hours/day	11	hours
	hours/year	2868	hours
Internal gains	Occupants	17	m2/pers
	Occupants (Total)	8.3	W/m^2
	Occupants (Dry)	5	W/m^2
	Appliances	12	W/m^2
	Lighting		
	Moisture production	3.53	g/(m2, h)
	CO$_2$ production	1.10	l/(m2, h)
Setpoints	Min T,op in unoccupied hours	16	°C
	Max T,op in unoccupied hours	32	°C
	Min T,op	20	°C
	Max T,op	26	°C
	Ventilation rate (min.)	0.8	l/(s m^2)
	Ventilation rate for CO2 emission	0.53	l/(s m^2)
	Max CO$_2$ concentration (above outdoor)	500	ppm
	Min. relative humidity	25	%
	Max. relative humidity	60	%
	Lighting, illuminance in working areas	500	lux
Other	Domestic hot water use	100	l/(m2 year)

Usage schedule

h	Energy calculation					
	Weekdays			Weekends		
	Occupants	Appliances	Lighting	Occupants	Appliances	Lighting
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0.2	0.2	0.2	0	0	0
9	0.6	0.6	0.6	0	0	0
10	0.6	0.6	0.6	0	0	0
11	0.7	0.7	0.7	0	0	0
12	0.7	0.7	0.7	0	0	0
13	0.4	0.4	0.4	0	0	0
14	0.6	0.6	0.6	0	0	0
15	0.7	0.7	0.7	0	0	0
16	0.7	0.7	0.7	0	0	0
17	0.6	0.6	0.6	0	0	0
18	0.2	0.2	0.2	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0
*u.r.	0.55	0.55	0.55	0.00	0.00	0.00

* u.r. : Usage rate, summed load factors/usage time

Table 15 - Occupancy and internal gains for the office function (source: EN16798-1)



Meeting room

Parameters and setpoints

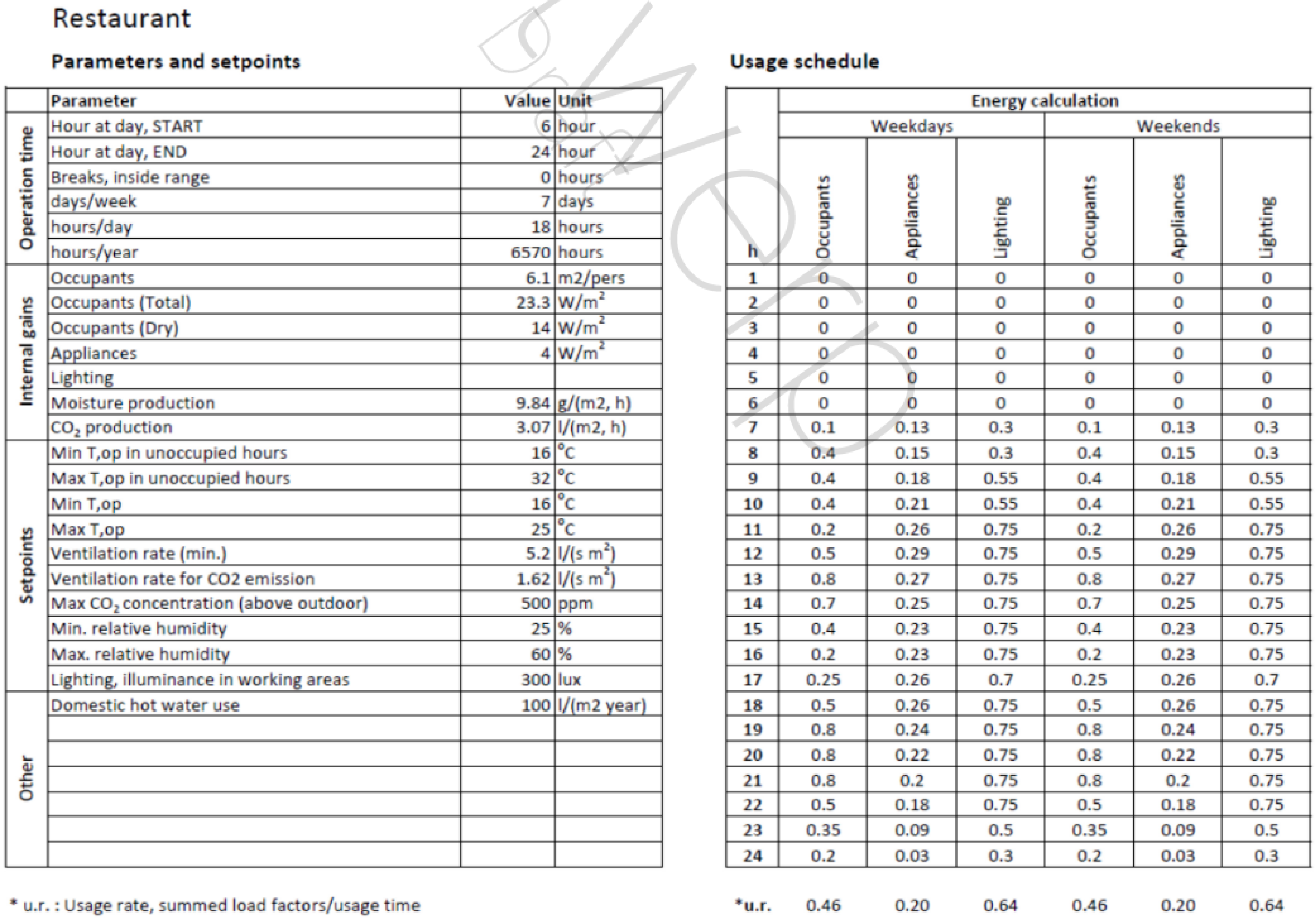
	Parameter	Value	Unit
Operation time	Hour at day, START	7	hour
	Hour at day, END	18	hour
	Breaks, inside range	0	hours
	days/week	5	days
	hours/day	11	hours
	hours/year	2868	hours
Internal gains	Occupants	2	m2/pers
	Occupants (Total)	8.3	W/m^2
	Occupants (Dry)	5	W/m^2
	Appliances	12	W/m^2
	Lighting		
	Moisture production	30.00	g/(m2, h)
	CO$_2$ production	9.35	l/(m2, h)
Setpoints	Min T,op in unoccupied hours	16	°C
	Max T,op in unoccupied hours	32	°C
	Min T,op	20	°C
	Max T,op	26	°C
	Ventilation rate (min.)	3.8	l/(s m^2)
	Ventilation rate for CO2 emission	5.11	l/(s m^2)
	Max CO$_2$ concentration (above outdoor)	500	ppm
	Min. relative humidity	25	%
	Max. relative humidity	60	%
	Lighting, illuminance in working areas	500	lux
Other	Domestic hot water use	100	l/(m2 year)

* u.r. : Usage rate, summed load factors/usage time

Usage schedule

	Energy calculation					
	Weekdays			Weekends		
h	Occupants	Appliances	Lighting	Occupants	Appliances	Lighting
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0.5	0.5	0.5	0	0	0
10	0.8	0.8	0.8	0	0	0
11	0.9	0.9	0.9	0	0	0
12	0.8	0.8	0.8	0	0	0
13	0	0	0	0	0	0
14	0.7	0.7	0.7	0	0	0
15	0.8	0.8	0.8	0	0	0
16	0.8	0.8	0.8	0	0	0
17	0.7	0.7	0.7	0	0	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0
*u.r.	0.55	0.55	0.55	0.00	0.00	0.00

Table 16- Occupancy and internal gains for the conference / meeting room function (source: EN16798-1)



Restaurant

Parameters and setpoints

	Parameter	Value	Unit
Operation time	Hour at day, START	6	hour
	Hour at day, END	24	hour
	Breaks, inside range	0	hours
	days/week	7	days
	hours/day	18	hours
	hours/year	6570	hours
Internal gains	Occupants	6.1	m2/pers
	Occupants (Total)	23.3	W/m^2
	Occupants (Dry)	14	W/m^2
	Appliances	4	W/m^2
	Lighting		
	Moisture production	9.84	g/(m2, h)
	CO$_2$ production	3.07	l/(m2, h)
Setpoints	Min T,op in unoccupied hours	16	°C
	Max T,op in unoccupied hours	32	°C
	Min T,op	16	°C
	Max T,op	25	°C
	Ventilation rate (min.)	5.2	l/(s m^2)
	Ventilation rate for CO2 emission	1.62	l/(s m^2)
	Max CO$_2$ concentration (above outdoor)	500	ppm
	Min. relative humidity	25	%
	Max. relative humidity	60	%
	Lighting, illuminance in working areas	300	lux
Other	Domestic hot water use	100	l/(m2 year)

* u.r. : Usage rate, summed load factors/usage time

Usage schedule

	Energy calculation					
	Weekdays			Weekends		
h	Occupants	Appliances	Lighting	Occupants	Appliances	Lighting
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0.1	0.13	0.3	0.1	0.13	0.3
8	0.4	0.15	0.3	0.4	0.15	0.3
9	0.4	0.18	0.55	0.4	0.18	0.55
10	0.4	0.21	0.55	0.4	0.21	0.55
11	0.2	0.26	0.75	0.2	0.26	0.75
12	0.5	0.29	0.75	0.5	0.29	0.75
13	0.8	0.27	0.75	0.8	0.27	0.75
14	0.7	0.25	0.75	0.7	0.25	0.75
15	0.4	0.23	0.75	0.4	0.23	0.75
16	0.2	0.23	0.75	0.2	0.23	0.75
17	0.25	0.26	0.7	0.25	0.26	0.7
18	0.5	0.26	0.75	0.5	0.26	0.75
19	0.8	0.24	0.75	0.8	0.24	0.75
20	0.8	0.22	0.75	0.8	0.22	0.75
21	0.8	0.2	0.75	0.8	0.2	0.75
22	0.5	0.18	0.75	0.5	0.18	0.75
23	0.35	0.09	0.5	0.35	0.09	0.5
24	0.2	0.03	0.3	0.2	0.03	0.3
*u.r.	0.46	0.20	0.64	0.46	0.20	0.64

Table 17 - Occupancy and internal gains for the restaurant function (source: EN16798-1)

5.5. Calculating the heat balances

The calculation of the thermal balance between energy gains and energy losses determines the amount of additional energy (in the form of heating or cooling) that is required at any point in time in the building. For the case of the MEGA Building, the manual calculations are done for a monthly interval in order to showcase the seasonal energy behavior in the building. The energy balances are also calculated on an hourly basis for a typical day during heating period (Jan 21st) and during cooling period (July 21st).

Following, the different parameters assumed in order to set up the heating balances are presented and explained, while all manual calculations are described in detail in Appendix 1

5.5.1. Internal heat gains

The internal heat gains are calculated according to Chapter 10 of **NEN7120.** The calculation is simplified as follows:

$$\Phi_{,int} = \Phi_{,int:oc} + \Phi_{,int:A} \qquad (5)$$

Where:

$\Phi_{,int}$ is the total internal heat gain in W

$\Phi_{,int:oc}$ is the total internal heat gain due to occupants in W

$\Phi_{,int:A}$ is the total internal heat gain due to appliances and equipment in W

The internal heat gain due to occupants is calculated as follows:

$$\Phi_{int:oc} = \sum_{usi}(q_{oc:usi} \cdot \tau_{usi} \cdot A_{g:usi}) \quad (6)$$

Where:

$\Phi_{,int:oc}$ is the total internal heat gain due to occupants in W

$q_{oc:usi}$ is the internal heat load due to occupants in W/m^2

$A_{g:usi}$ is the total surface of the examined thermal zone in m^2

τ_{usi} is the correction factor according to Table 10.1. page 124 of NEN7120

The internal heat gain due to appliances and equipment is calculated as follows:

$$\Phi_{int:oc} = \sum_{usi}(q_{oc:usi} \cdot A_{g:usi}) \qquad (7)$$

Where:

$\Phi_{,int:A}$ is the total internal heat gain due to appliances and equipment in W

$q_{A:usi}$ is the internal heat load due to appliances and equipment in W/m^2

$A_{g:usi}$ is the total surface of the examined thermal zone in m^2

The above parameters are chosen for the different functions as follows:

Function	q,oc (W/m^2)	q,A (W/m^2)	τ_{usi}
Housing	5	3	0.4
Hotel	3	2	0.4
Offices	5	4	0.3
Courthouse	5	4	0.3

Table 18 – Internal heat gains

5.5.2. External heat gains

The external heat gains due to solar radiation are calculated in a simplified way as follows:

$$\Phi_{,sol} = I_{,glob}\cdot A_{,sol} = I_{,glob}\cdot g_{,gl}\cdot A_{,wp} \qquad (8)$$

Where:

$\Phi_{,sol}$ is the total heat gain due to solar radiation in W

$I_{,glob}$ is the global radiation received by the building envelope in W/m^2

$g_{,gl}$ is the solar factor of the transparent parts on the building envelope

$A_{,wp}$ is the total area of the transparent part on the building envelope in m^2

The contribution of the shading system with blinds is conservatively neglected in the manual calculation but included in the building simulation.

5.5.3. Ventilation

The energy losses or gains through ventilation are calculated in a simplified manner as follows:

$$\Phi_{,vent} = (Q_{,vent} + Q_{,inf})\cdot \rho\cdot c\cdot (T_{,ext} - T_{,int}) \qquad (9)$$

Where:

$\Phi_{,vent}$ is the total heat loss/gain through ventilation in W

$Q_{,vent} + Q_{,inf}$ is the total air supply by ventilation or infiltration in m3/s

ρ is the density of indoor air 1.2 kg/m3

c is the thermal capacity of indoor air = 1 J/kg K

T_{ext}, T_{int} are the external and internal temperatures respectively in deg. Celsius

5.5.4. Transmission

The energy losses or gains through transmission of the building envelope are calculated in a simplified manner as follows:

$$\Phi_{,tr} = (A_{,gl}\cdot U_{,gl} + A_{,wall}\cdot U_{,wall})\cdot (T_{,ext} - T_{,int}) \qquad (10)$$

Where:

$\Phi_{,tr}$ is the total heat loss/gain through transmission in W

$A_{,gl}$,$A_{,wall}$ is the total surface of transparent and wall parts of the building envelope in m^2

$U_{,gl}$,$U_{,wall}$ is the thermal transmission coefficients of transparent and wall parts of the building envelope in m^2

T_{ext}, T_{int} are the external and internal temperatures respectively in deg. Celsius

The calculation of the profiles was performed as a first step using Excel, in order to produce the hourly and monthly energy demand profiles for every function. The detailed results and the calculation process are compiled and presented in Appendix 1.

5.6. Simulation and modelling

The first step of determining the energy demand for the MEGA building, was performed by means of manual calculations. In order to produce more detailed simulation and determine the energy behavior of the building for smaller intervals, such as days, hours and even sub-hourly, a simulation model was produced with the help of energy simulation software Design Builder.

All the input data and assumed parameters described in the previous sections were introduced in the model. The MEGA building was simulated as a combination of the 4 main functions. Every function was considered as a specific thermal zone, namely residential, office, hotel and courthouse. The span on different floors was modelled by means of a zone multiplier, as floors housing the same function were assumed to have the same characteristics. The function zones were connected together with adiabatic blocks, in order to position the floors realistically in 3D.

In order to calculate the heating and cooling demand, simple HVAC was assumed, and the calculations were performed based on no infiltration rates, and the minimum required ventilation according to comfort regulations. The setback temperatures were set to 18 ^{O}C for heating and 24 ^{O}C. The detailed input of parameters and simulation results from Design Builder are presented in Appendix 2.

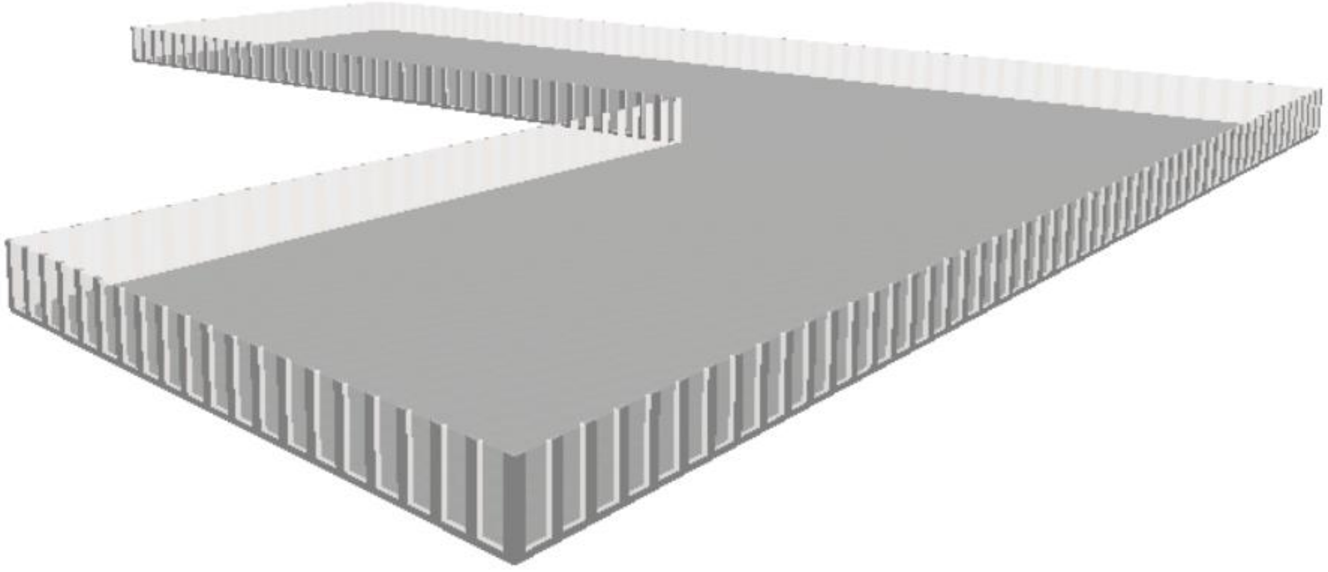


Figure 34 - Rendered aspect of a sample floor including the building envelope

5.7. Energy Demand Profiles

The results of the manual calculations and simulations are organized in graphs. The graphs are presenting the energy demand for heating and cooling for the different functions as well as the building in total, for different time steps of months, days and hours. It is important to showcase that from all the parameters that are calculated in the Design Builder model, zone heating and total cooling in Kilo Watts or Kilo Watts x hours are the relevant values that are used for the energy profiling.

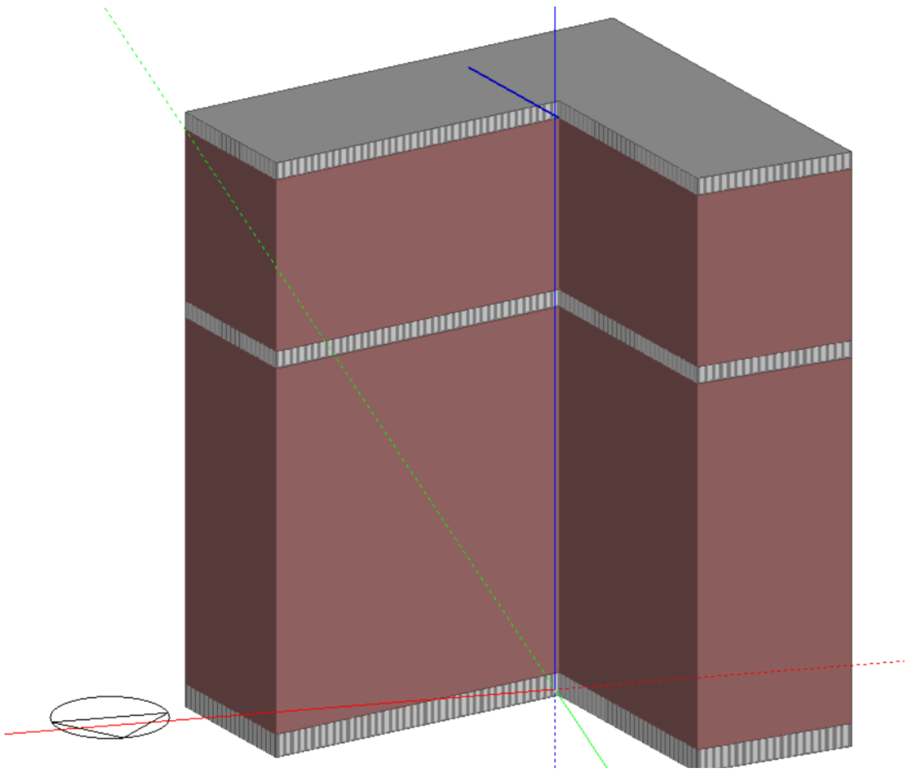


Figure 35 - Design Builder model of the main building functions

Below in figures 24 and 25, the monthly demand for the MEGA building in total are presented. It is evident that cooling is the dominant demand for the building during the whole year, while certain amount of heating energy is required during the winter months. The scale of results is similar, and it is evident that larger functions with large internal heat loads such as the courthouse, demand a large amount of energy for cooling almost throughout the whole year.

The detailed profiles of the simulations are presented in Appendix 2.

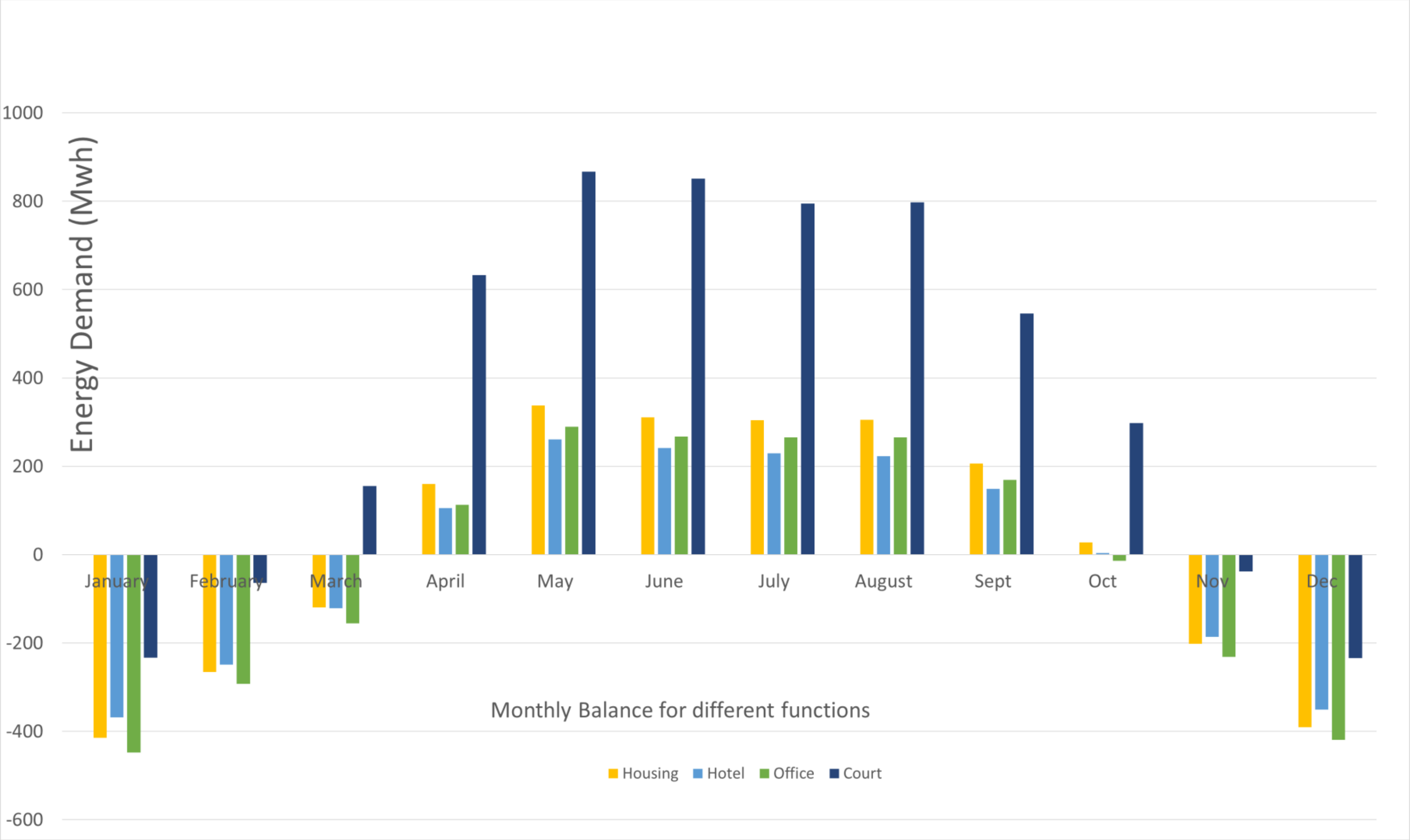


Figure 36 - Monthly energy demand for the whole building (manual calculation)

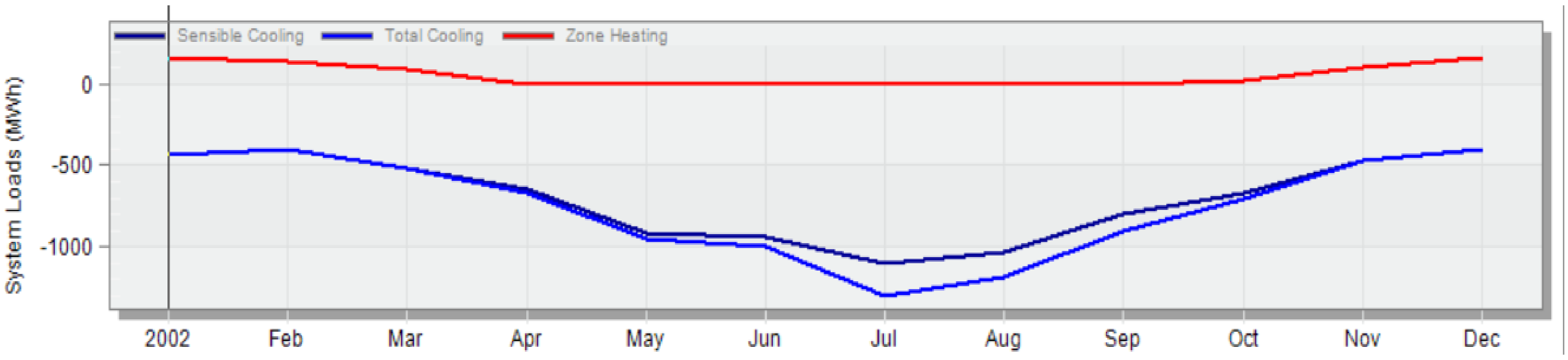


Figure 37 - Monthly energy demand profile for the whole building (DB simulation)

5.8. Building specific energy scatter for mixed functions

Since the MEGA building contains many different functions, it is difficult to determine the exact energy patterns within a specific amount of time. While office function has a rather normal schedule, hotel and housing functions are highly influenced by the behavior of their users. This results in an unusual scheme that also affects the energy demand during the day or even hourly.

It is not uncommon for a mixed-use building, that due to different functions operating simultaneously, both heating and cooling are required at the same time. This is a very important parameter, in order to determine the synergetic potential of the mixed-use scheme. As mentioned in chapter 2 and 3, the concept of thermal storage is based on the closed circle of heating or cooling one or several function and using the residual energy (warm water after cooling and cold water after heating) in order to charge the storage reservoirs. Therefore, it is important to know, how many hours or days within a year, simultaneous heating and cooling is required for the building.

The energy scatter diagram is used as a visual representation, in order to showcase the amount and distribution of simultaneous heating and cooling during the year, as well as the energy amount required. It is produced by assigned points with **X** and **Y** coordinates that correspond to the **total cooling demand** for that specific time step and **the zone heating** respectively.

The points that lie on the vertical and horizontal axis, represent the time steps where no simultaneous heating and cooling is required. These points also represent the maxima for energy capacities as usually the peak demands take place during the strictly cooling or heating season. The mixed-scheme points show a certain mid-range distribution that can be represented by the regression line of the scatter equation. Below, the scatter diagrams for the MEGA building are presented for daily and hourly intervals within the control year.

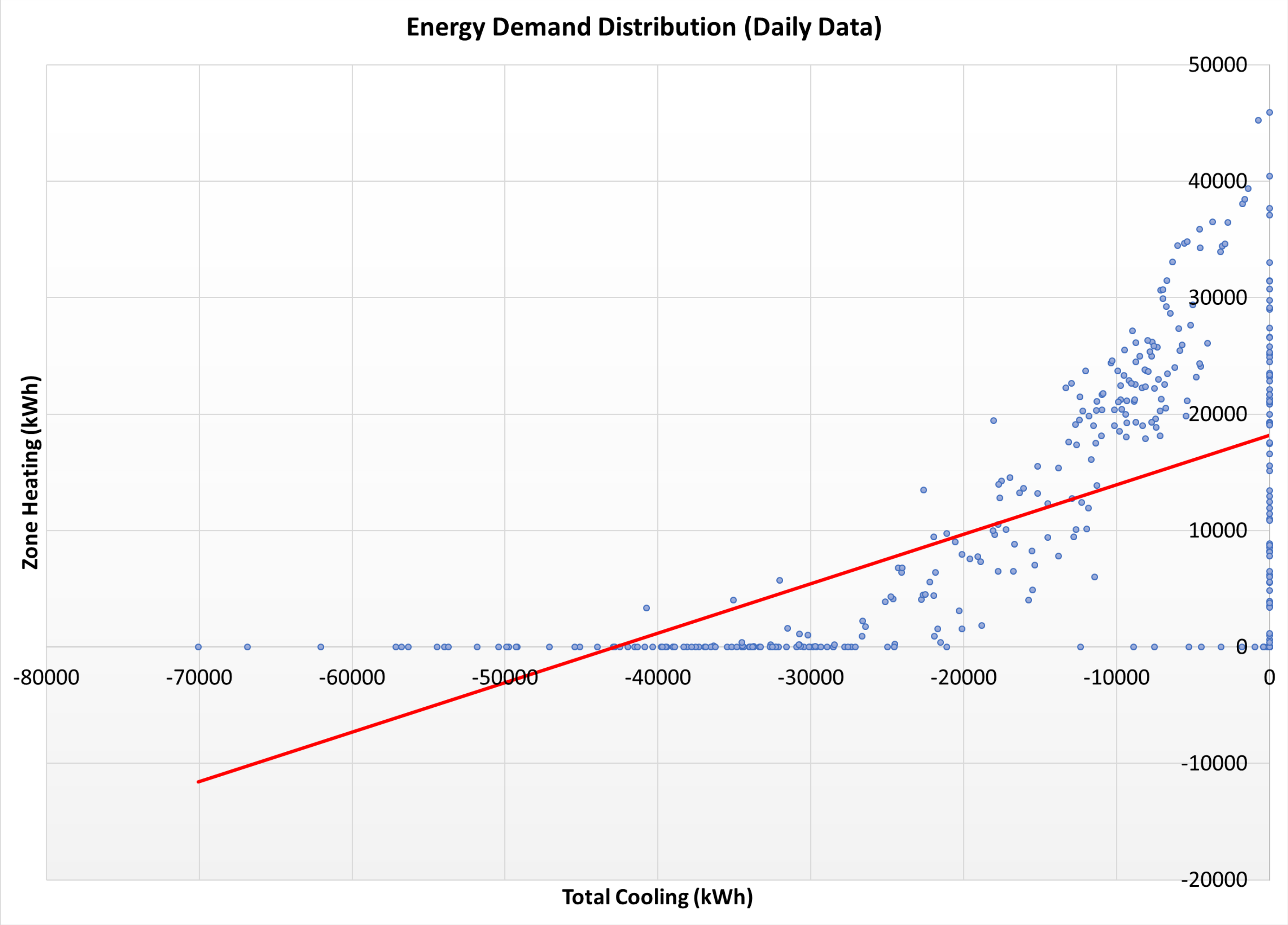


Figure 38 - Energy demand scatter for the MEGA building using daily intervals

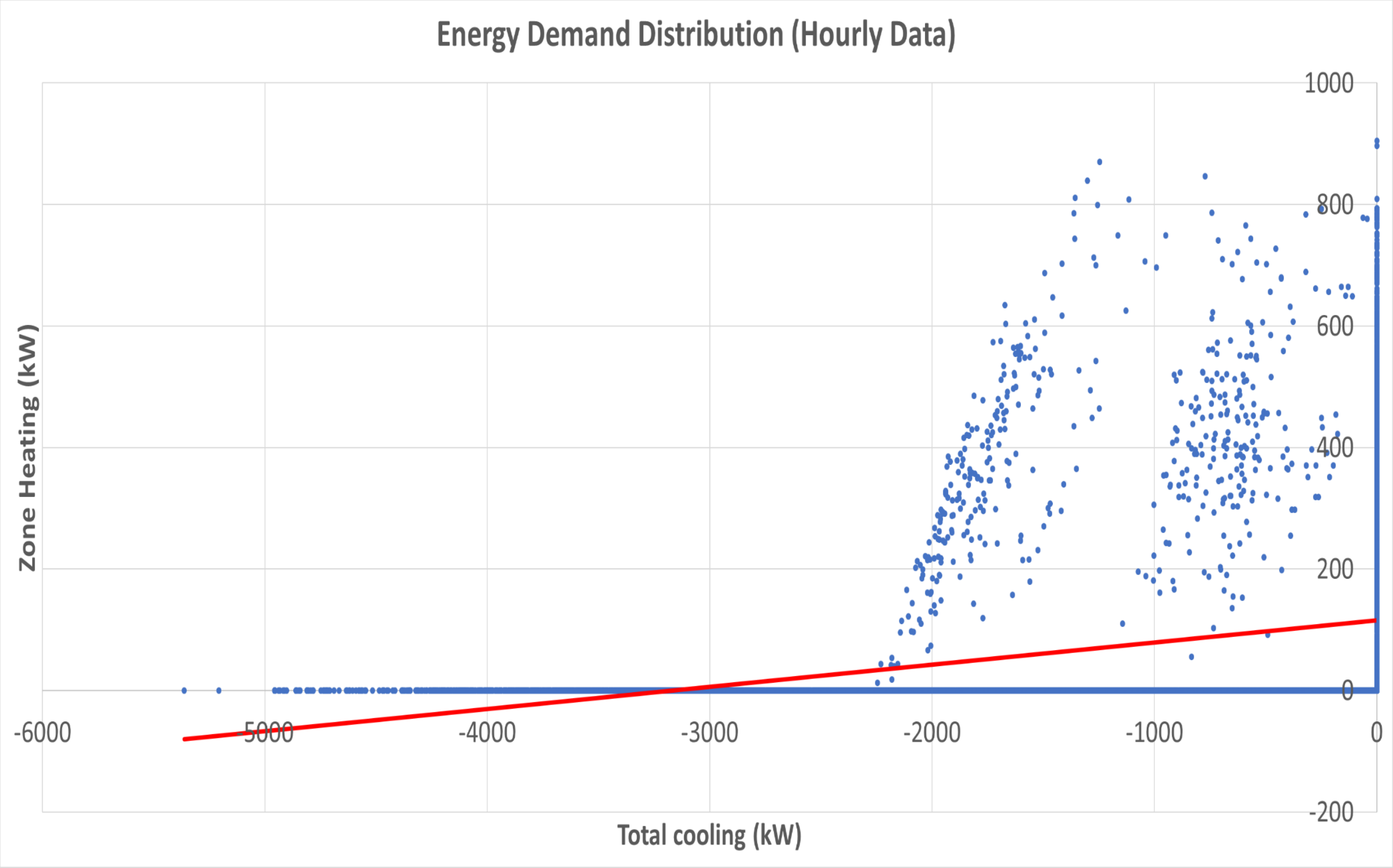


Figure 39- Energy demand distribution for the MEGA building using hourly intervals

In the next chapter, the energy demand scatter profiles, are analyzed further in order to determine the synergy potential of the building and the parameters that can be used for the design and sizing of the energy systems. In general, it can be said that the energy scatter profile is the "energy profile" of the mixed-use building. However, a similar profile is not limited to buildings only, but can be produced by a group of buildings or a district of buildings where different functions are present. What is important is always the size and distribution of peak demands during the year and the amount / distribution of the hours where simultaneous heating and cooling is required.

6. From function to installation

“Het Strijkijzer” – Den Haag

(source: hotsta.net)

6.1. Interpreting the energy demand scatter diagram

Buildings that accommodate many different functions, show a variable energy behavior during different time periods, but also different energy consumption patterns during one specific time period. As presented in Chapter 5, the different functions of the MEGA building, have different energy demand profiles during a specific day. The presence of office spaces and the courthouse create a larger demand for cooling, which is the dominant case for energy demand in the building.

The difference between the energy demand profiles for each function creates difficulty in the visualization of the overall building image. This problem was addressed in Chapter 5, by introducing the building specific energy demand scatter diagram. As mentioned before, the energy scatter diagram depicts the demand for total cooling and zone heating within the building, at any given set time step (month, day, hour, sub-hour) for one year. In this manner, the existence of functions becomes irrelevant. Different demand patters are translated into a single visualization that can showcase the energy behavior of the building.

The diagram consists of scatter points with **X** and **Y** coordinates that represent the **total cooling** demand and **zone heating** demand respectively for each specific time step.

The interpretation of the diagram is based on recognizing the most important information that can provided. The information is explained based on the main interpretation points of the diagram that are:

1. **Peak demands for heating and cooling**

   The peak demands for either heating and cooling, are representing by the maximum value points on the diagram that are located on the X axis for cooling and Y axis for heating. That means that during those time steps no simultaneous heating and cooling is required.

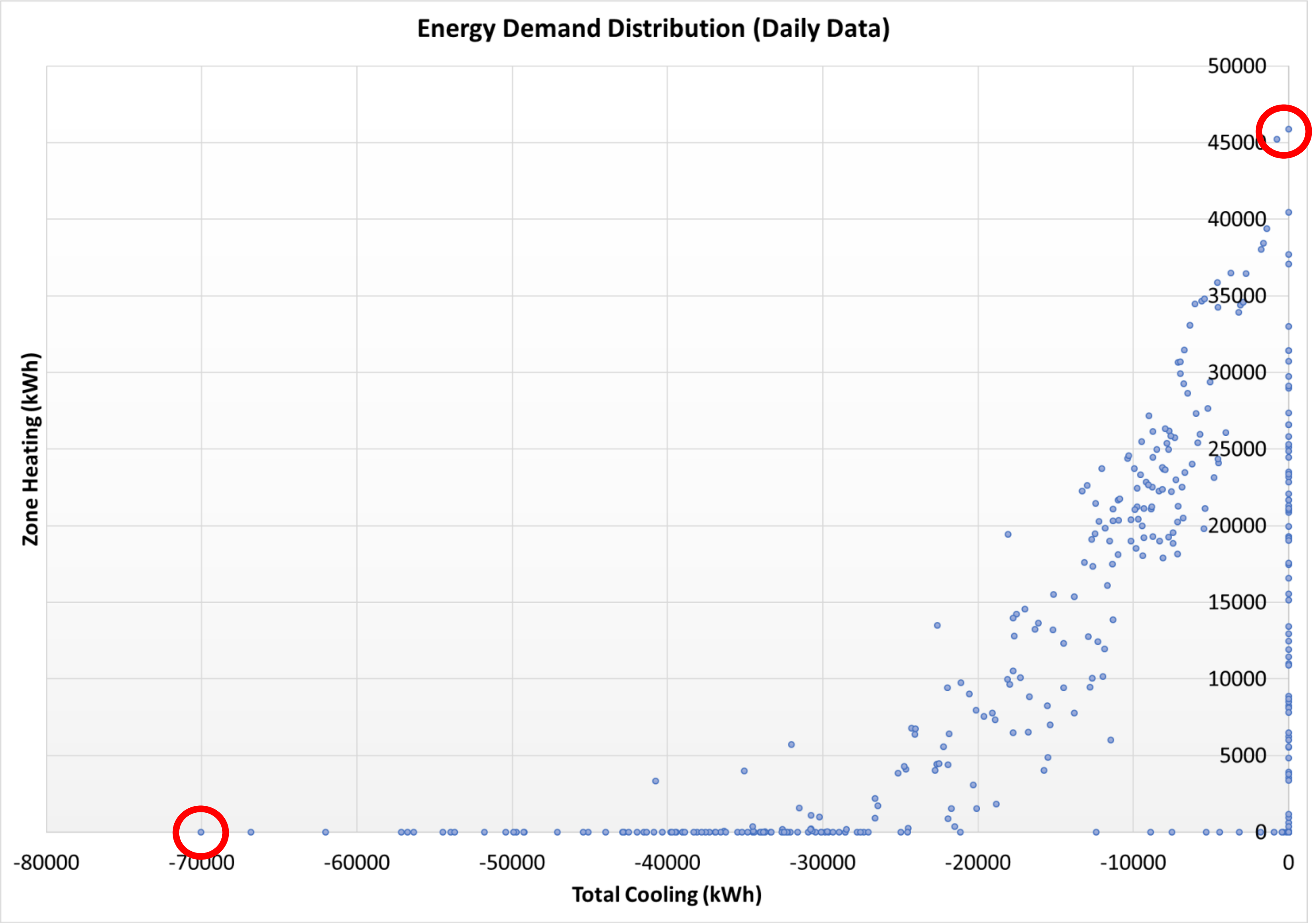


Figure 40 – Peak demands for heating and cooling (highlighted in red) as represented in a energy demand scatter diagram

2. **Simultaneous heating and cooling requirement**

   The points that are located outside of the axes are the points that present a (X,Y) value different than zero. These points represent the time steps during the year that simultaneous heating and cooling is required. Simultaneous heating and cooling demand usually create problems for buildings, and thus the locations and distribution of these “dual” points actually show that a synergetic energy concept is feasible for this building or set of buildings.

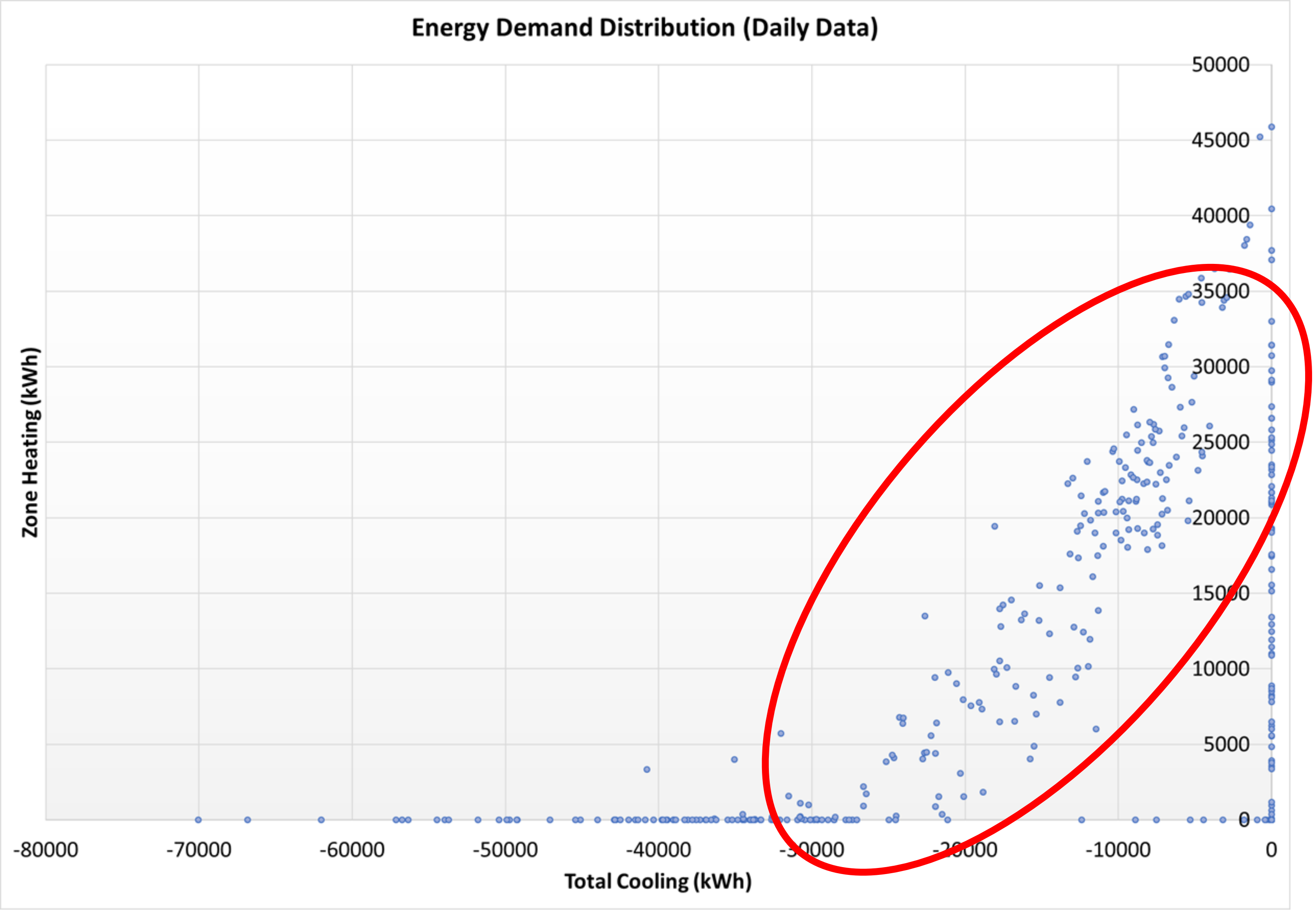


Figure 41 – Cloud of time steps when simultaneous heating and cooling is required.

3. Balanced / Unbalanced heating and cooling requirement

As presented in the previous chapters, accommodating different functions within the same building can greatly influence the energy demand profile. Normally, functions with high human occupancy and use of equipment such as offices, present a larger demand for cooling. Housing functions usually remain unoccupied during morning hours and are mainly used during evening hours when outdoor temperatures are considerably lower. This result in a larger demand for heating energy. In general, there is no absolute rule when designing heating and cooling installations for mixed-use buildings, however a requirement for simultaneous heating and cooling is considered unfavorable, when conventional HVAC installations are used. A requirement for simultaneous heating and cooling would require the existence of separate systems, that would usually be used for a less than optimal amount of time.

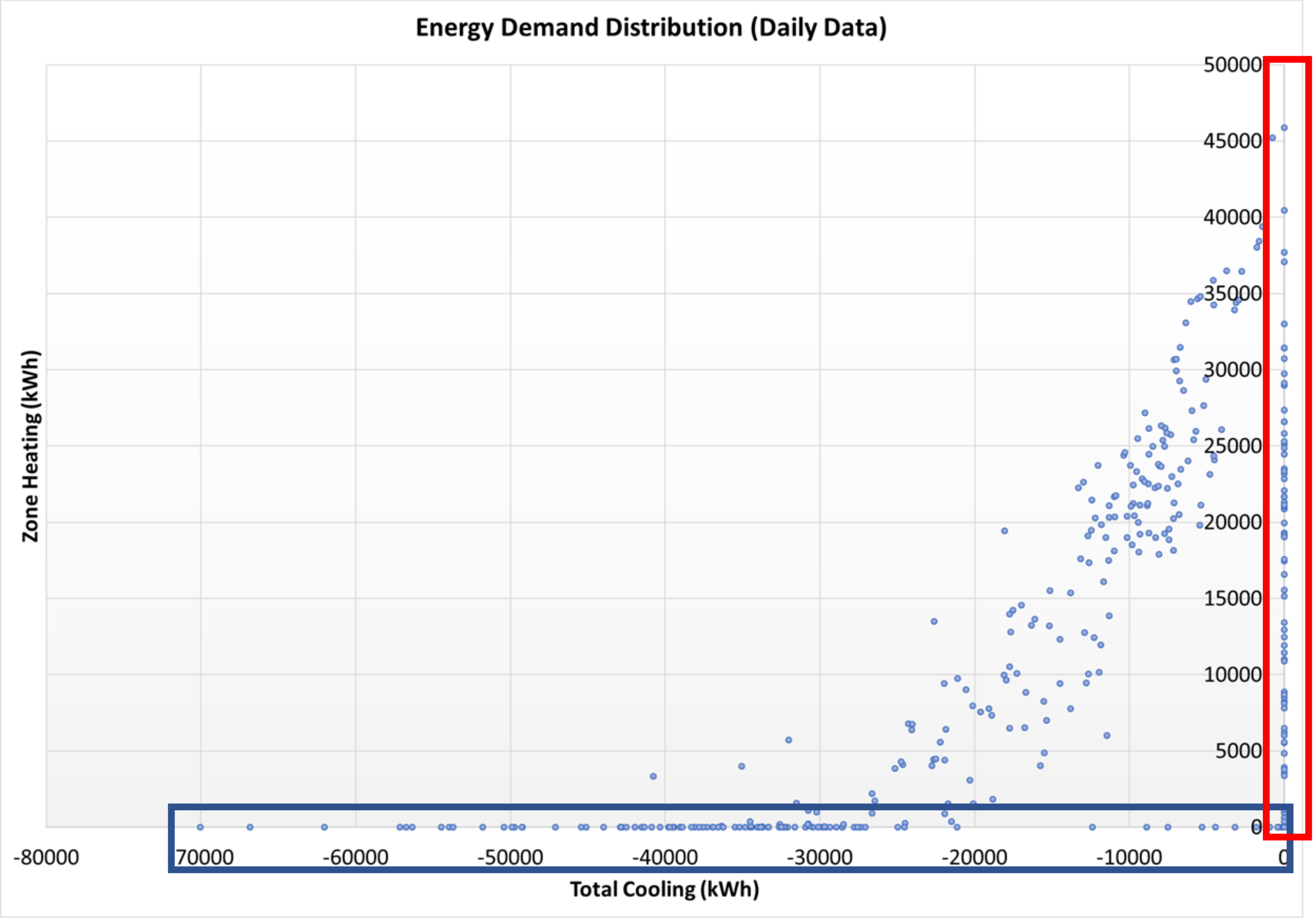


Figure 42 – Example of an unbalanced energy demand scatter as calculated for the case study of the MEGA building.

In a synergetic concept, the energy used for heating the building is based on energy exchange and storage. If water circulation within the building is combined with water storage tanks, the cold water that would result after heating the building can be easily stored and used for cooling at a later stage. The synergetic concept that is used for the MEGA building is explained in detail in Chapter 7. According to this concept, the use of water storage tanks can enable the circulation of hot and cold water within the building at any given time. The use of heating energy is translated into storing cooling energy and vice versa. As a result, it is more favorable that a synergetic building is designed to have a balanced requirement of heating and cooling, regarding the peak demand.

6.2. Sensitivity analysis

6.2.1. The effects of comfort requirements

The quality of indoor living and working spaces is directly affected by the comfort level within the examined space. The different comfort requirements include acceptable temperature, air quality and illuminance levels according to the specific function for every space. While building characteristics such as material choice, level of insulation and orientation of openings and shading play a major role in the energy performance, comfort levels are also very important.

As mentioned in Chapter 5, the choice of comfort levels is that parameter that will determine the operational and setback temperatures during heating and cooling of the building as well as the rate of ventilation. The combination of these parameters results in creating the quantitative “energy identity” of the building, namely being the energy demand profiles for heating and cooling during a predefined time period.

There is extensive research and literature over the optimal comfort parameters for spaces with a specific function, most commonly office and housing. However, in the case of the MEGA building, the accommodation of different functions within the same building and under the same envelope characteristics creates a more complex situation.

The chosen comfort strategy for the mixed-use MEGA building, is to create a uniform comfortable environment for all different functions. The temperature range for heating and cooling was chosen to accommodate for both office and housing spaces, while comfort levels for the hotel and courthouse functions are very similar and can be accommodated as well within the acceptable limits. The option in order to differentiate the needs of specific functions, was to enable different levels of ventilation. In this case, while the heating and cooling temperatures would be the same for every function, the ventilation levels can be adapted to each function in order to support and improve the function-specific comfort requirements.

In the concept of a synergetic building system, it is important to investigate how the total energy demand is affected by fluctuations in the comfort levels. Based on what mentioned before, in order to create a balanced energy demand, it is useful to assume different levels of comfort. This sensitivity analysis can be summarized as follows in table 9.

Function	**Heating Setpoint (^{o} C)**	**Heating Setback (^{o} C)**	**Cooling Setpoint (^{o} C)**	**Cooling Setback (^{o} C)**
Housing	20	18	25	29
Hotel	20	18	25	29
Office	20	18	25	29
Courthouse	20	18	25	29

Table 19 – Case 1 of comfort sensitivity analysis.

It is noticeable that by allowing wider limits for the heating related functions, the already dominated by cooling demand MEGA building presents a higher demand for heating, and a more balanced energy demand profile, as shown in Figure 31.

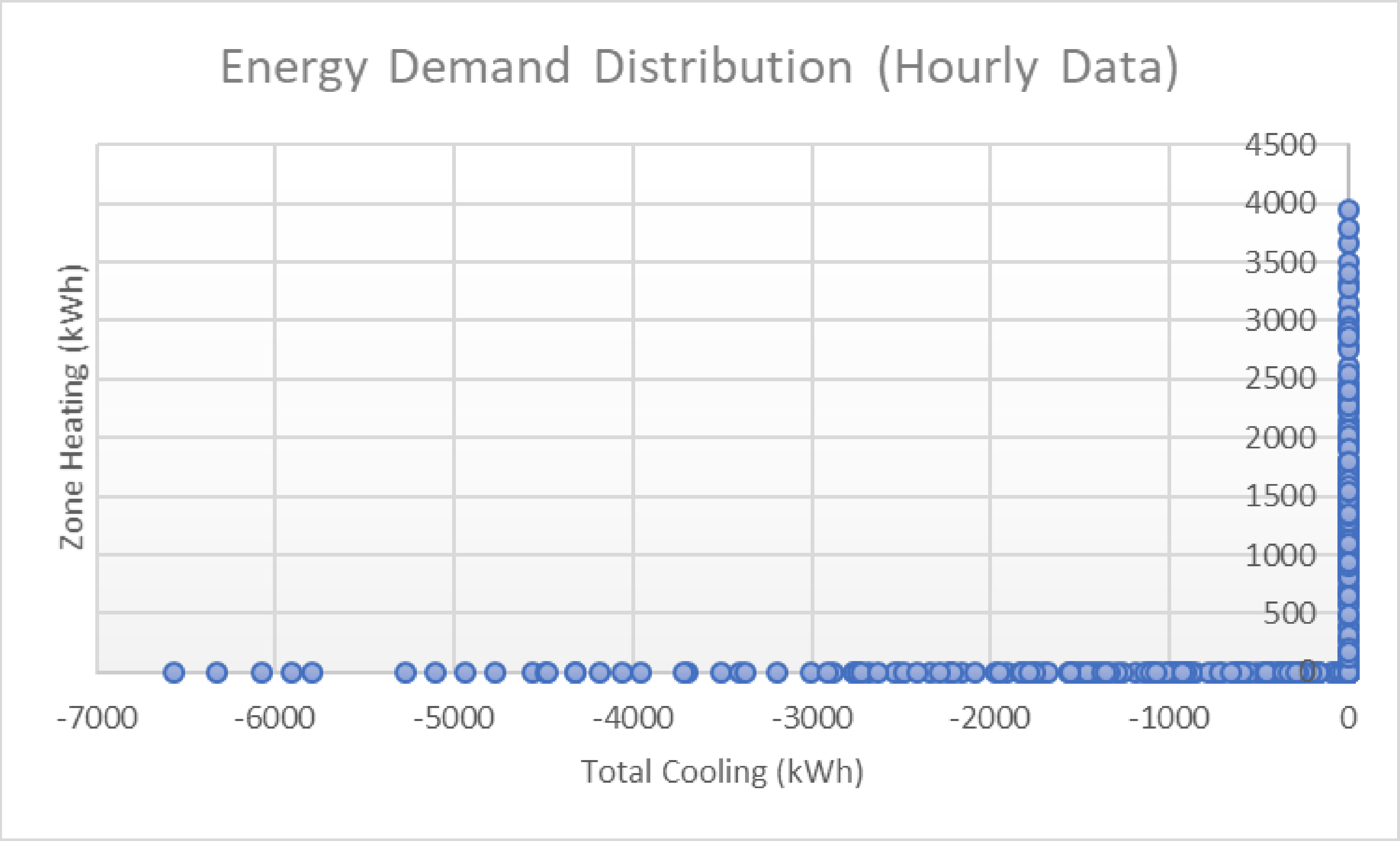


Figure 43 – Energy demand scatter of comfort sensitivity analysis

6.2.2. The effects of Domestic Hot Water requirements

The energy mapping of a modern building is a complex process. State-of-the art high-rise buildings usually consist of complex building service systems. Depending on the functions accommodated, additional requirements arise, for example high performance lighting and ventilation for a hospital or constant water supply for commercial or recreational areas.

In the case of the MEGA building, the existence of the Hotel and residential functions, create the requirement for domestic hot water supply. While the Office and Court functions have a smaller demand, the large gross floor area of domestic functions have a considerable effect on the heating demand of the building.

It is assumed in this point that the supply of DHW is also included in the synergetic storage and exchange system. DHW is supplied with the help of an electricity fueled boiler. The water is supplied with an average temperature of 60 **º C,** whereas municipal water supply is assumed to have an average temperature of 10 º C. The boiler is assumed to supply DHW with a performance coefficient $COP,_{DHW}$ = 0.9.

The demand is included in the thermal balance model in Design Builder, for standard comfort requirements and wider comfort margins, as described in the previous unit. As shown below in Figure 32, the addition of DHW demand highly increases the peak demand for heating energy. DHW use is always dependent on the different occupancy and water consumption pattern for its functions but contributes to a more realistic overview of the energy demand for the MEGA building. It is also evident that the consideration of DHW, creates once again the demand for simultaneous heating and cooling energy, although on a smaller scale and frequency.

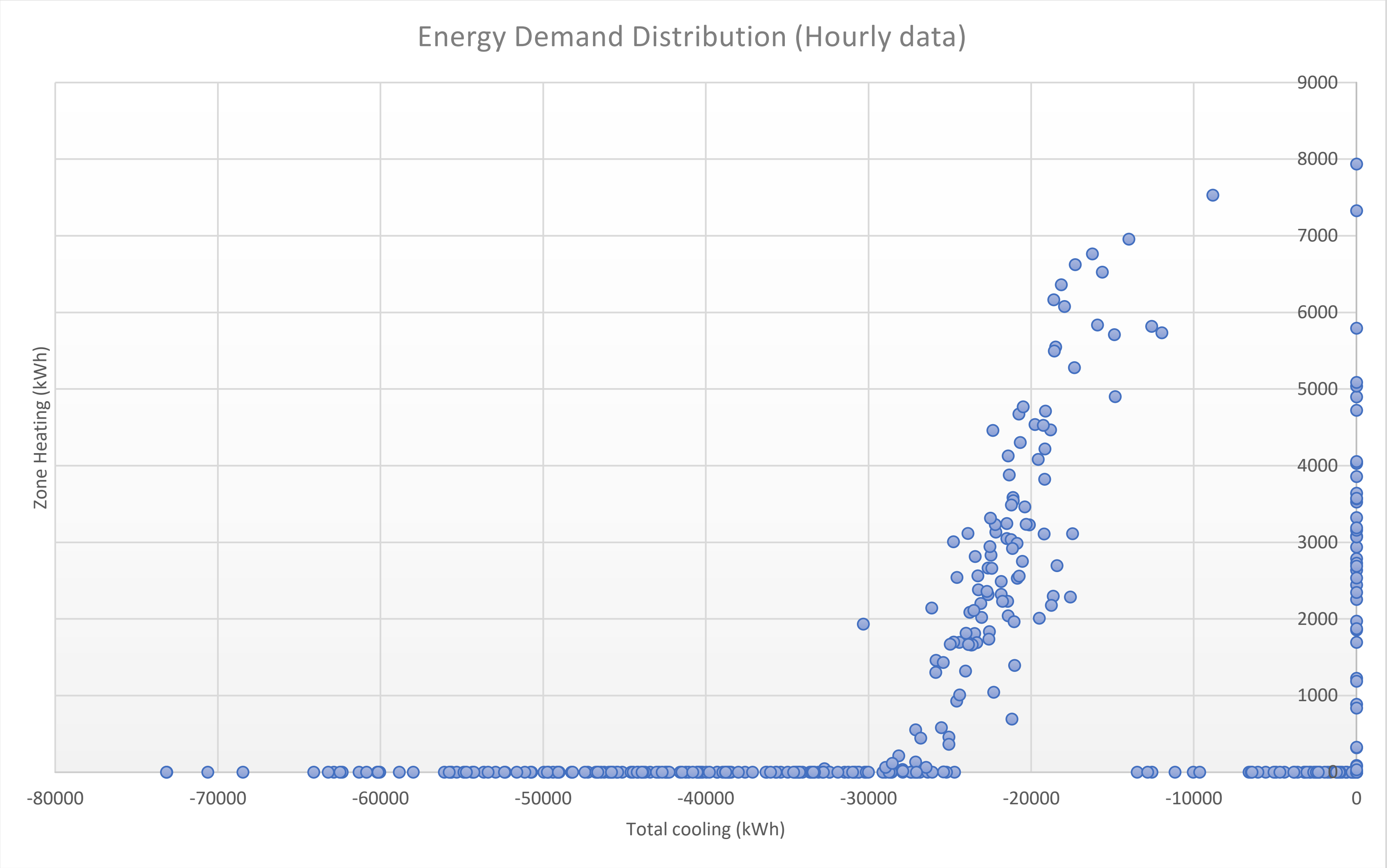


Figure 44 – Energy demand distribution including DHW

6.3. Investigation of additional cases for energy scatter profiles

As shown in the previous part, the profile of the energy demand for the building on a daily or hourly basis, is important in order to translate the building characteristics into a scalable installation system. The influence of different variables such as comfort limits and the requirements for additional energy such as emergency functions or domestic hot water supply, is considerable. This implies that data based only on the conceptual MEGA building are not sufficient to determine and explain the potential for energy synergy within a building and the possible energy savings.

The concept of synergy is not limited only within the context of a single building. The basis of simultaneous heating and cooling demand can be created also by a group of buildings or small community. Thus, synergetic patterns can be created within the context of different buildings, on the terms that different functions are accommodated. The existence of different functions is the basis for creating a balanced energy demand in order for a storage and exchange concept to be viable.

It is important therefore, that the basis of data for the calculation of different types of energy demands, is expanded in order to examine perfectly balanced cases, or completely cases dominated from heating and cooling, in order to incorporate extremes into the data pool. For this reason, additional conceptual models are created, based on the fundamental functions of a mixed-use building, being the Residential and Office functions. The functions are considered to be the most explicit in terms of energy demand, with housing usually having a larger demand for heating, while office spaces tend to have a larger demand for cooling within a specific year.

Based on that concept, the 55 floors of the MEGA building are adapted to reproduce different cases of reference buildings, that have a different ratio of mixed-uses, from 0%, being a heating dominated building, to 100% being the conceptual MEGA building. Several intermediate iterations are created, with 50% being a balanced energy demand profile, with approximately the same amount of energy required for heating and cooling within the same year.

The effect of time steps during a year that simultaneous heating and cooling is required is also an important parameter, however difficult to reproduce due to the random nature of cloud points, within the energy demand scatter. The case of simultaneous heating and cooling is also largely dependent on outdoor conditions, with seasonal variations or extremes also being responsible for the appearance of dual energy demand within the year.

On the following pages, the different cases of conceptual buildings, are presented along with the produced energy demand scatter diagrams, for daily and hourly time steps, with the aid of Design Builder. These cases serve as the input for the MATLAB/Simulink model that is explained in Chapter 7, in order to calculate the potential energy savings and favorable ranges of storage capacity and distribution power.

6.3.1.Case 1 - 100% Residential function

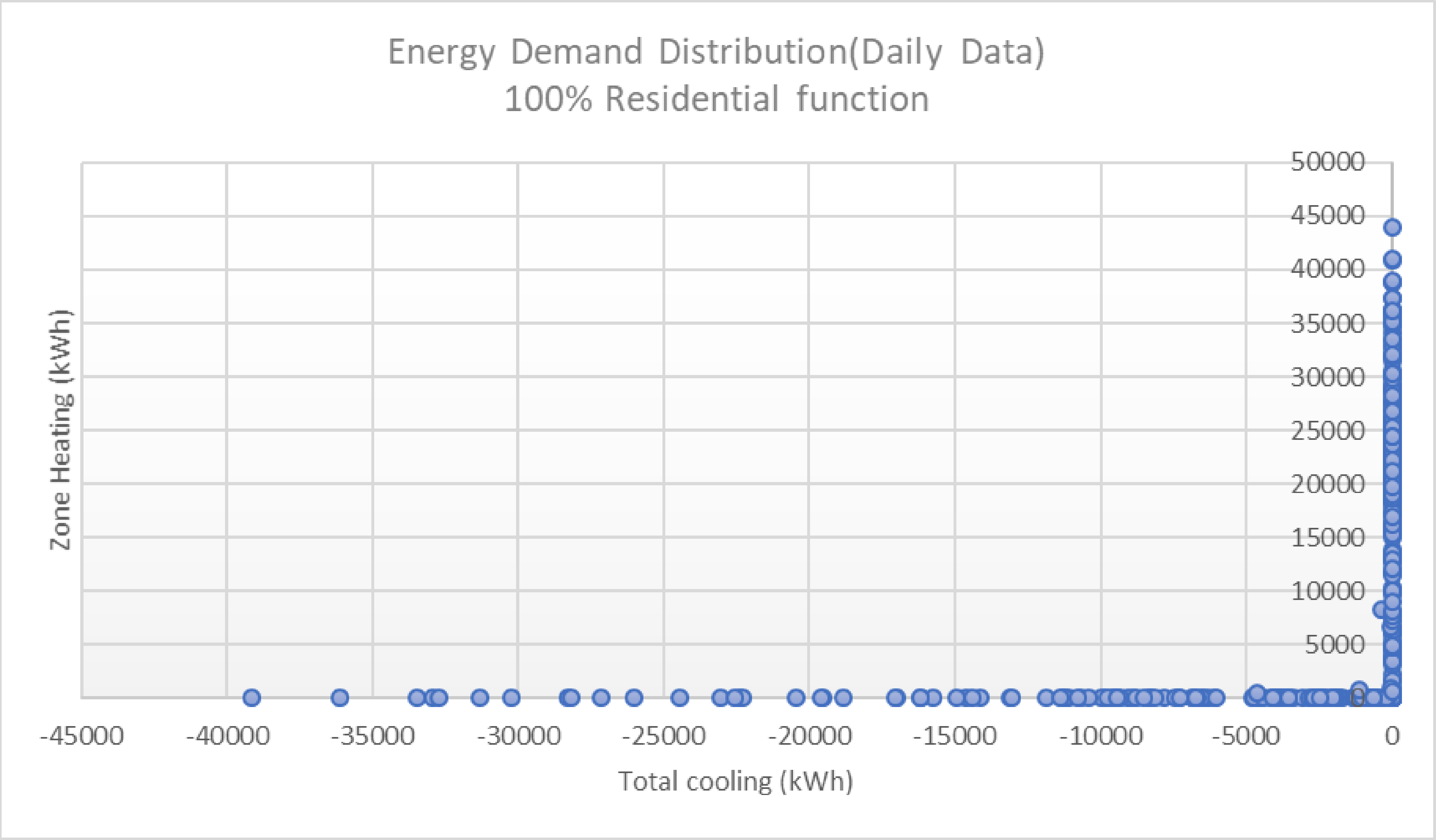


Figure 45 – Daily energy demand distribution for 100% Residential Function

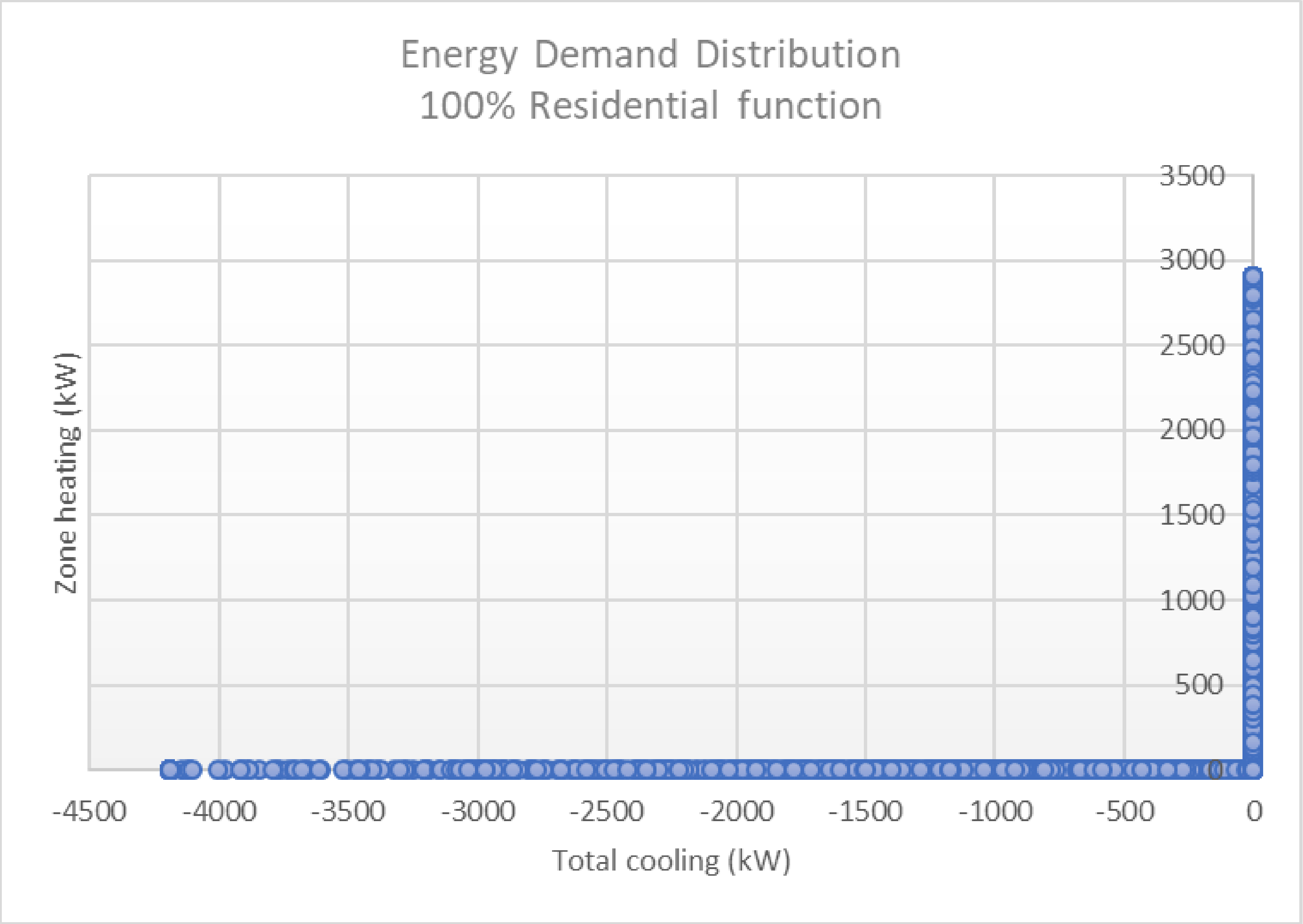


Figure 46 – Hourly energy demand distribution for 100% Residential Function

6.3.2. Case 2 - 25% Residential function + 75% Offices function

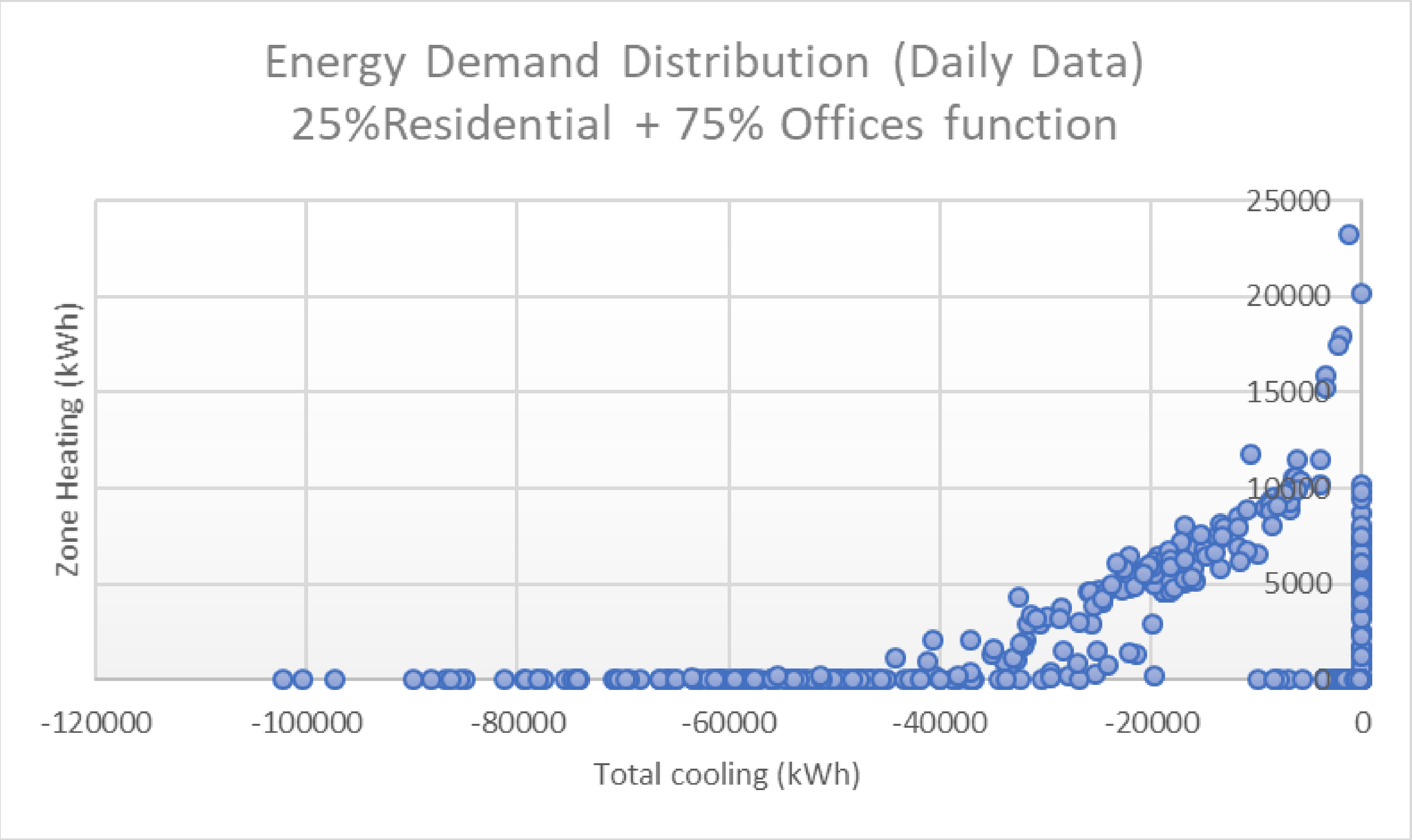


Figure 47 – Daily energy demand for Case 2 of additional building cases

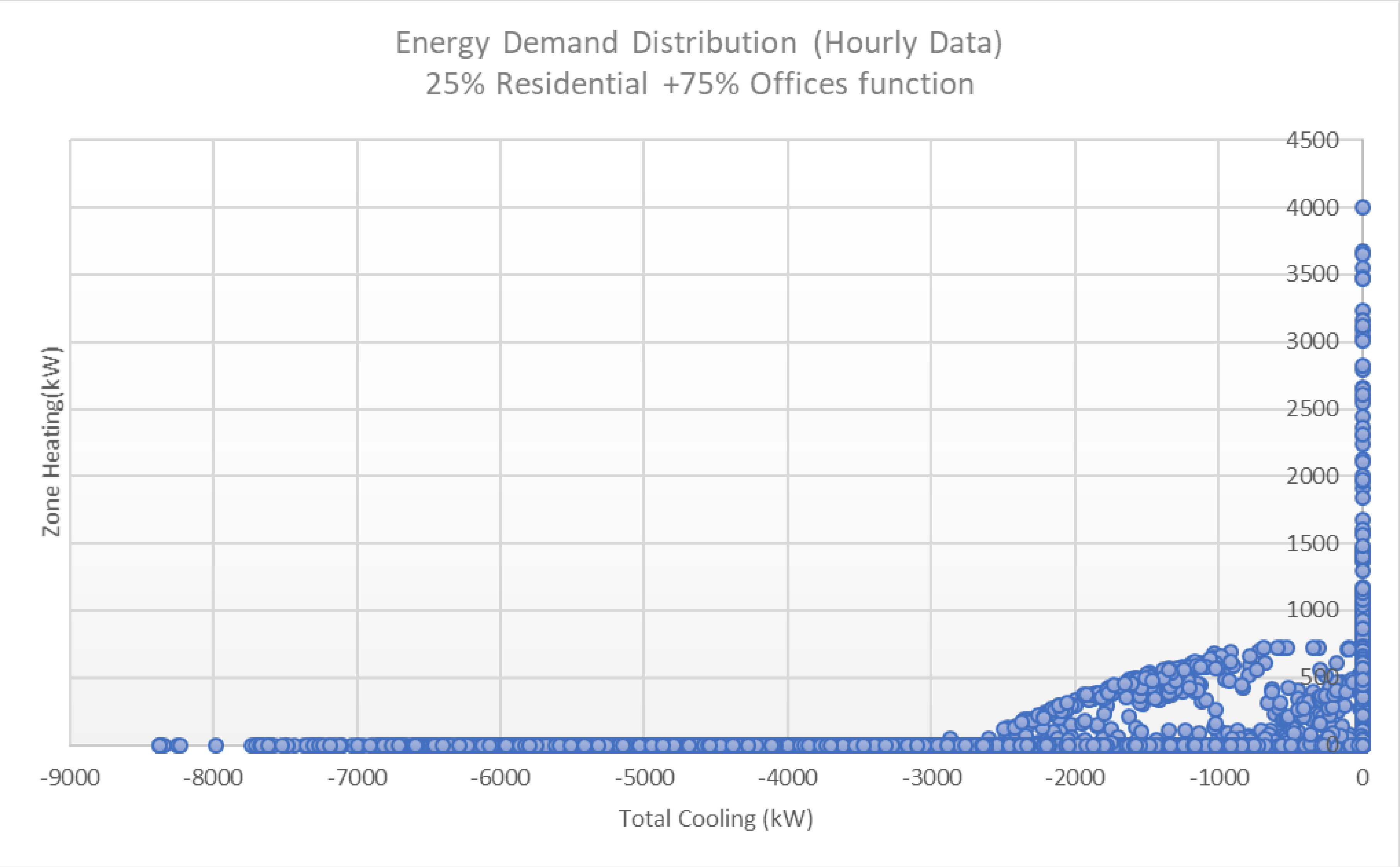


Figure 48 - Hourly energy demand for Case 2 of additional building cases

6.3.3. Case 3 - 50% Residential function + 50% Offices function

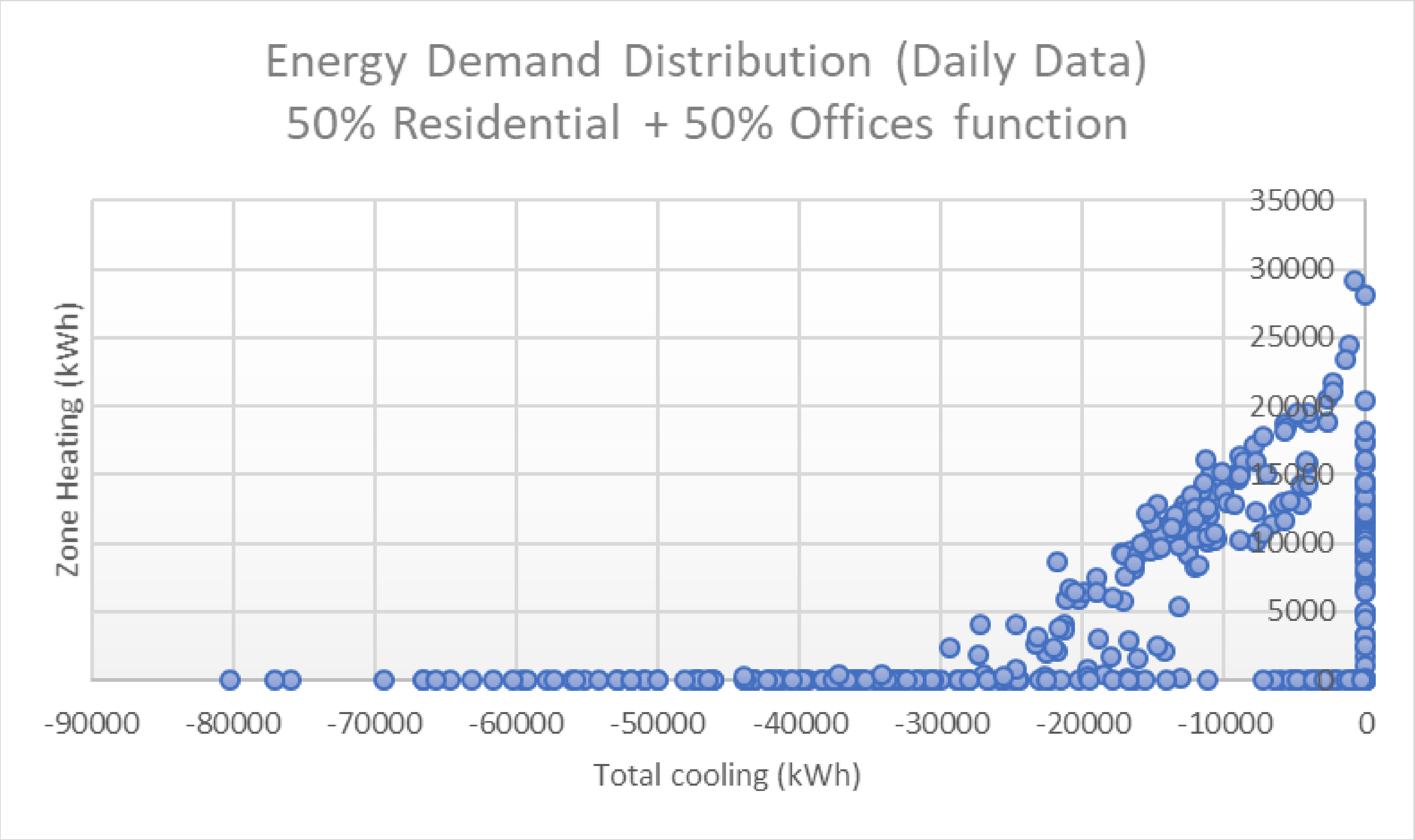


Figure 49 - Daily energy demand for Case 3 of additional building cases

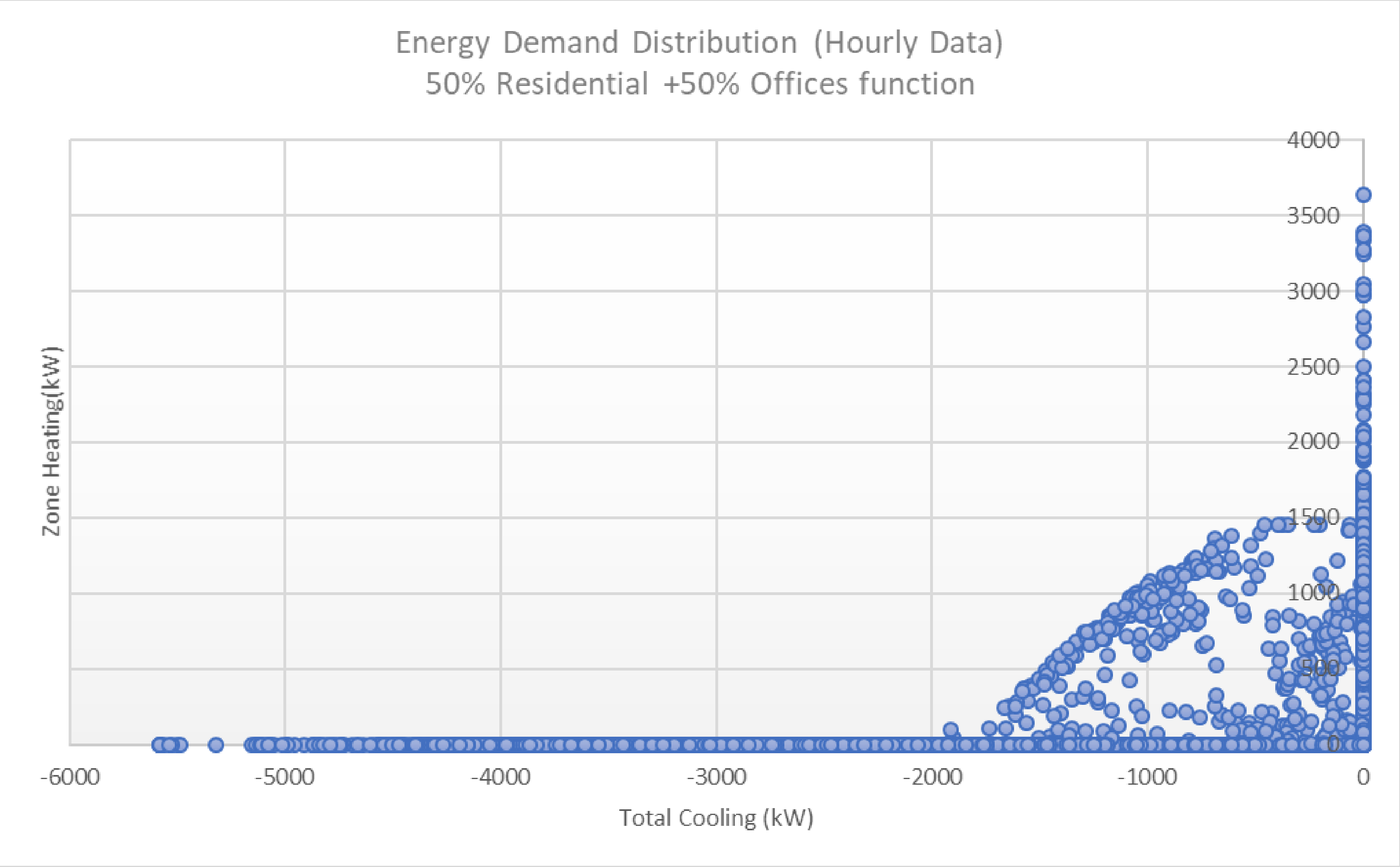


Figure 50 - Hourly energy demand for Case 3 of additional building cases

6.3.4. Case 4 - 75% Residential function + 25% Offices function

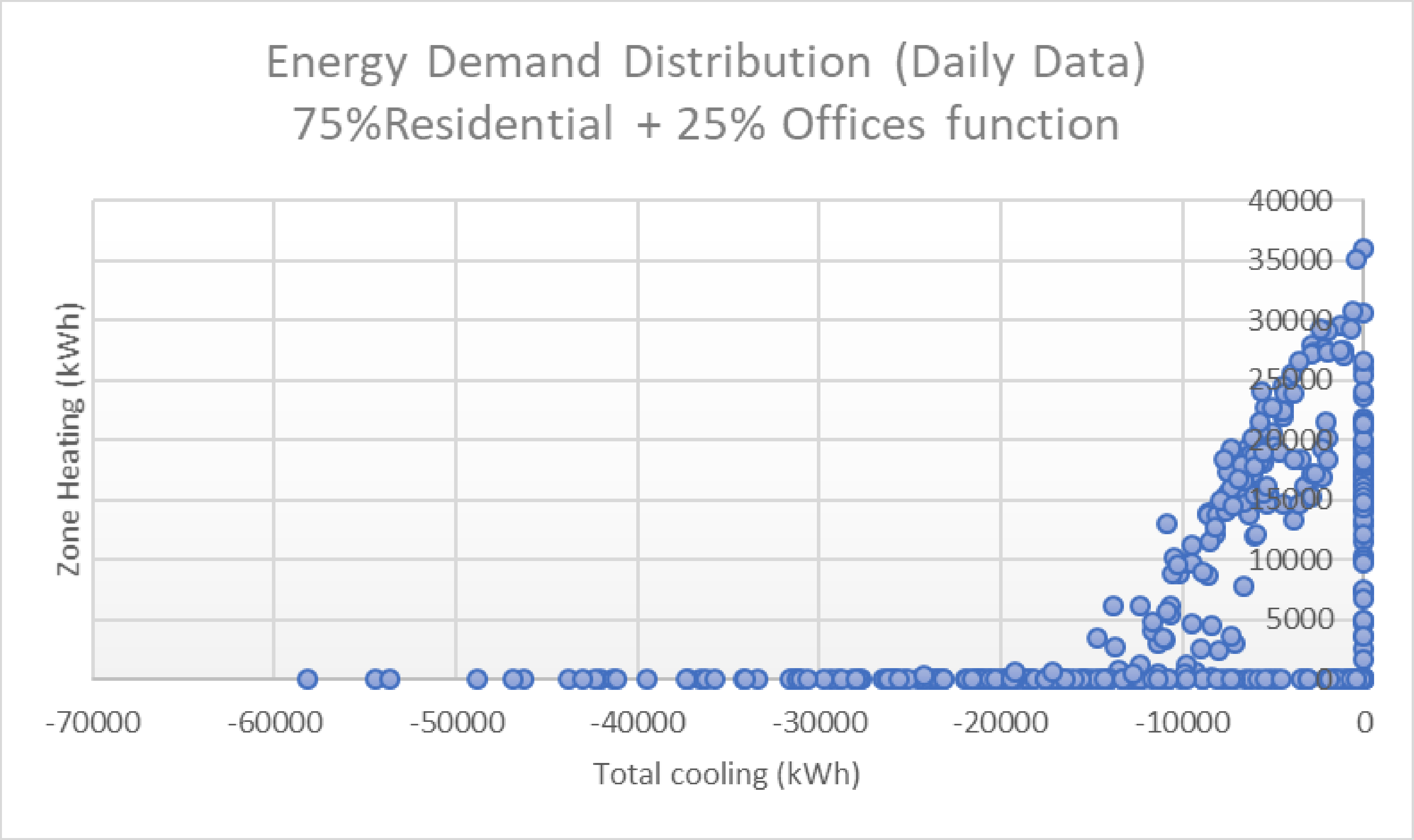


Figure 51 - Daily energy demand for Case 4 of additional building cases

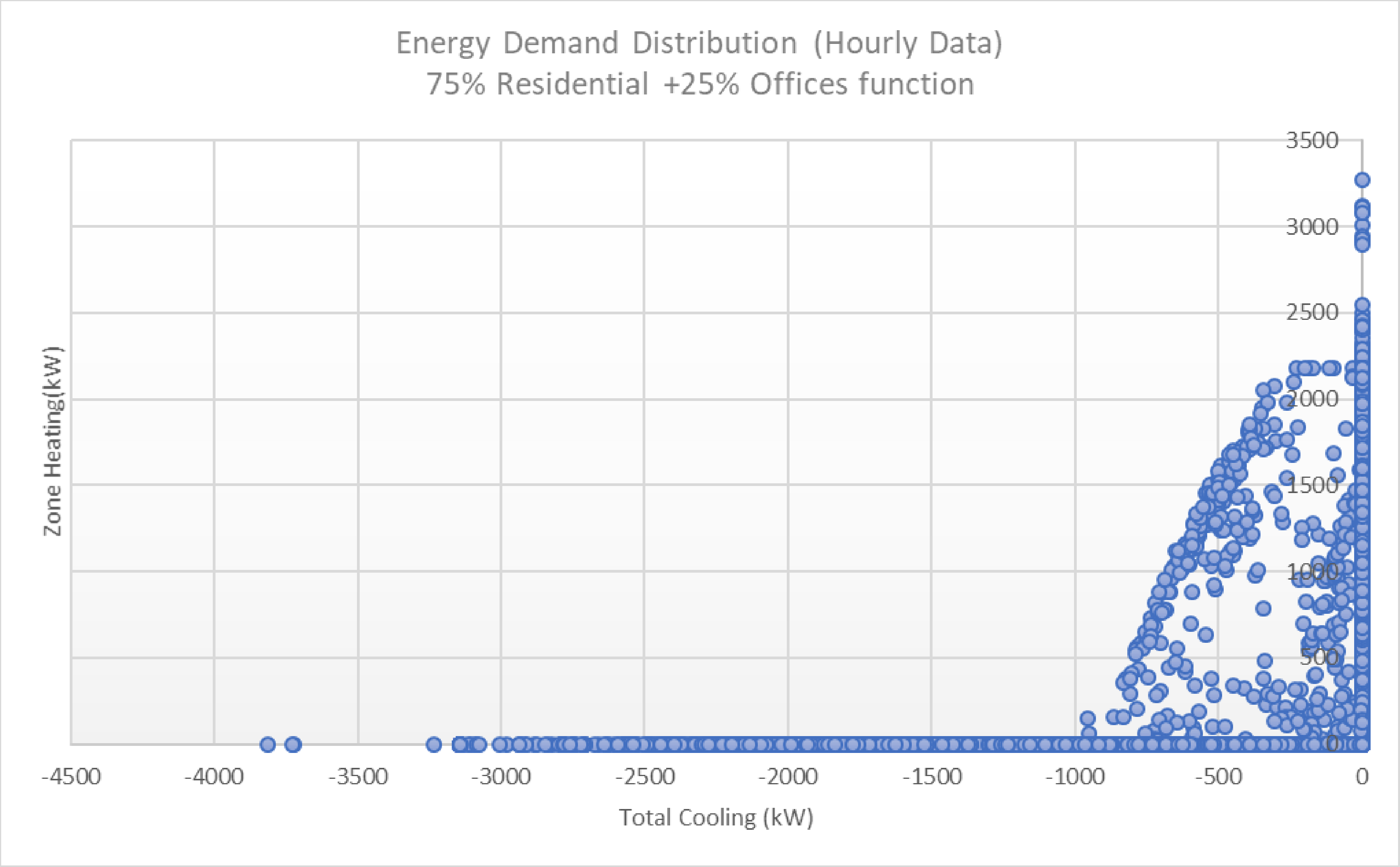


Figure 52 - Hourly energy demand for Case 4 of additional building cases

6.3.5. Case 5 - 100% Offices function

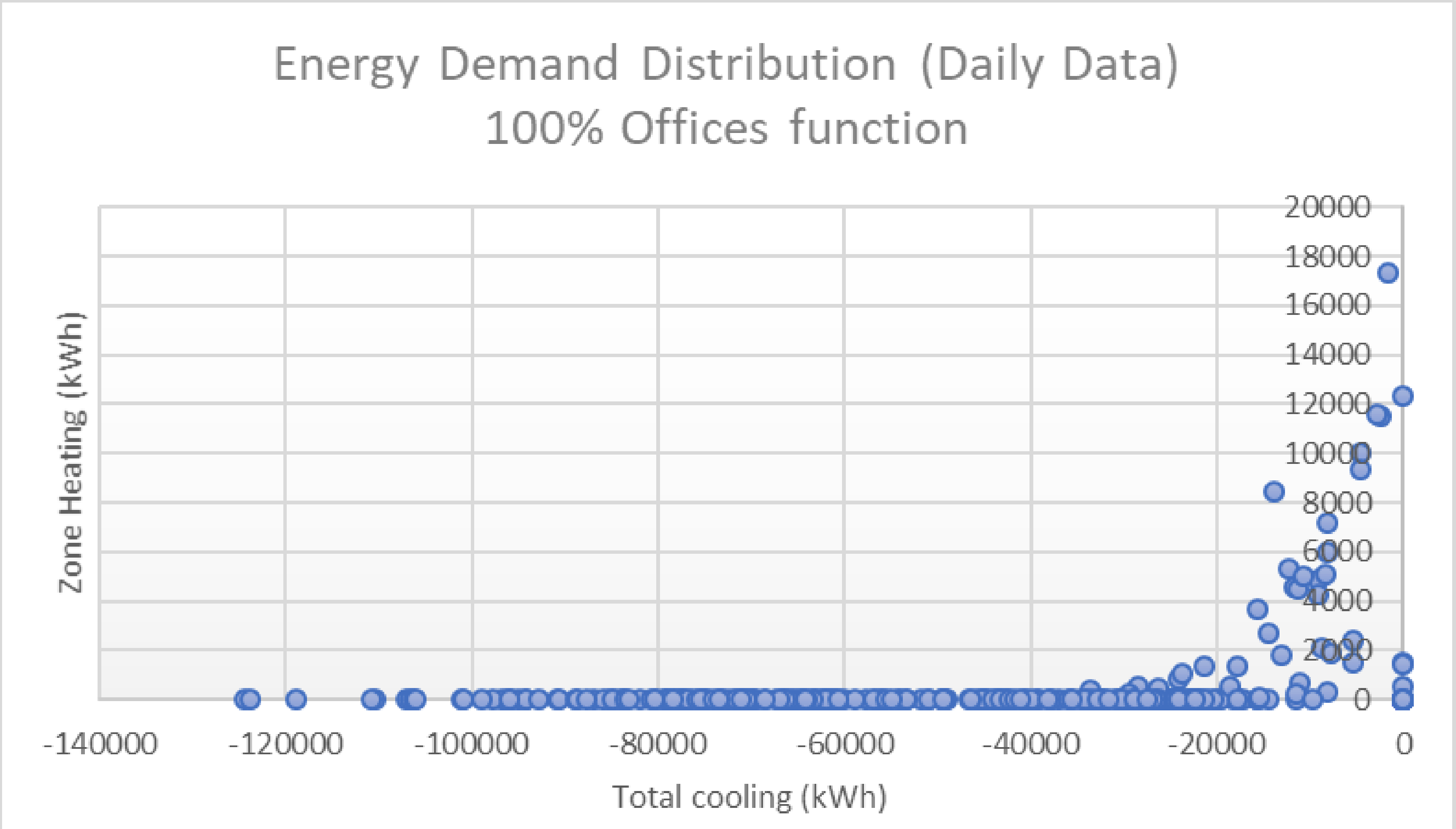


Figure 53 - Daily energy demand for Case 5 of additional building cases

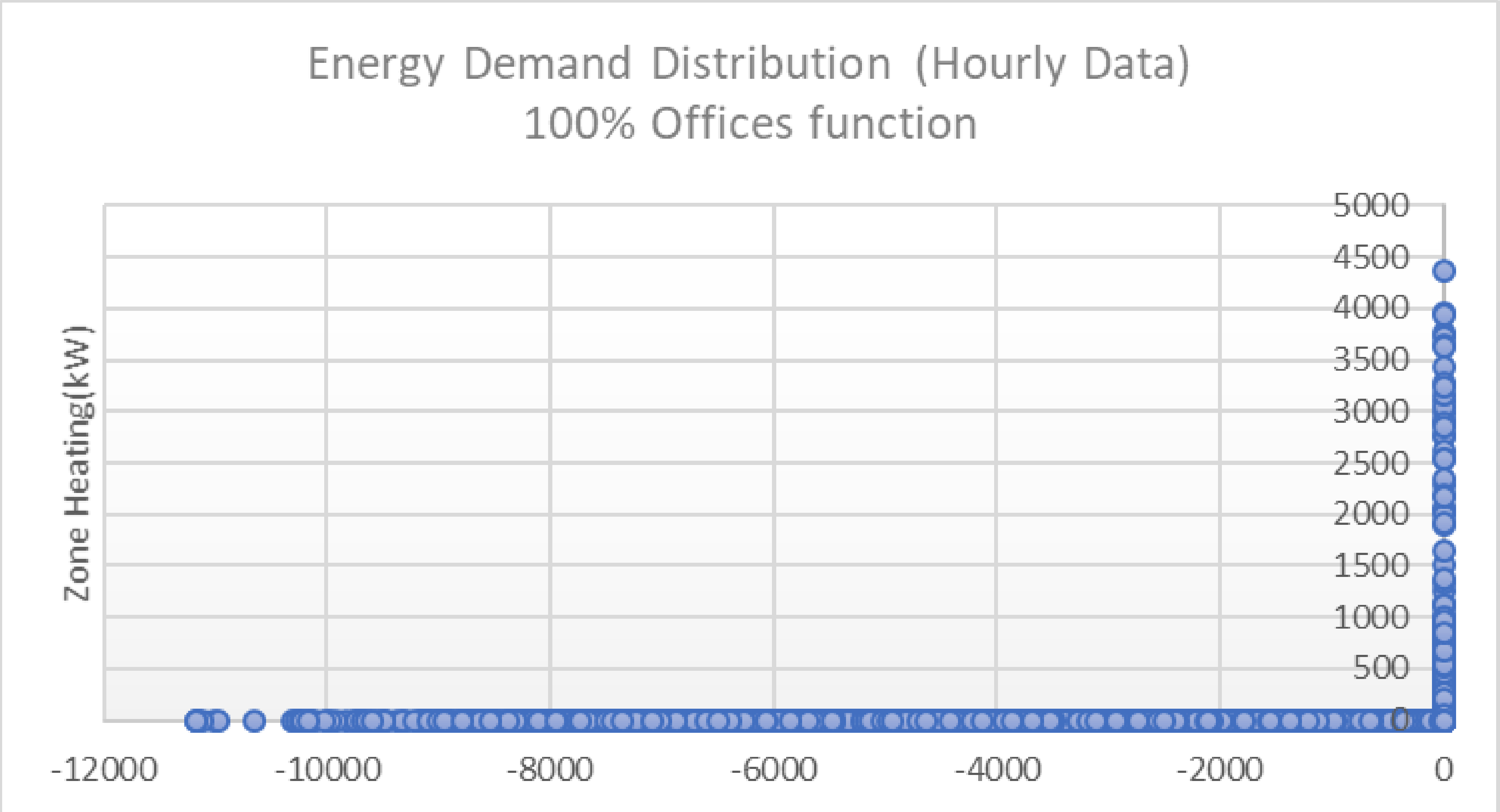


Figure 54 - Hourly energy demand for Case 5 of additional building cases

7. Synergetic Installation concept

“Leyweg 813” – Den Haag

(source: Unsplash Photography)

7.1. Introduction

Modern comfort requirements as regulated in different standards around the world, render the design of energy systems for buildings a very complex task. The variety of HVAC systems available commercially, can accommodate for the different needs of designers and custom-made arrangements can de designed to satisfy unusual building concepts.

In general, the main components that regulates the climate of the building is its early design parameters. As also shown in Chapter 4, building orientation and shape are the first parameters that affect the solar gain and wind effects around the building. At a second level, envelope characteristics, proper insulation and shading regulate the thermal exchange between the building and the environment. Finally, occupancy patterns affect the internal gains and thus formulate the main part of a building's thermal balance.

It is therefore appropriate to say that HVAC systems are not installed in buildings to influence the climate or the thermal balance, but rather to "correct" it instead. It is during unusual or extreme weather conditions or use that building services are used to regulate the internal climate of the building back to the acceptable comfort limits that are predecided by the designer. Most conventional energy systems for buildings have a sustainable view, from the aspect of savings in electricity and primary energy in combination with smart controls that help detect and adapt to any larger or smaller changes of the indoor conditions. Sustainability is accommodated with the option for heat recovery within the system.

Taking into account the concept of the adapted Trias Energetica, heat recovery is a form of re-using excess energy. However, this concept is more of a passive approach that depends on the operation of the main heating or cooling system. The introduction of storage possibilities in combination with a recovery system render the design of a heating and cooling system as more "synergetic" taking into consideration the circular concept that was described in Chapters 1 and 2. The possibility to use and store energy in the form of hot and cold water allows the ability to regulate the internal climate more actively as both sources are available at the same time. In the following parts, the synergetic energy system for the MEGA is analyzed in detail together with its component of heat pump and water storage tanks. In this Chapter, modelling the synergetic system with the aid of MATLAB and Simulink is explained and the calculation cases are set in combination with the different energy demand profiles described in Chapter 6.

7.2. Heating and cooling scheme

The synergetic concept described in this report, is based on the principles of energy storage and exchange between the different functions of a multipurpose building. As described in Chapter 3, there are various methods where energy can be stored in physical or chemical form. In modern buildings, the most common construction techniques for energy storage is the thermal mass of the building's materials, while research has proven various physical or chemical methods. Water, hydrogen or different forms of phase change materials can be used to shift the use of energy from the production moment, to a different moment in time.

In the MEGA building, the simple concept of storing thermal energy in the form of hot or cold water, with the aid of insulated tanks or underground (aquifer thermal storage) is examined. In order to investigate the effects of storage and exchange within the building, it is assumed that all required energy for heating and cooling resulting from the thermal balance calculations as presented in Chapter 5, is supplied by 2 storage tanks (buffers). In his model the tanks are not in contact or mixing with one another and are assumed adiabatical for exchange with the outdoor environment.

7.2.1. Heat pump installation

The thermal storage system is combined with an installation of an air source heat pump. The capacity of the heat pump is used in order to recharge the storage tanks and restore the default operational temperatures. The heat pump arrangement can perform to charge only one storage tank (heating or cooling mode) as well as charge both storage tanks simultaneously (simultaneous mode).

7.2.2. Thermal buffering and distribution

The physical form of the storage installation is irrelevant. The tanks can have a circular or rectangular shape according to the calculated dimensions for the desired water and thermal capacity. What is important is that storage tanks are properly insulated or constructed underground in order to maintain a relevant constant temperature.

The circulation system for the synergetic installation concept can consist of distribution networks of only 2 pipes (warm and cold loops) or 4-pipe distribution networks (warm and cold loops including feedbacks of residual heat or cold water).

7.3. Modelling and simulation

The synergetic installation concept as described in the previous part, is analyzed in 4 different system modes, based on the contribution of the heat pump and/or storage tanks, in order to cover the energy demand within the building. The system mode is also affecting the energy consumption for the synergetic installation, as the variability of the time that the heat pump is on, affects directly the electricity consumption of the investigated installation system. The performance of the system and the potential for energy savings, can be derived based on a variable analysis of the heat pump capacity and the storage capacity of the buffering tanks. The operational temperatures for the system including maximum and minimum temperature for charging the hot and cold storage tanks are presented in Table 10. The setpoint temperature is introduced in order to describe the process where one of the storage tanks has reached the maximum capacity and temperature already, the other storage tank can still be charged but with a lower threshold. These values are of course also subject to sensitivity analysis but the contribution the overall performance of the model is less considerable compared to the influence of the heat pump and storage capacity.

Operational Temperatures	Hot Storage Tank	Cold Storage Tank
Maximum Temperature (O C)	55	15
Minimum Temperature (O C)	45	7
Setpoint temperature (O C)	50	11

Table 20 – Operational temperatures for the hot and cold storage tanks

The total synergetic heating and cooling scheme was modelled with the aid of modelling and calculation software MATLAB and Simulink v.2018a. The full model analyzed in modules is presented in Appendix 4.

The 4 different modes and their characteristics are presented below.

7.3.1. System Mode 1 – Simultaneous Heating and cooling demand

In System Mode 1, the synergetic installation is performing in a metaphorically described “cooperation loop”. The demand of the building can be in the form of heating or cooling energy, that is derived from the relevant hot or warm storage tank respectively. While one storage tank is providing the necessary energy to cover the energy demand of the building for a specific time step, the opposite storage tank is charged back to its operational temperature points, by using the resulting residual heat water. The characteristic of mode !, is that both heating and cooling are provided at the same time, and both storage tanks are charged by residual heat water.

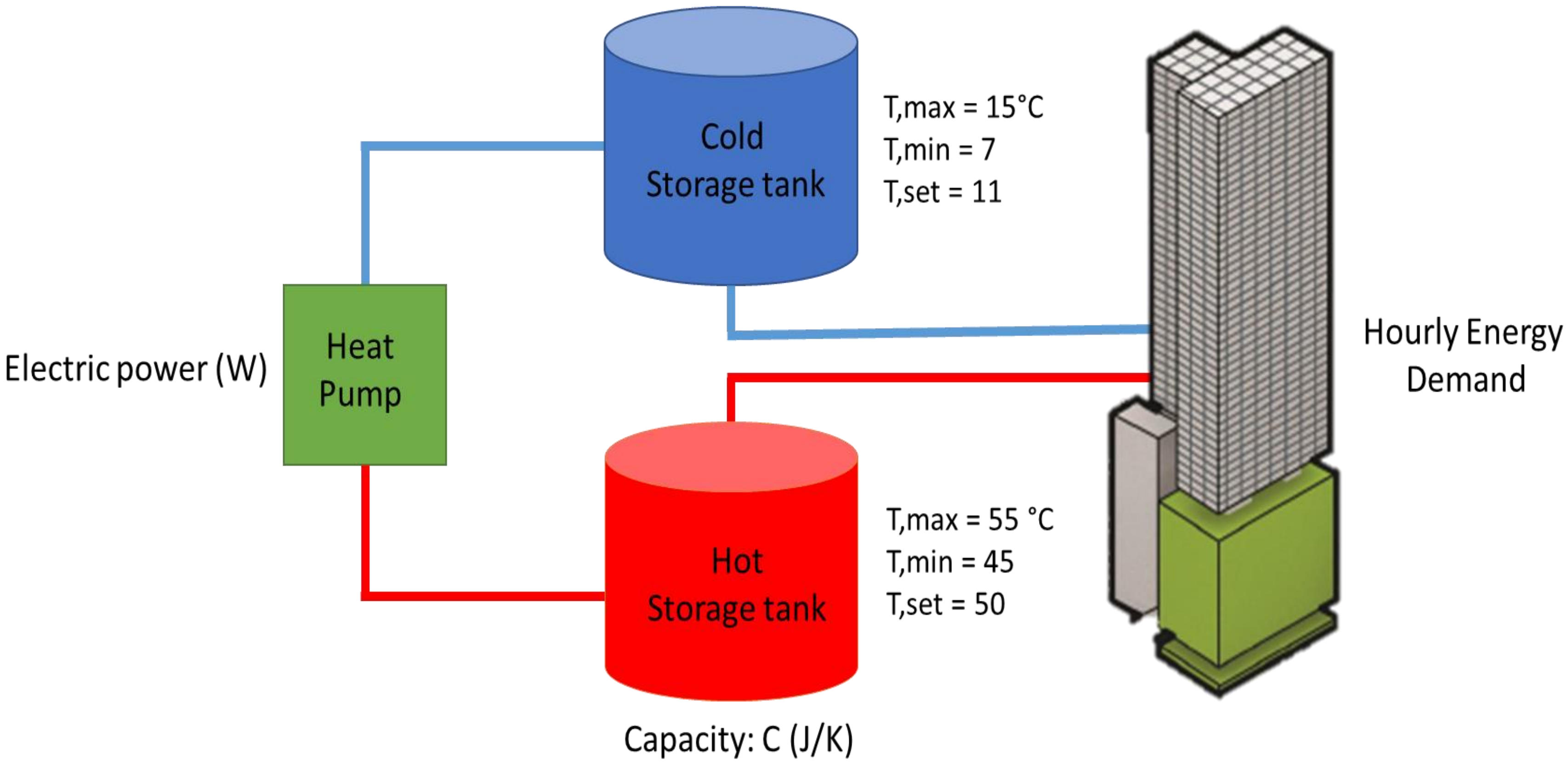


Figure 55 – Schematic representation for System Mode 1 of the synergetic installation system

7.3.2. System Mode 2 – Heating Mode

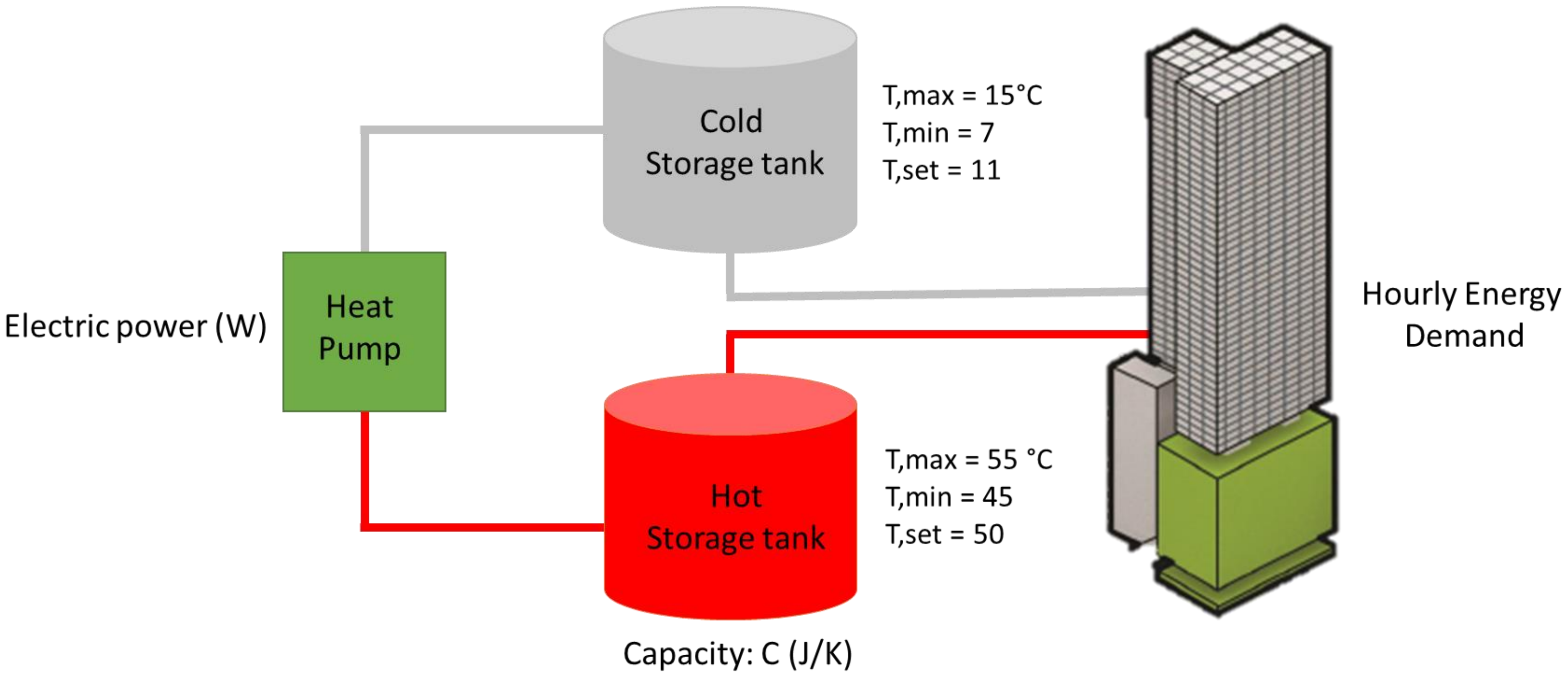


Figure 56 - Schematic representation for System Mode 2 of the synergetic installation system

In Mode 2, the building is presenting a heating demand for the relevant time step. At this point, the hot storage tank is providing the heating demand and the heat pump installation is charging the hot storage tank up to its default operational settings.

7.3.3. System Mode 3 – Cooling Mode

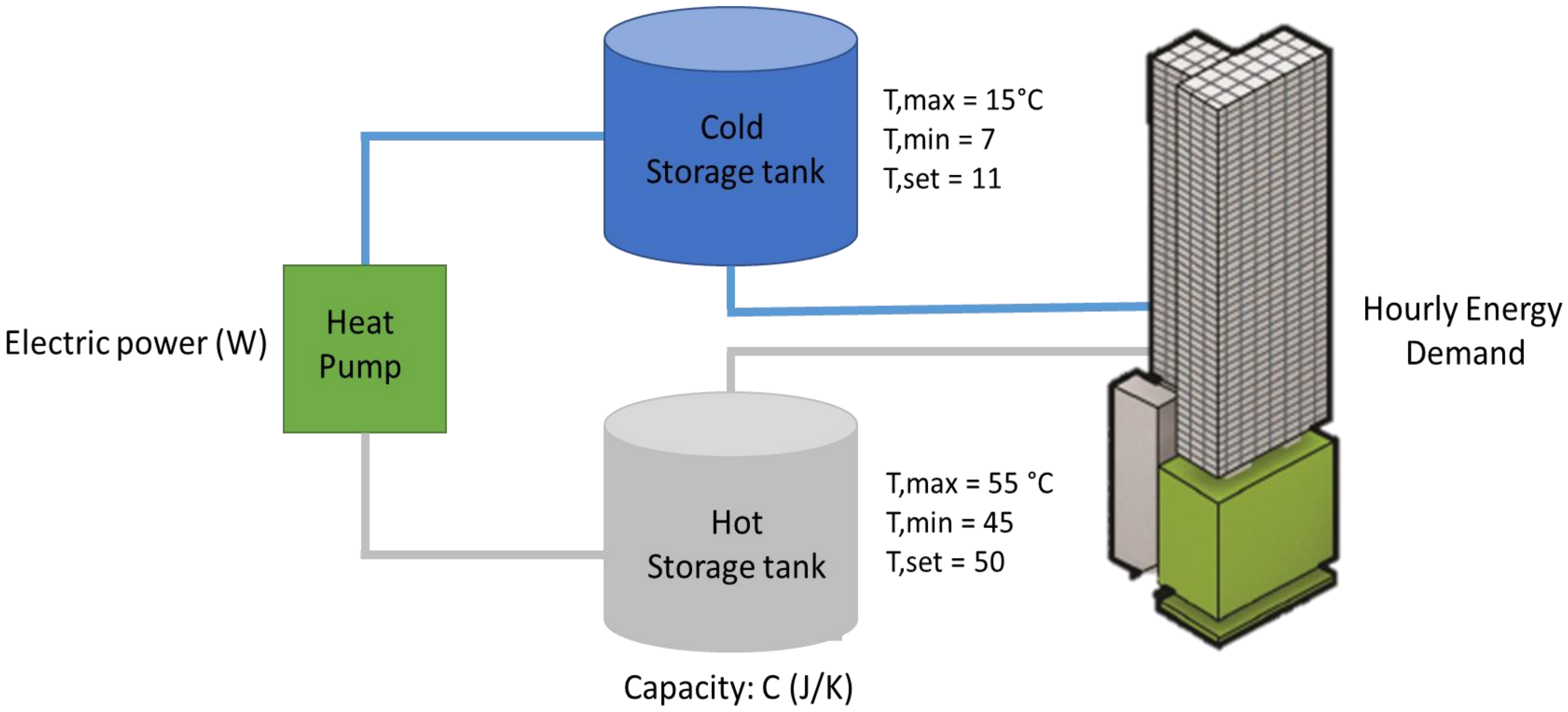


Figure 57 - Schematic representation for System Mode 3 of the synergetic installation system

In Mode 3, the building is presenting a cooling demand for the relevant time step. At this point, the cold storage tank is providing the cooling demand, and the heat pump installation is charging the cold storage tank up to its default operational settings.

7.3.4. System Mode 4 – Neutral Mode

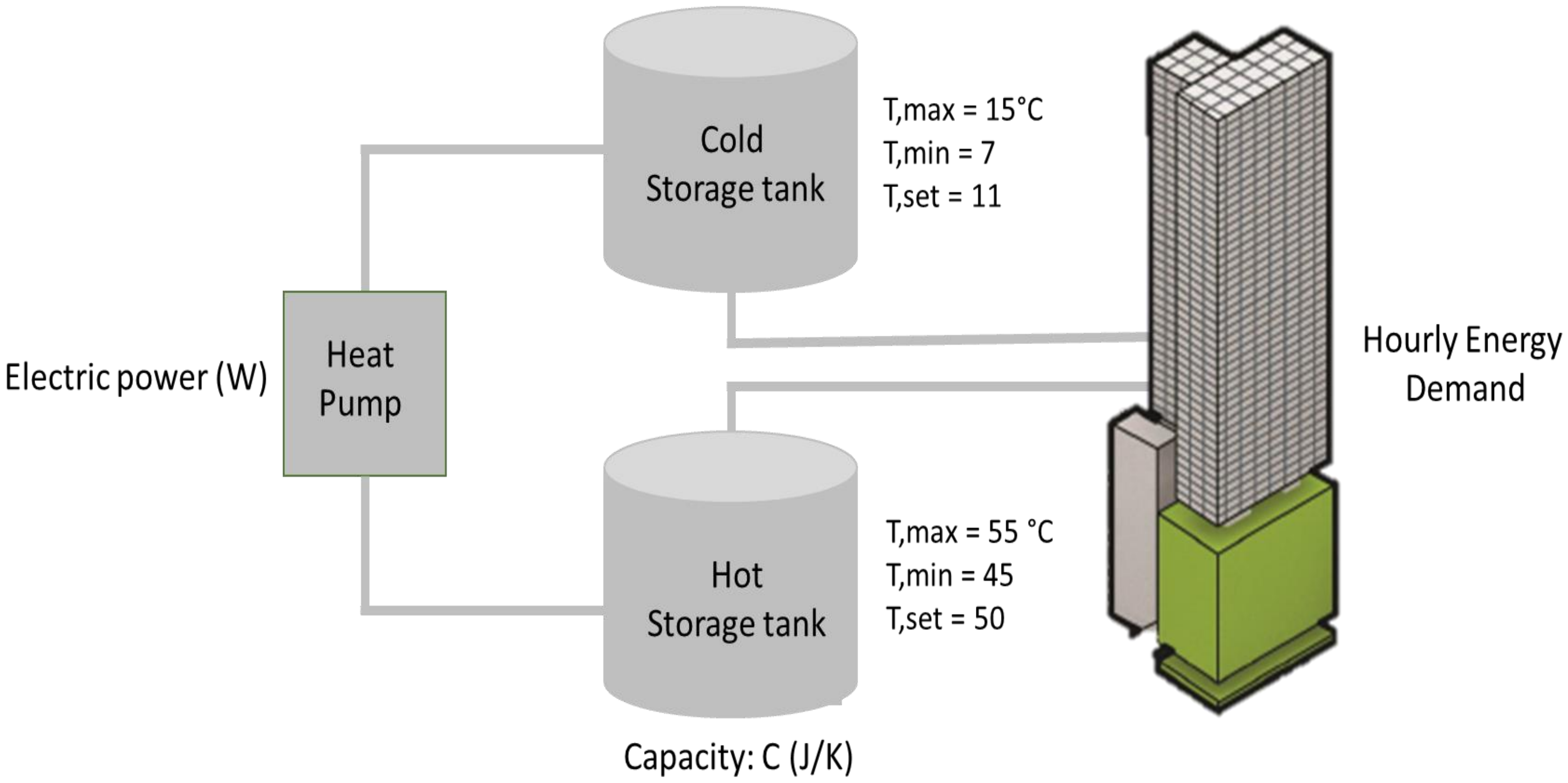


Figure 58 - Schematic representation for System Mode 4 of the synergetic installation system

In System Mode 4, no interaction between the building and the storage installation is present, and no storage tank is charged. The heat pump installation is not operating.

7.4. Calculating the energy savings

Reference case – Separate Heating and Cooling scheme

In order to calculate the energy benefits from a synergetic installation concept, it is important to establish a reference case, in order to use to as the base point for comparison. For the case of the MEGA building, the option of using a similar building with only one function as a reference case, was deemed unrealistic, as the mixed-use scheme creates a special demand scheme, where simultaneous heating and cooling demands are present within the same specific time step.

It was instead deemed favorable, that the building is used in its conceptual form, but instead assuming a capacity for only separate heating and cooling, by means of a dual system or 2 independent systems.

It was assumed that individual heating is provided in the building with a performance coefficient $COP,_{ref,H} = 4$, while individual cooling is provided with a performance coefficient $COP,_{ref,C} = (1 - COP,_{ref,H)}) = 3$.

Operational time of heat pump installation

The overall amount of energy savings is dependent on the operational time of the heat pump in the synergetic system. The operational time is derived, by integrating the sum of individual time steps that the heat pump is operating within the 4 different modes. The result for the final electricity consumption is independent of the heating or cooling operation of the heat pump, and entirely dependent on the electric power of the heat pump, thus the calculation is performed as follows:

Electricity consumption C (Joules) = *Heat Pump Capacity* P (Watts) x *integrated operational time* T (seconds)

In this simple manner, is therefore easy to compare the electricity consumption for the reference case, and the synergetic installation concept.

The energy savings were calculated for 2 distinct approaches. The first approached examined the energy savings based on the thermal capacity of the water storage tanks expressed in Joules / ºC. The parameter of the power attributed to the heat pump installation in Watts, was kept constant with a value of 2000 MWatts.

For the second approach, the sensitivity of energy savings was investigated for an increasing heat pump power. The thermal capacity of the buffering tanks was kept constant with a value of $3x10^9$ Joules / ºC.

The results are presented at the following figures,

Case study – MEGA Building

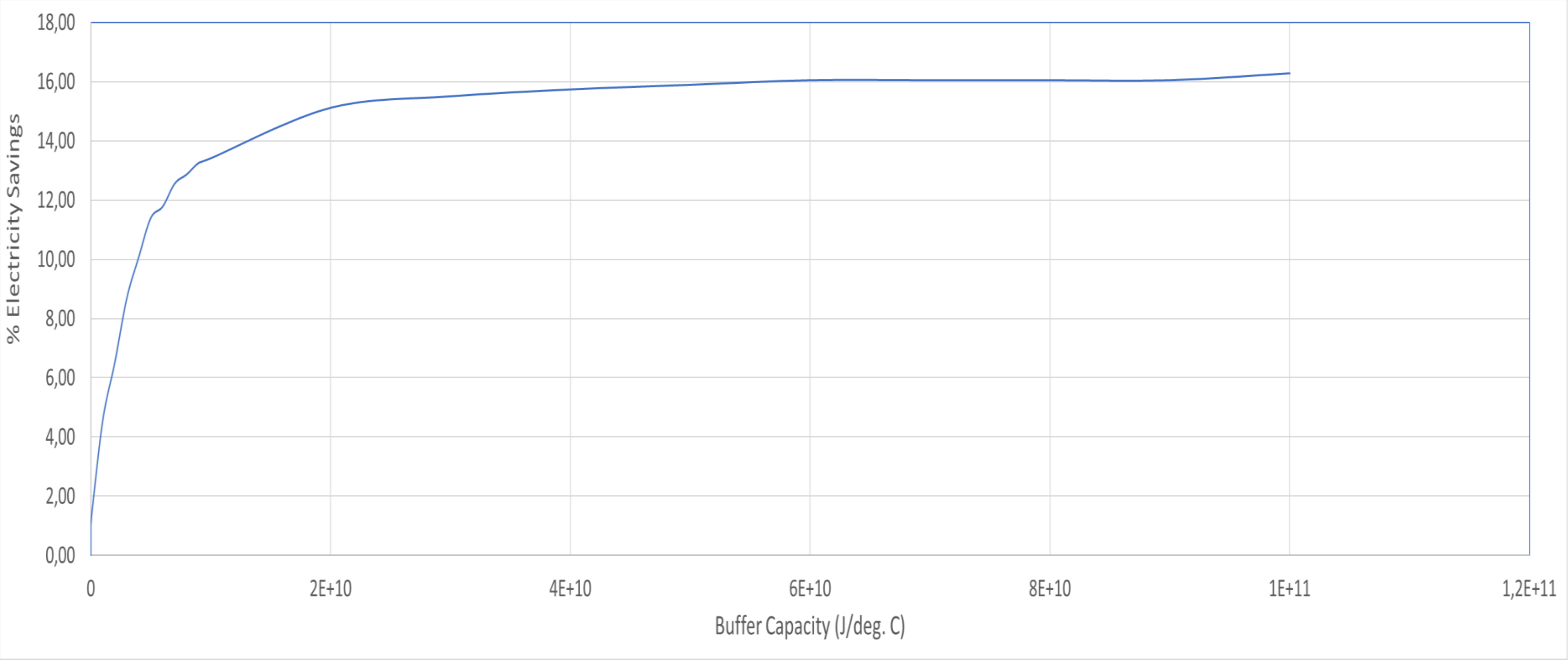


Figure 59 – Percentage of energy savings compared to the reference case for the MEGA building – Variable buffering capacity

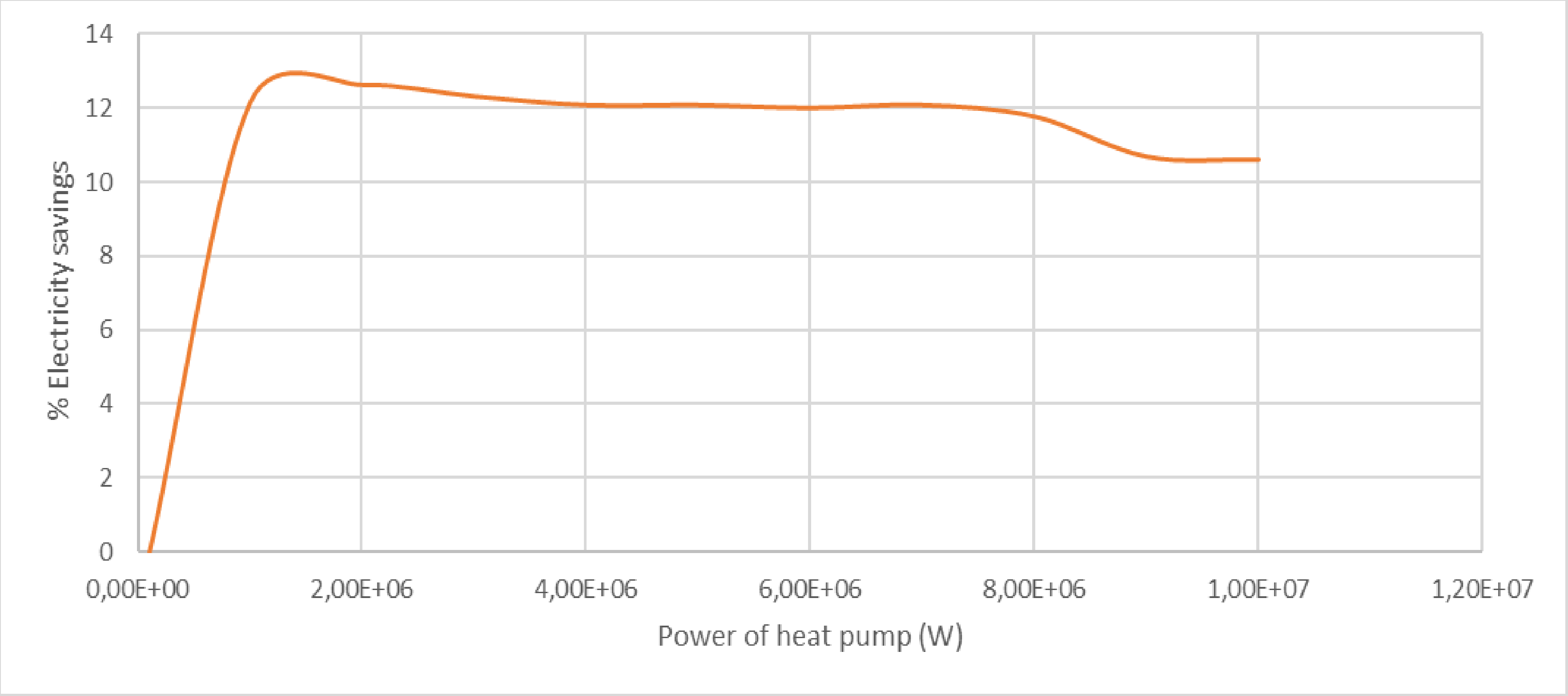


Figure 60 – Percentage of energy savings compared to the reference case for the MEGA building – Variable heat pump power

As shown in Figure 47, a variable increase on the thermal storage capacity results in increasing energy savings within the MEGA building. The savings line follows an approximate exponential pattern, with a maximum saving reached around the area of 10^{11} J/deg, Celsius. While the maximum savings are calculated around 16.3 % compared to the reference case of separate heating and cooling schemes, considerable savings 10% - 14% can be achieved with a much lower buffering capacity.

The contribution of the heat pump installation is becoming relevant in the model at the starting point of 2000MW, thus the steep increase of saving at the lower values. The increase of the power for the heat pump installation, shows a relevantly stable pattern with a decrease for extreme values, which would be unrealistic in practice.

Case 1 – 100% Residential function

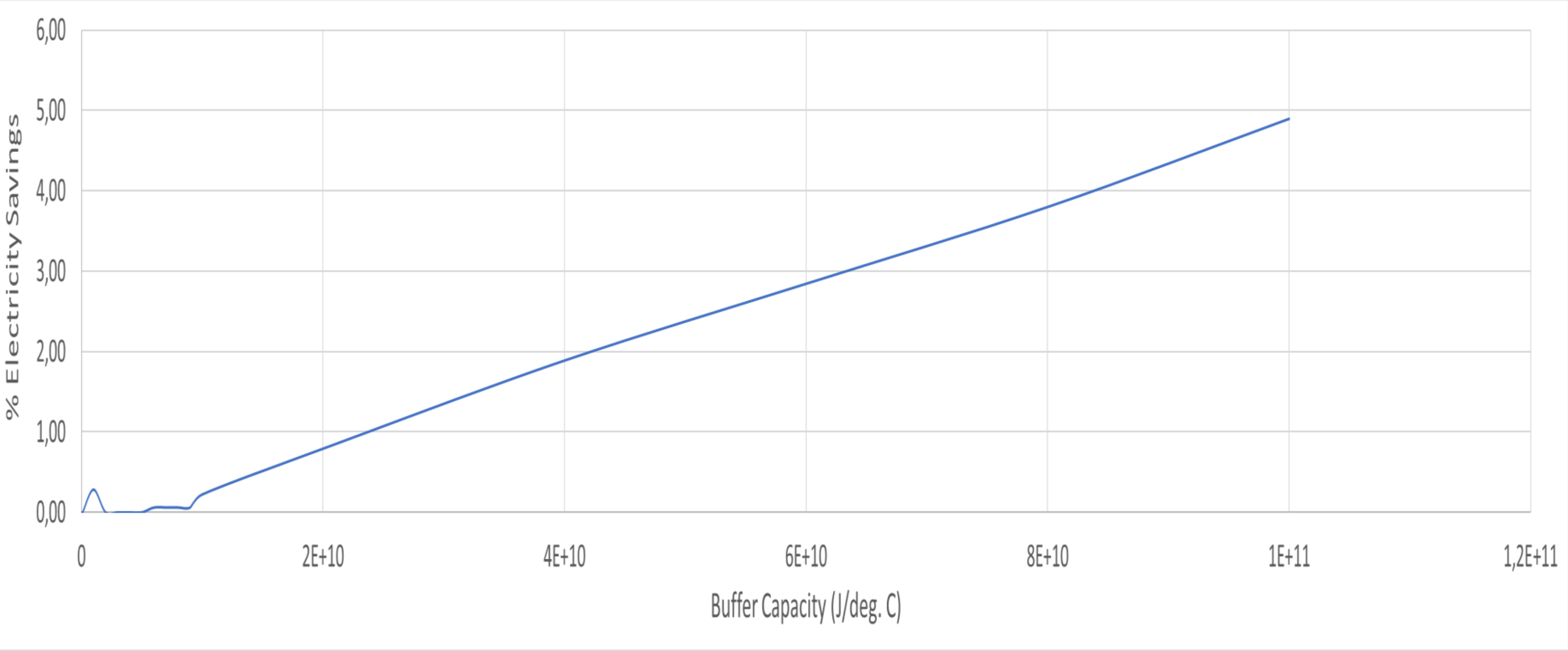


Figure 62 – Percentage of energy savings compared to the reference case for 100% Residential function – Variable buffering capacity

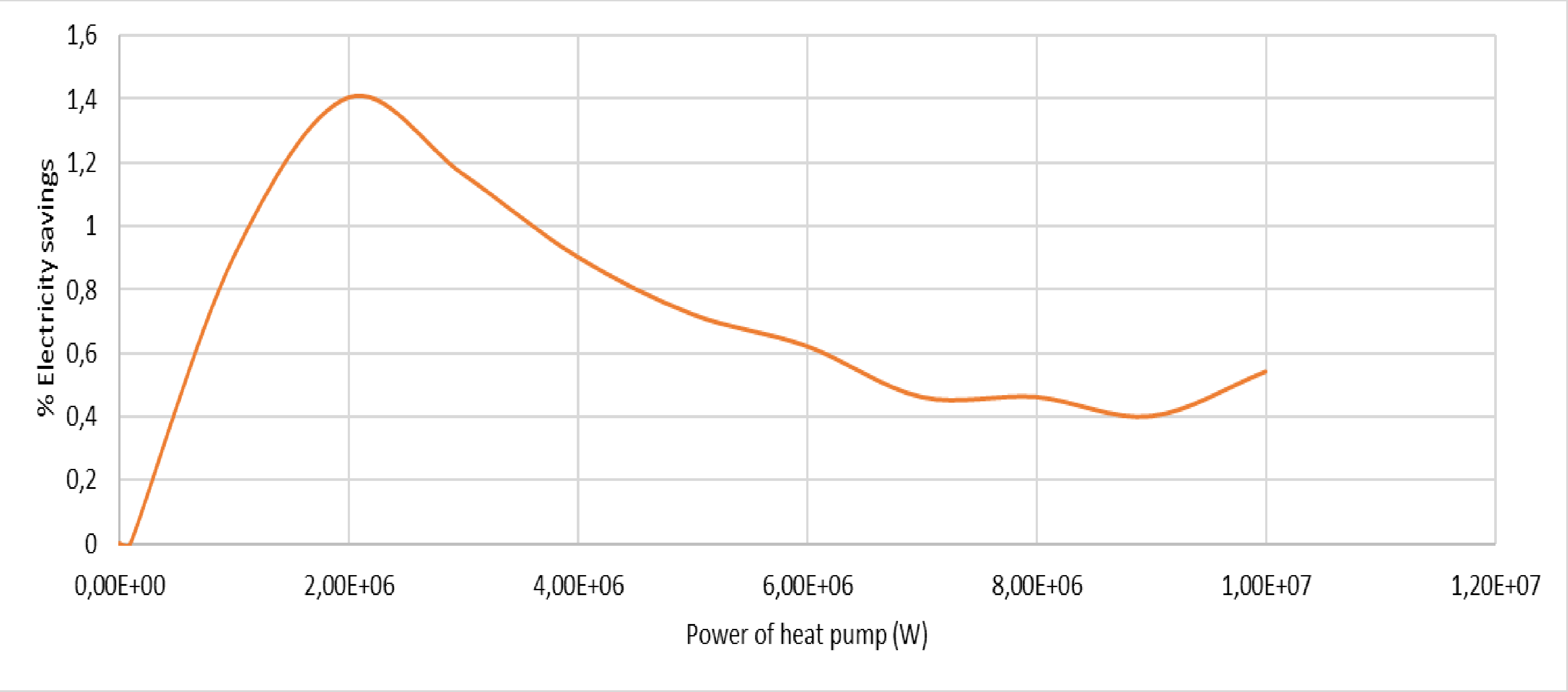


Figure 61 – Percentage of energy savings compared to the reference case for 100% Residential function – Variable heat pump power

In Figure 49, the pattern of the savings for the single use residential tower shows a linear increase. This can be partly explained by the absence of simultaneous heating and cooling hours within the examined year. The thermal storage tanks perform similarly to a separate heating and cooling installation, and for this reason the maximum savings are calculated at around 4.6%. The heat pump power becomes relevant once again at around 2000 MW, while increasing the capacity results in less savings, as the operational time for the heat pump installation remains approximately constant.

Case 2 – 25% Residential + 75% Office

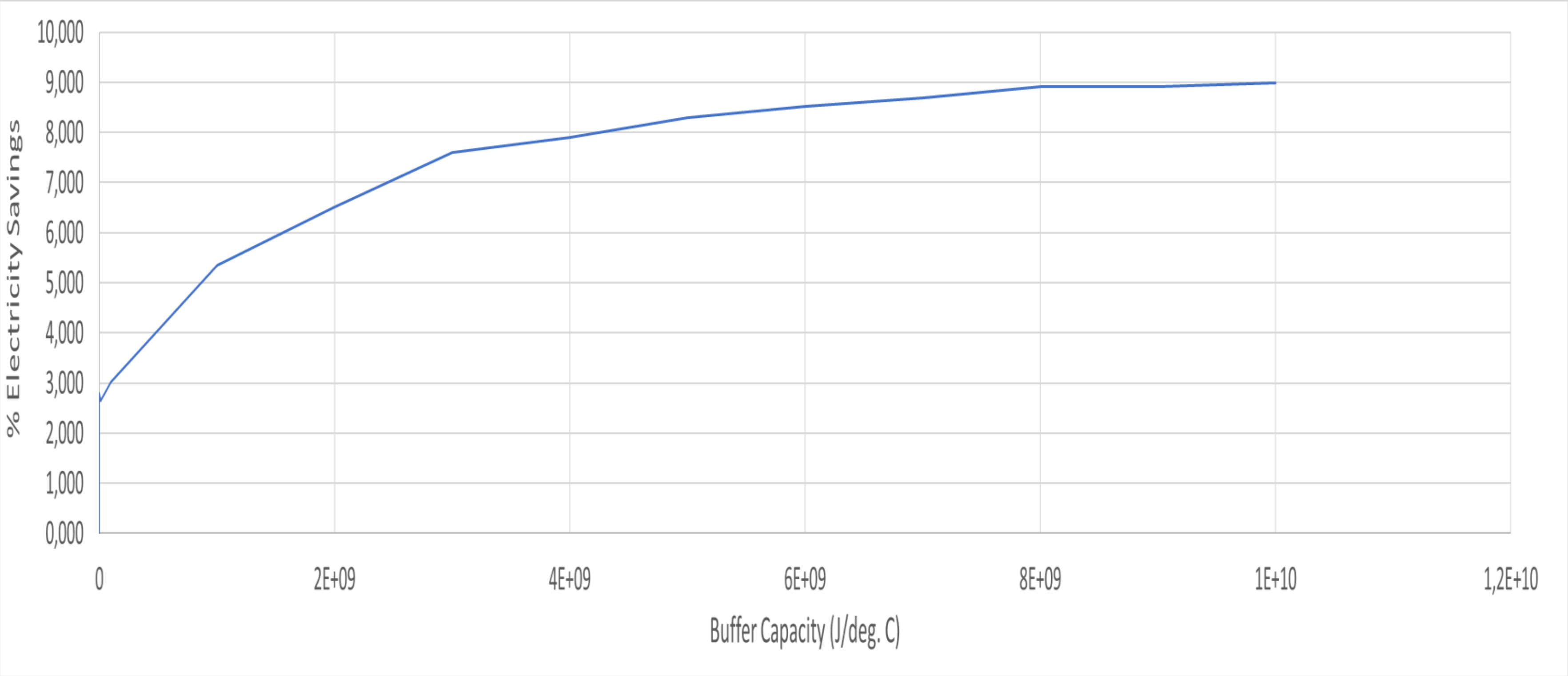


Figure 64 – Percentage of energy savings compared to the reference case for 25% Residential + 75% Office function – Variable buffering capacity

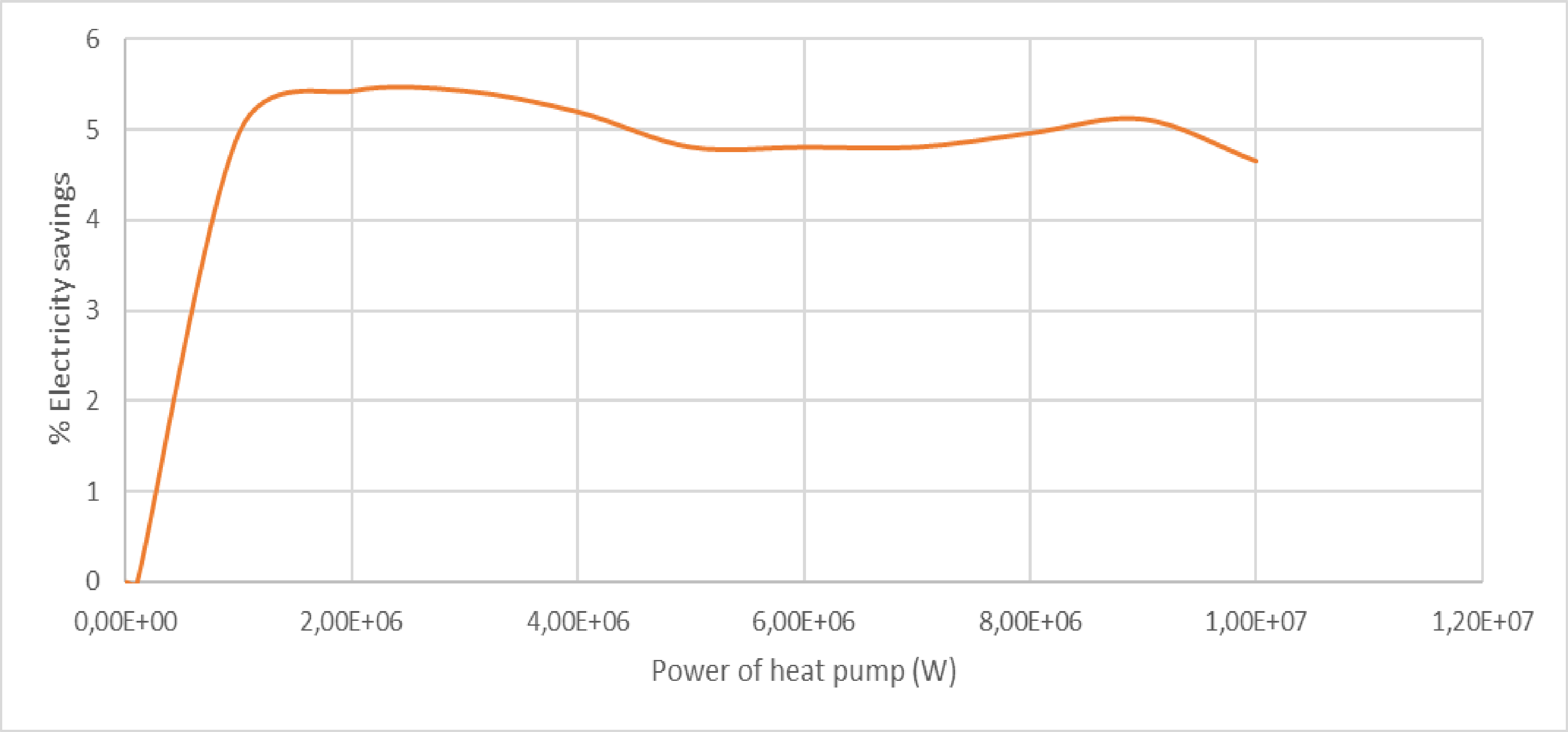


Figure 63 – Percentage of energy savings compared to the reference case for 25% Residential + 75% Office function – Variable heat pump power

In Figure 51, the energy savings for the mixed-use case with a dominant office function, shows a similar pattern with the one calculated for the case study of the MEGA building. The increase has an approximate exponential style, with a less acute increase rate. That can be partially explained by the low density of hours with a simultaneous heating and cooling demand within the sample year. The maximum savings are calculated up to 9.3%.

The contribution of the capacity of the heat pump installation is not affecting the performance of the total system, similar to the case of the MEGA building.

Case 3 – 50% Residential + 50% Office

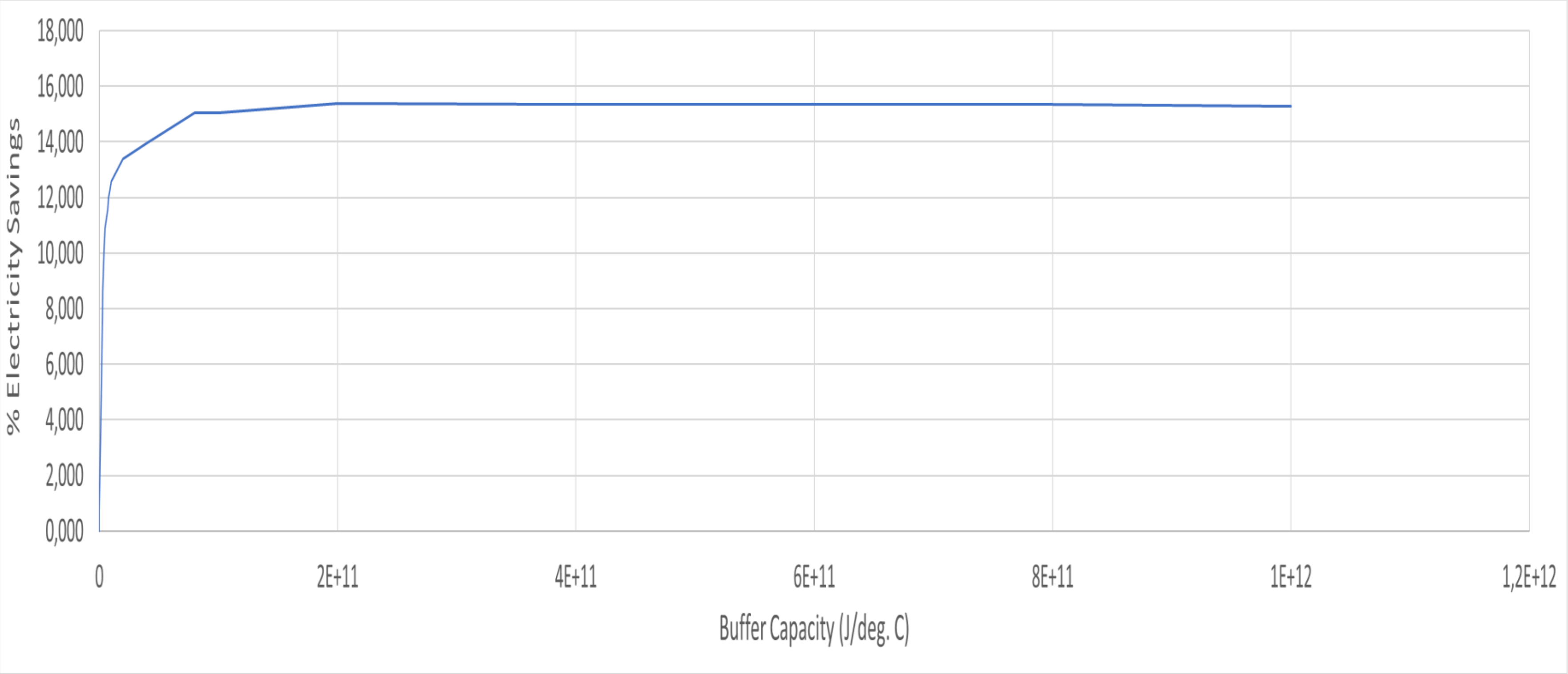


Figure 66 ***– Percentage of energy savings compared to the reference case for 50% Residential + 50% Office function – Variable buffering capacity***

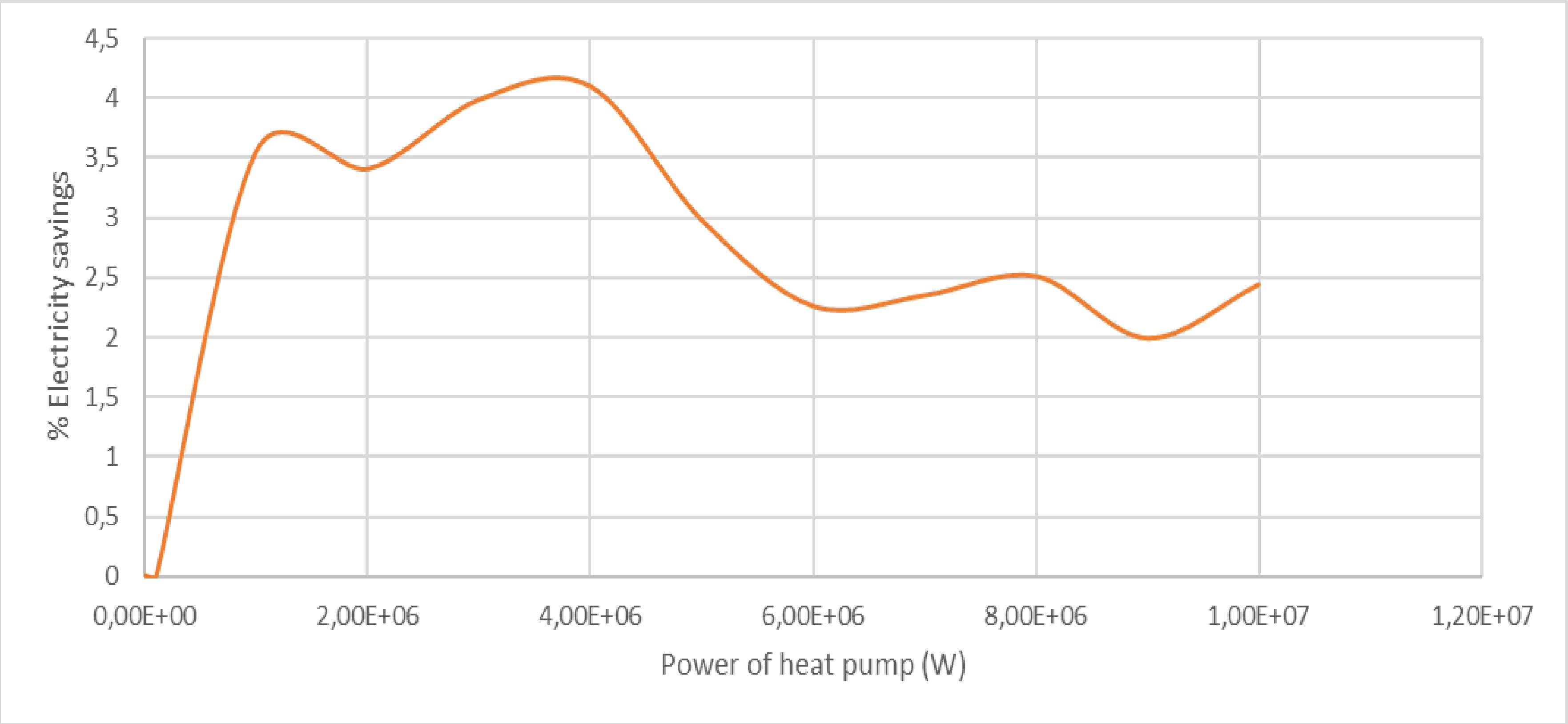


Figure 65 ***– Percentage of energy savings compared to the reference case for 50% Residential + 50% Office function – Variable heat pump power***

In Figure 54, the savings pattern for the 50% mixing of functions is relevant to the previously presented case. The maximum savings are calculated at around 15.4%. The sensitivity analysis for the heat pump capacity, is again showing a decreasing pattern.

Case 4 – 75% Residential + 25% Office

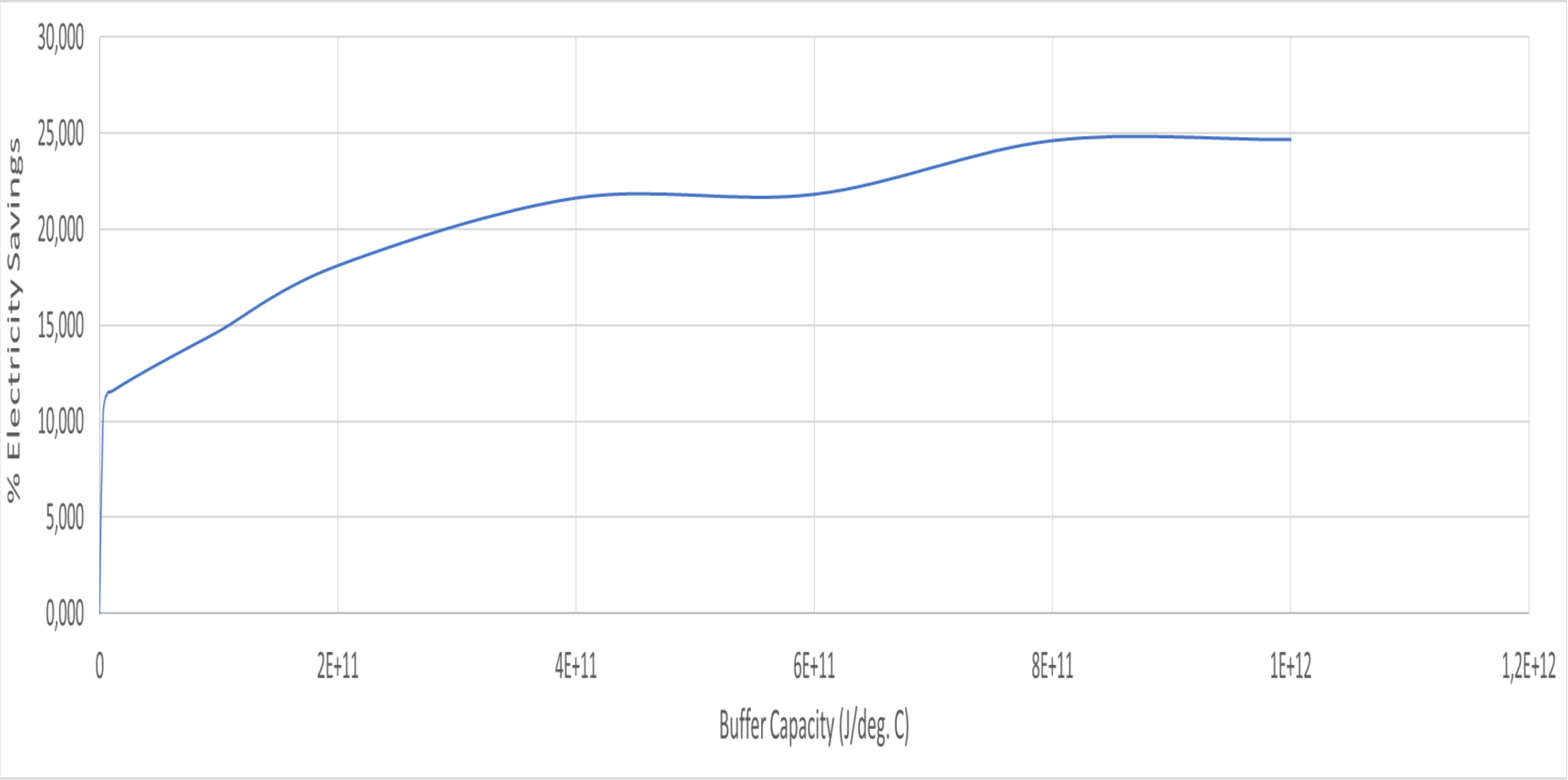


Figure 68 – Percentage of energy savings compared to the reference case for 75% Residential + 25% Office function – Variable buffering capacity

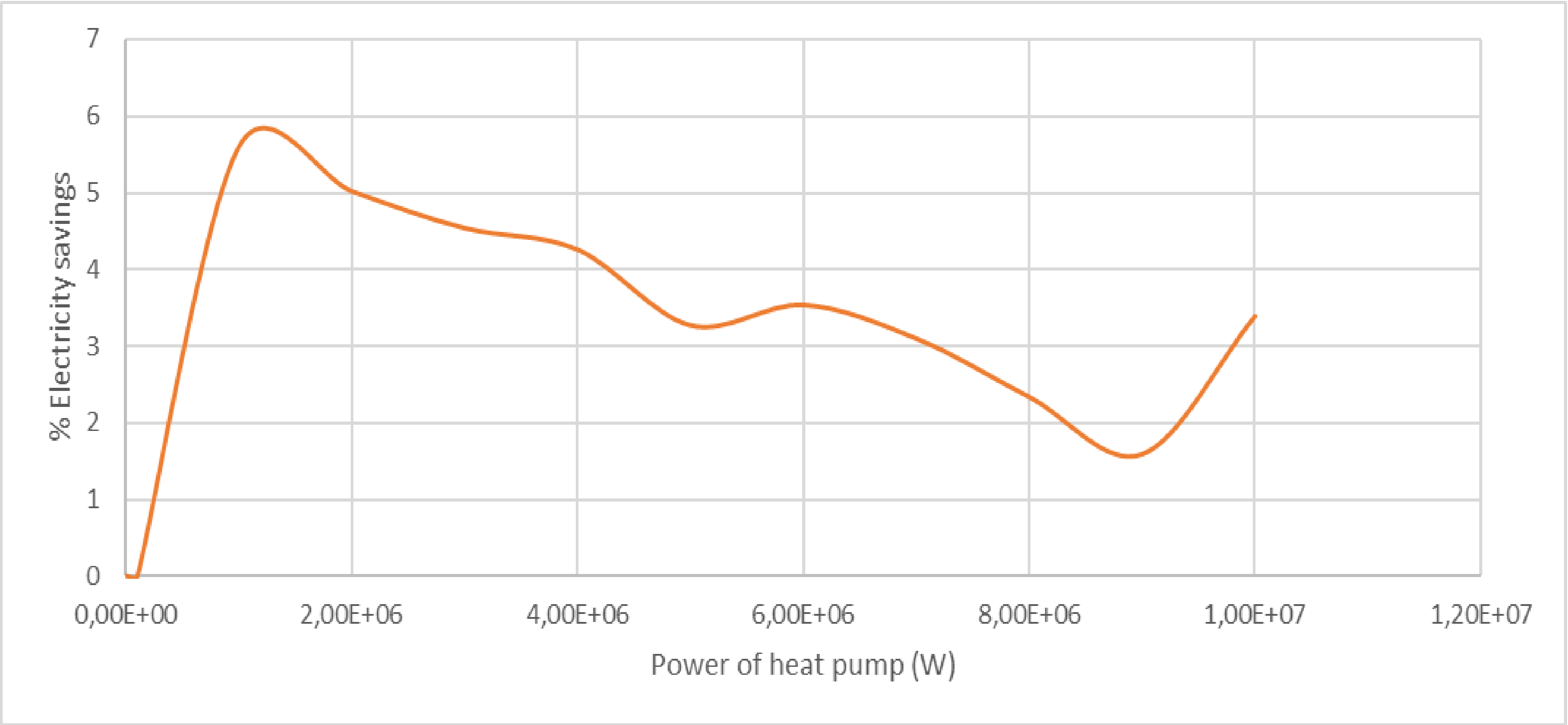


Figure 67 – Percentage of energy savings compared to the reference case for 75% Residential + 25% Office function – Variable heat pump power

For Case 4, the energy savings graph shows a more unusual pattern. While a relevant percentage of savings (10%) are achieved for a relevantly low thermal storage capacity, the increase of the capacity from 2x10^{11} J/deg. Celsius, results to an additional 14.7% of saving, thus reaching a maximum savings capacity of 24.7% compared to the reference case where heating and cooling are supplied separately.

The higher percentage of energy savings can be partially explained by the large number of hours within the year, with a simultaneous heating and cooling demand. The demand scatter diagram for Case 5, presents the most balanced distribution with approximately similar peak demands and a large cloud of dual points within the year. In this manner, the heat pump installation is performing for a longer time on System Mode 1 (simultaneous heating and cooling mode). The reduced time of heat pump operation results to lower electricity consumption.

The lower operational time can be also supported by the pattern of the variable heat pump capacity, that is showing a decreasing tendency for savings. The total operational time has little variation, thus a large capacity results to higher consumption.

Case 5 – 100% Office

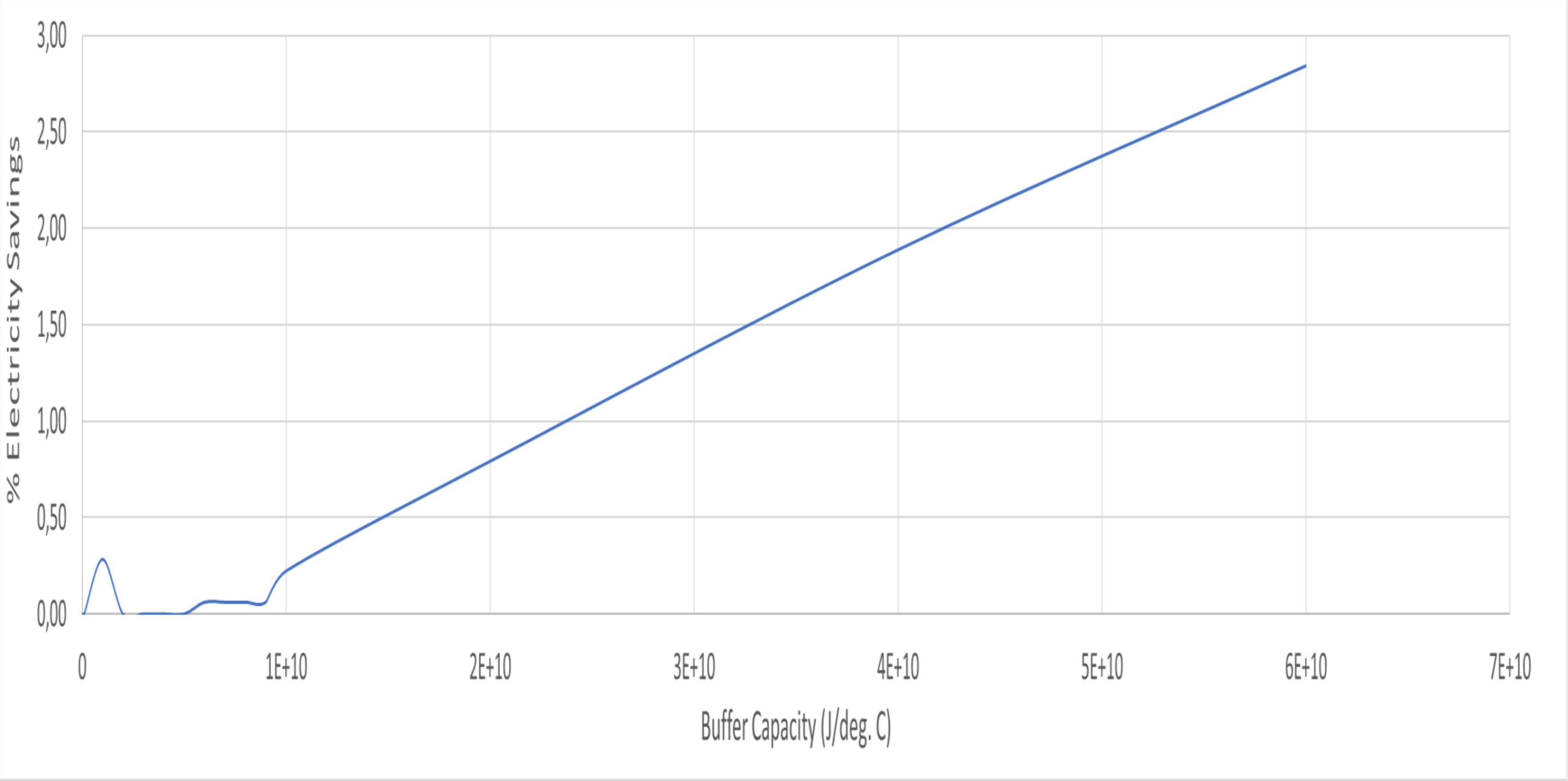


Figure 70 – Percentage of energy savings compared to the reference case for 100% Office function – Variable buffering capacity

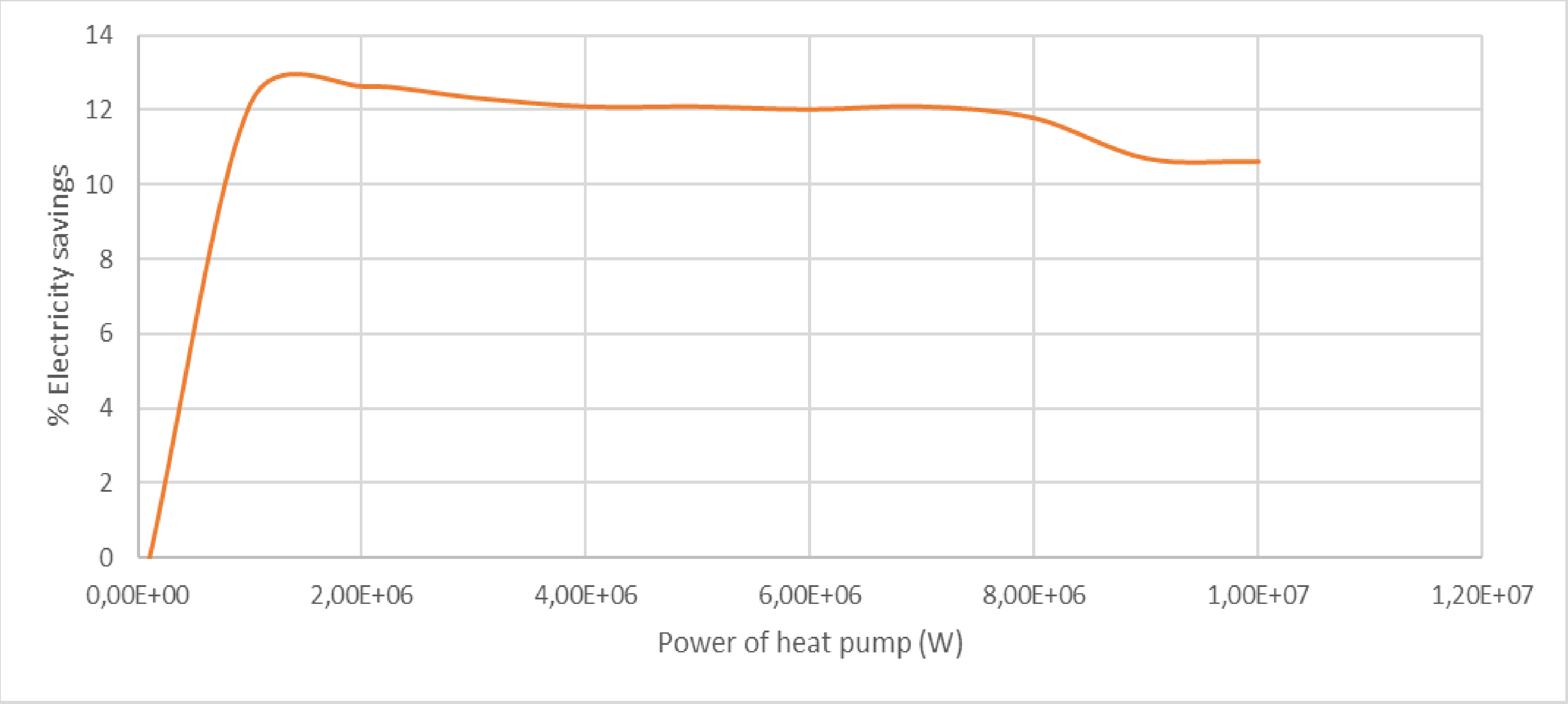


Figure 69 – Percentage of energy savings compared to the reference case for 100% Office function – Variable heat pump power

The case of the single office function building is showing many similarities with the 100% residential building. The savings pattern is approximately linear, with a small savings percentage of 2.8%. The large cooling demands combined with the almost zero demand for heating and very few dual hours, can explain the savings pattern. The system is mostly performing on cooling mode which is similar to the reference case.

7.5. Overview of maximum electricity savings

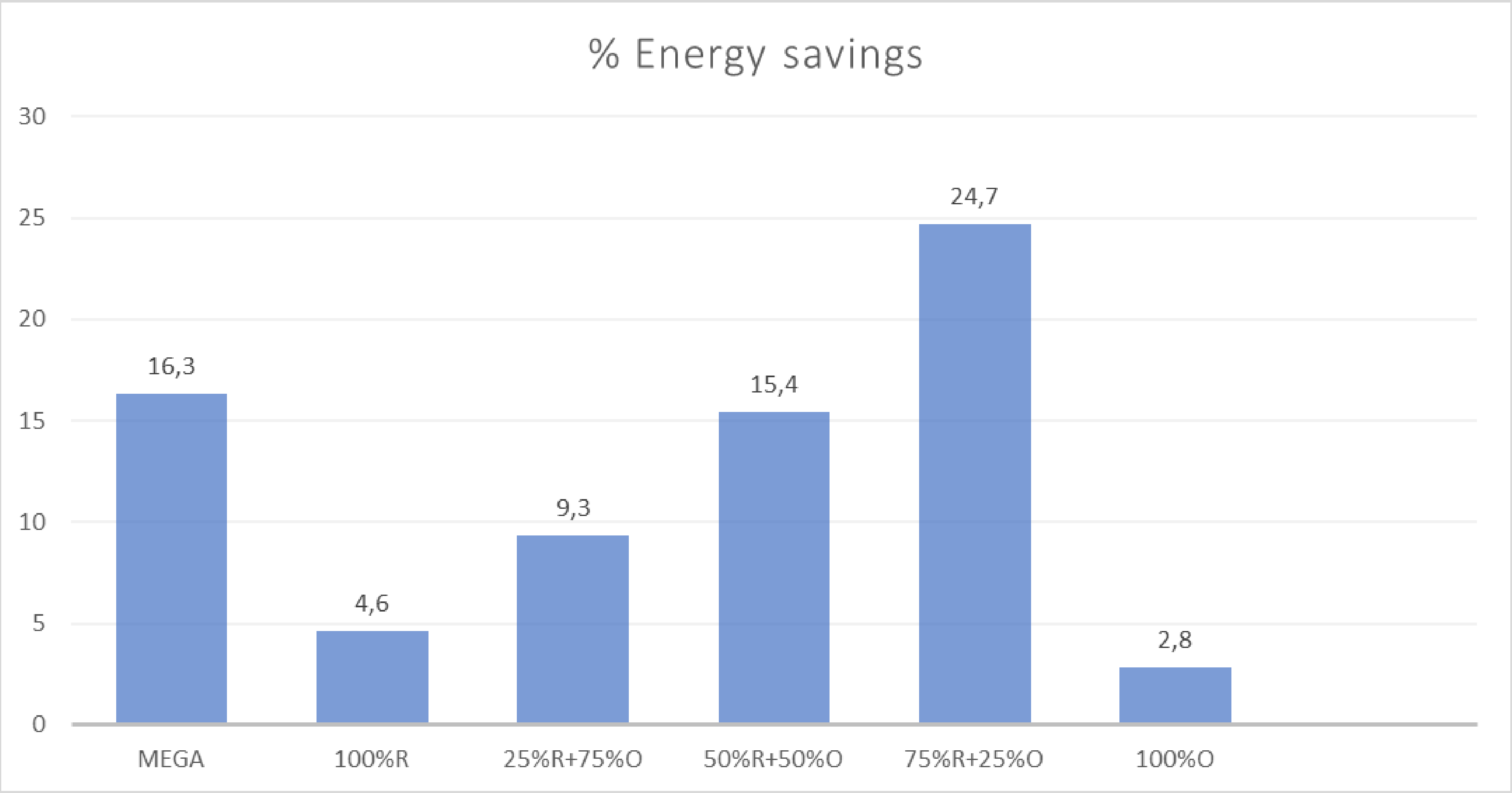


Figure 71 – Overview of maximum energy savings for the investigated cases

In order to sum up the results after modelling the operation of a synergetic heating and cooling system for the different cases as presented in Chapter 6, the maximum savings calculated for the different cases are presented in Figure 59. The savings for the case study of the MEGA building are considerably up to 16.3%, which is an encouraging result for the actual feasibility and use of synergetic systems in practice.

The buildings with a single function are showing the smallest percentages for savings, with 4.6% for a purely residential MEGA tower, and 2.8% for an entirely office use tower. This can be partially explained by the low density of dual points in the scatter diagrams. Dual points enable the use of the synergetic mode in the proposed system, thus the number of dual hours within the year increases the potential for energy savings.

Cases 2 to 4 present a gradually increasing saving in electricity consumption. A 25% mixing in Case 2 shows 4.6% of savings, a 50% mixing of functions 9.3%, and a 75% mixing of functions has the maximum amount of savings, calculated to 24.7%. This can be attributed to the fairly balanced energy demand of the concept building in Case 4. The 75% of residential function is balancing the demand and activity of a 25% office function, and the building profile is presenting a large number of dual hours within the year. As a result, the synergetic system can perform on Mode 1 (simultaneous heating and cooling) for a larger amount of time, thus resulting to a lower overall consumption of electricity.

8. Conclusions and Discussion

“KPN Telecom Toren” – Rotterdam

(source: Pinterest)

8.1. Overview of the research methodology and results

This research project focused on investigating the potential for energy synergy in buildings with the special characteristic of accommodating more than one function. The case study of the MEGA building as it was conceptualized in the course AR0026 MEGA. The MEGA building was analyzed to its functional components, in order to determine t.)he user patterns and occupancies. The steps that were followed in order to reach relevant results are summarized below.

The first step of the research focused on analyzing the MEGA building down to all spaces, main and secondary. All space dimensions and volume were calculated as well as the position in the building. Assumptions were made for the average and maximum occupancy, as well as occupancy profiles during the day. As a result of this process, spaces were separated into cooling and heating dominant, and a first identification of heat sources and sinks inside the building was performed.

The second step focused on applying modern regulation requirements, in order to determine the appropriate comfort levels inside the building. Current European and Dutch standards were used, and acceptable comfort limits were set for the different functions in the building. Secondary parameters such as internal gains and equipment schedules were also set in order to effectively determine the heating and cooling demand in the building.

In the third step of the research process, the energy balanced of the total building was performed according to the predetermined parameters. The balance was calculated manually and with the aid of Design Builder software in order to validate the relevance and scale of results. All the different profiles for heating and cooling on a monthly, daily and hourly time frame were calculated for each function, in order to note peak demands and heating / cooling patterns. In this step, the concept of the energy demand scatter diagram was introduced, in order to visualize and assess the synergetic potential in a building or system of buildings.

The fourth step focused on translating the energy scatter demand profiles into guidelines in order to determine and design the synergetic system of the building. Peak demands and distribution of points within the year were simultaneous heating and cooling is required, were deemed the relevant parameters to be used in the design of the energy storage and re-use installation. In order to create a broader scope for the project, a set of 5 complementary cases of buildings of different mixing ration between residential and office functions were created in order to determine the effect of balanced/unbalanced energy demand profiles.

The fifth step focused on properly designing and simulating the synergetic system of the building. A combination of water storage tanks and a heat pump installation was chosen and an algorithm in order to describe the operation of the system was designed and simulated with the aid of MATLAB / Simulink. The simulations were performed for all relevant cases, with a focus on sensitivity of the involved parameters.

The sixth step focused on producing quantitative results, regarding the saving in electricity consumption. The results were interpreted in order to determine an algorithmic guideline to design and asses synergetic heating and cooling installations in a mixed-use building, as well as the potential for energy savings from a design stage.

8.2. Overview of energy savings

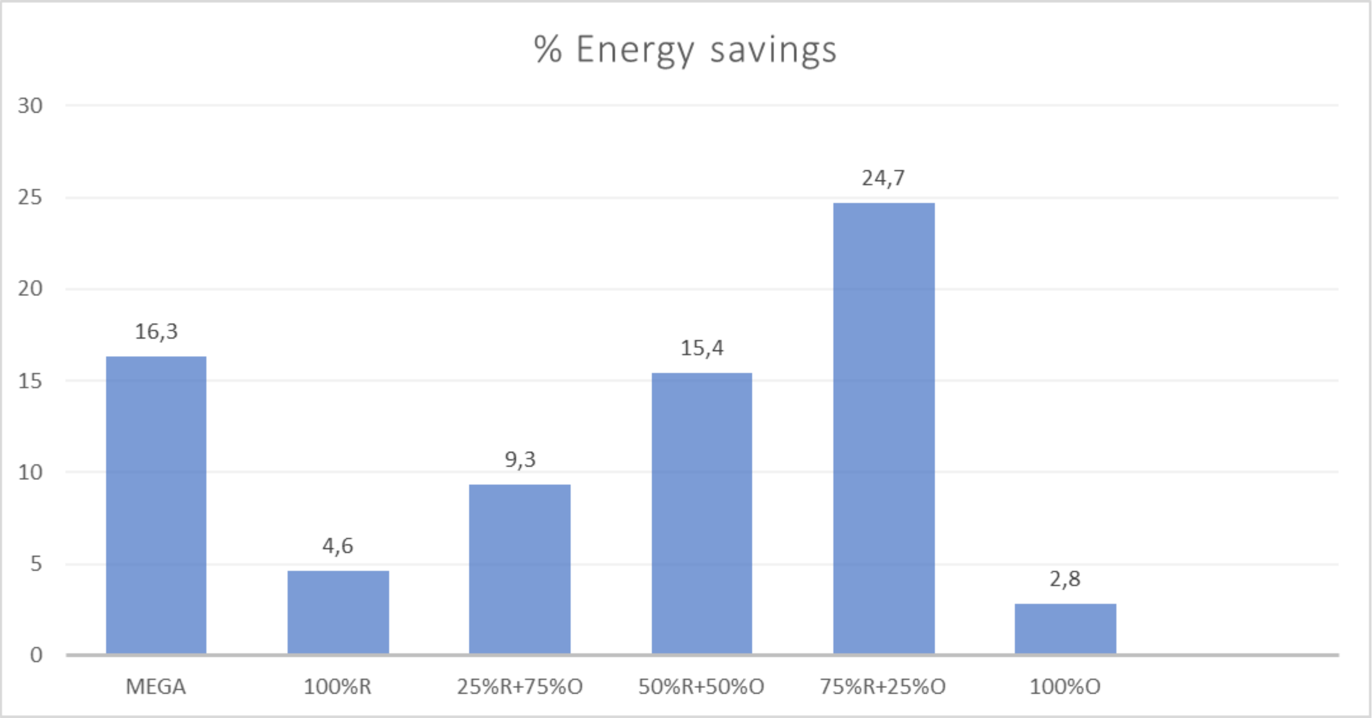


Figure 72 - Overview of maximum energy savings for the investigated cases

As mentioned in detail in Chapter 7, the maximum savings calculated for the different cases are presented in Figure 67. The savings for the case study of the MEGA building are considerably up to 16.3%, which is an encouraging result for the actual feasibility and use of synergetic systems in practice.

The buildings with a single function are showing the smallest percentages for savings, with 4.6% for a purely residential MEGA tower, and 2.8% for an entirely office use tower. This can be partially explained because single functions present no or limited hours within the year when simultaneous heating and cooling is required. In the rarest of cases, a synergetic system could be used in a single building only in extreme weather climate, where cooling is required during the day and heating during the night.

The potential for energy savings by a synergetic system, present a gradually increasing saving in electricity consumption with an increasing ration of mixing the functions within the building and balancing the energy demand profiles. A 25% mixing in Case 2 shows 4.6% of savings, a 50% mixing of functions 9.3%, and a 75% mixing of functions has the maximum amount of savings, calculated to 24.7%. This can be attributed to the fairly balanced energy demand of the concept building in Case 4. The 75% of residential function is balancing the demand and activity of a 25% office function, and the building profile is presenting a large number of dual hours within the year.

8.3. Research questions and goals

At the start of the research project, relevant research questions were set in order to describe the different sub-goals of the project and determine the intermediate steps in order to investigate the original hypothesis of implementing a synergetic energy system in a high-rise building with multiple functions. Upon completing the analysis, the answers to the research can help synthesize an overall conclusion regarding the value of energy synergy in a construction setting.

Main question

“How can energy demand in a mixed-use high-rise building be reduced by means of energy exchange between different functions?”

Energy demand is primarily dependent on the design characteristics of the building, namely being its orientation in space, shape, properties of the building envelope, and occupancy schedules. On a second level, the required comfort conditions that must be maintained in the building based on its function have a large impact on the thermal energy demand. Energy demand in this setting is thus irrelevant of the potential for energy storage and exchange. The properties of the designed building will determine the level of energy demand that is depicted in its energy demand scatter profile diagram. This diagram is the basis of any further consideration.

The concept of energy storage and exchange focuses on delivering the required energy demands for heating and cooling in a more energy efficient way, thus resulting in less electricity consumption. The combination of a heat pump installation and sensible heat storage in the form of water tanks has proved considerable consumption savings. As a result, the energy demand for heating and cooling can be reduced by active and passive measured in the building, while energy storage and exchange can result in a better performance of the HVAC equipment and considerable electricity consumption saving during heating and cooling seasons.

Sub-question 1

What is the influence of a mixed-use program on the energy design of the building?

Accommodating different uses in the building is translated into different occupant schedules and comfort requirements. This creates the problem of designing an HVAC strategy that can cater for all different requirements within the building. In the case of traditional HVAC installations where heating and cooling are supplied individually, the most common issue in mixed-use buildings is the requirement for simultaneous heating and cooling.

For the case of synergetic heating and cooling, the existence of hours or days within the year where simultaneous heating and cooling is required is beneficial. As presented in Chapter 5 and 6, the amount and distribution of cloud points outside the axes in the energy scatter diagram, show the potential of the building to perform synergistically, According to the simulation of the heat pump / storage cooperation system, simultaneous heating and cooling results in less electricity consumption, as the ability to supply heating and cooling energy at the same time is used at the best advantage.

Sub-question 2

“ What are the potential energy benefits from a mixed-use scheme for the MEGA Building?”

The case of the MEGA building was used as a realistic concept to examine the application of energy synergy. The MEGA building applies totally to the mixed-used concept, however the balance of energy demand for heating and cooling is not completely even. The cooling demand is dominant due to the existence of both an office function and a courthouse function, while the demand for auditorium halls both for the courthouse, and the conference hall of the hotel function increased the cooling demand radically. IN this context and always according to the initial design for the shape, orientation, envelope characteristics and assumptions for occupancy and comfort, the maximum energy consumption savings for the MEGA building using a synergetic system were calculated to 16%, compared to the reference case of separated heating/cooling supply.

Sub-question 3

“What technical solutions can be used for a synergetic energy concept?”

The main requirement for a synergetic concept is the availability of energy storage. Energy storage can be performed in various techniques as presented in Chapter 3. The most relevant technical solutions for the building industry are storage in thermal mass, that is the basis for the Trombe wall and concrete core activation systems with hysteretic thermal behavior. This technique can be used mostly for passive measures in order to reduce the demand in the building. In order to effectively store and distribute thermal energy in a HVAC installation, sensible or latent heat storage in combination with an air-source heat pump arrangement has proved a viable solution in this project. The choice of storage medium can variate according to the temperature levels required, but sensible heat storage in water is the solution that involves the highest cost efficiency and les risks.

Sub-question 4

“What are the general design guidelines that can be derived from the analysis of a synergetic energy system in a high-rise mixed-use building?”

The simulation and analysis part of this project focus on the use of an air-source heat pump installation combined with a hot and cold tank for sensible thermal energy storage using water. The basic design conclusions, considerations and algorithmic steps are summarized and presented below.

- The initial design of the building is relevant to the point that the energy balances are calculated. A synergetic system does not focus on reducing the energy demand but supplying the required heating and cooling in a more efficient manner. The calculation of the energy demand scatter diagram is “the image” of the energy behavior of the building and all other characteristics are irrelevant. The concept of the energy scatter diagram can be expanded beyond one single building and can be calculated for a group of buildings that each have a different function but can perform synergistically.

- The calculation of the energy demand scatter is the main visualization method of the synergetic potential in the building. Hourly data are more accurate than daily data, as the distribution in time is more representative. The most relevant parameters that can be drawn from the energy scatter diagram is the peak demands for heating and cooling and their ratio, as well as the number of hours were simultaneous heating and cooling is required and the ratio between simultaneous heating and cooling loads. Profiles with balanced peak demands and a large number of dual points within the examined year have shown larger energy savings, thus the potential for energy synergy is larger.

- The influence of comfort levels in the building influences the amount and quality of dual points within the year. By choosing wider comfort limits, the amount of simultaneous heating and cooling within the same building is reduced
.
- The consideration of the demand for domestic hot water in the system can influence the distribution and image of the energy scatter diagram. If supply of DHW is included in the system, the warm storage means must have a higher maximum operational temperature(>60^{O}C) that can influence the efficiency of the heat pump. While an added demand for domestic hot water can “balance” the energy demand of an “unbalanced” building, it is preferable that DHW is supplied in standard temperatures and the increase in temperature can be performed with an auxiliary boiler system.

- The capacity of the storage means directly influences the maximum savings potential. A relative starting point for storage capacity in the case of the MEGA building and equal scale buildings is 3x10^9 J/deg. Kelvin, that translates to a storage tank with a diameter of 10 meters and a height of 10 m. Very high capacities have small sensitivity to the overall savings. The choice of the maximum storage capacity should at least cover the peak hourly demands. Additional capacity can be chosen and expanded according to cost criteria that were out of the scope for this project.

- The performance of the heat pump installation shows the best savings with a power level in the area of 2000 MW for the case and scale of the MEGA buildings. An increased heat pump power results in a considerable reduction of reduction of savings.

8.4. Conclusions and Recommendations for further research

The concept of energy synergy was covered in this project from a hypothetical point of view. While technical solutions combining solar energy collection and storage for domestic purposes have been widely discussed in literature, the literature regarding application of synergetic concepts for large scale applications is limited. Based on the research strategies drawn with this project, the future research could focus from one point of view of expanding the data base to determine the synergetic energy potential in buildings and on another point of view to optimize and determine the feasibility of the examined concept. Certain recommendations are summarized below that can prove useful to researchers that will decide to investigate further the concept of energy storage and re-use.

- Expanding the available data pool and simulating a synergetic energy system in different buildings. The building characteristics can vary in size, climate of the building location and different ratio of mixed-uses. The research can be valuable to show the variations on external climate, compared to the project that focuses in a temperate oceanic climate of the Netherlands.

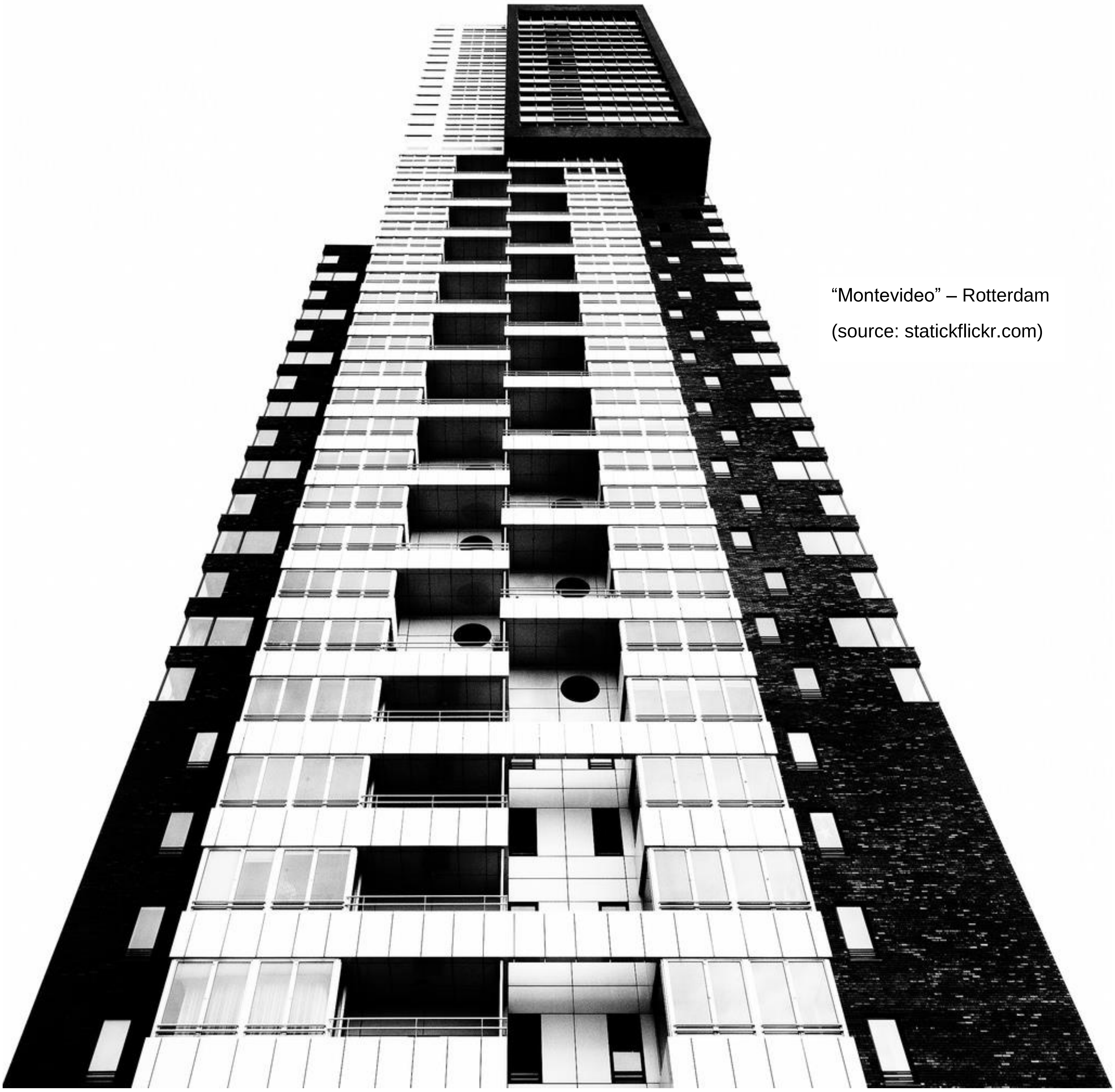
- Investigating the performance of another storage medium besides water with utilizing different phase change materials.

- Investigation of a synergetic concept adapted to a system or community of buildings with different functions. What are the differences and variations according to the energy demand of the examined system and what is the potential in that case?

- Investigating the statistical relation between the amount and distribution of dual hours with simultaneous heating and cooling within the year and express in a mathematical and statistical model the potential for energy synergy within a building.

- A design and optimization algorithm in order to design a synergetic energy system, according to external climate parameters, comfort parameters, and cost parameters for the construction, investment, maintenance and lifecycle of a combined heat pump/ sensible thermal storage system.

9. Appendices



“Montevideo” – Rotterdam

(source: statickflickr.com)

9.1. APENDIX 1: Manual **calculation of monthly and hourly thermal balances**

Table A.1. Functions data

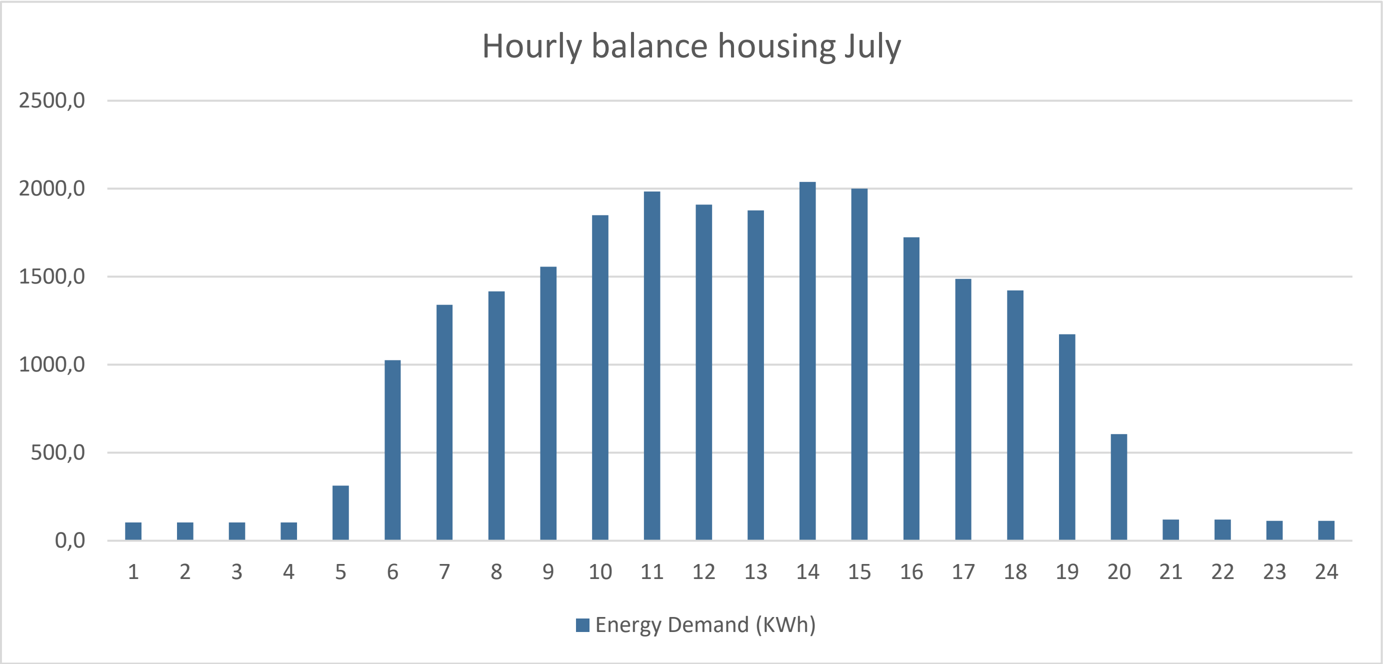
Functions	Gross Area (m2)	Height (m)	Volume (m3)	max. occupancy (people)	ventilation rate (m3/h)	min. ventilation (m3/h)	metabolism	temp. summer	temp. winter	humidity	heatload people W	heat load appliances W	total internal heat load W
Housing													
120 appts x 50 m2	6000	2,7	16200	212	21600	21600	1,2	23-26	20-24	30-70	12000	18000	30000
88 appts x 85,2 m2	7500	2,7	20250	265	27000	27000		23-26	20-24	30-70	15000	22500	37500
75 appts x 100 m2	7500	2,7	20250	265	27000	27000		23-26	20-24	30-70	15000	22500	37500
62 appts x 120 m2	7440	2,7	20088	263	26784	26784		23-26	20-24	30-70	14880	22320	37200
6 suites x 250 m2	1500	3,6	5400	53	5400	5400		23-26	20-24	30-70	3000	4500	7500
	29940		**82188**		**107784**	**107784**					**59880**	**89820**	**149700**
Office													
Generall office space	30000	2,7	81000	3000	151200	108000	1,2	20-26	20-24	30-70	**150000**	**120000**	**270000**
Hotel													
400 x normal rooms	6900	2,7	18630	371	24840	24840	1,2	23-26	20-24	30-70	20700	13800	34500
25 x junior suites	4800	2,7	12960	258	17280	17280		23-26	20-24	30-70	14400	9600	24000
20 x deluxe suites	4800	2,7	12960	258	17280	17280		23-26	20-24	30-70	14400	9600	24000
5 x presidential suites	350	3,6	1260	19	1260	1260		23-26	20-24	30-70	1050	700	1750
2x restaurant	3000	3,6	10800	492	60480	10800		23-26	20-24	30-70	9000	6000	15000
4x meeting rooms	600	4,5	2700	600	9072	2160	1,2	23-26	20-24	30-70	1800	1200	3000
Break area	600	4,5	2700	600	2160	2160	1,6	23-26	20-24	30-70	1800	1200	3000
Pool + Fitness	1500	3,6	5400	938	5400	5400	1	23-26	20-24	30-70	4500	3000	7500
Lobby	250	4,5	1125	250	900	900	1,6	23-26	20-24	30-70	750	500	1250
Corridors + BOH + storage	3050	2,7	8235	102	10980	10980	1,6	23-26	20-24	30-70	9150	6100	15250
	25850		**76770**		**149652**	**93060**					**77550**	**51700**	**129250**
International Court House													
8 main court rooms x 400 m2	3200	6	19200	640	51840	11520	1,2	23-26	20-24	30-70	16000	38400	54400
8 small court rooms x 200 m2	1600	6	9600	320	24192	5760		23-26	20-24	30-70	8000	19200	27200
10 meeting rooms x 100 m2	1000	3,6	3600	500	15120	3600		23-26	20-24	30-70	5000	12000	17000
office spaces	14000	3,6	50400	1400	70560	50400		23-26	20-24	30-70	70000	168000	238000
lobby	250	3,6	900	50	900	900	1,6	23-26	20-24	30-70	1250	3000	4250
restaurant	600	3,6	2160	98	12096	2160	1,2	23-26	20-24	30-70	8400	7200	15600
press hall	250	3,6	900	125	3780	900	1,2	23-26	20-24	30-70	2500	3000	5500
secured evidence room	1000	3,6	3600	33	3600	3600	1,6	23-26	20-24	30-70	5000	12000	17000
sale-du-pas perdu	30	6	180	1	108	108	1,6	23-26	20-24	30-70	0	360	360
services	90	3,6	324	3	324	324	1,6	23-26	20-24	30-70	0	1080	1080
	22020		**90864**		**182520**	**79272**					**116150**	**264240**	**380390**
Ground floor	2100	3,6	7560	300				23-26	20-24	30-70			
Services													
General parking	2100	2,7	5670										
Bike parking	1000	2,7	2700										
VIP parking	60	2,7	162										
Court parking	60	2,7	162										

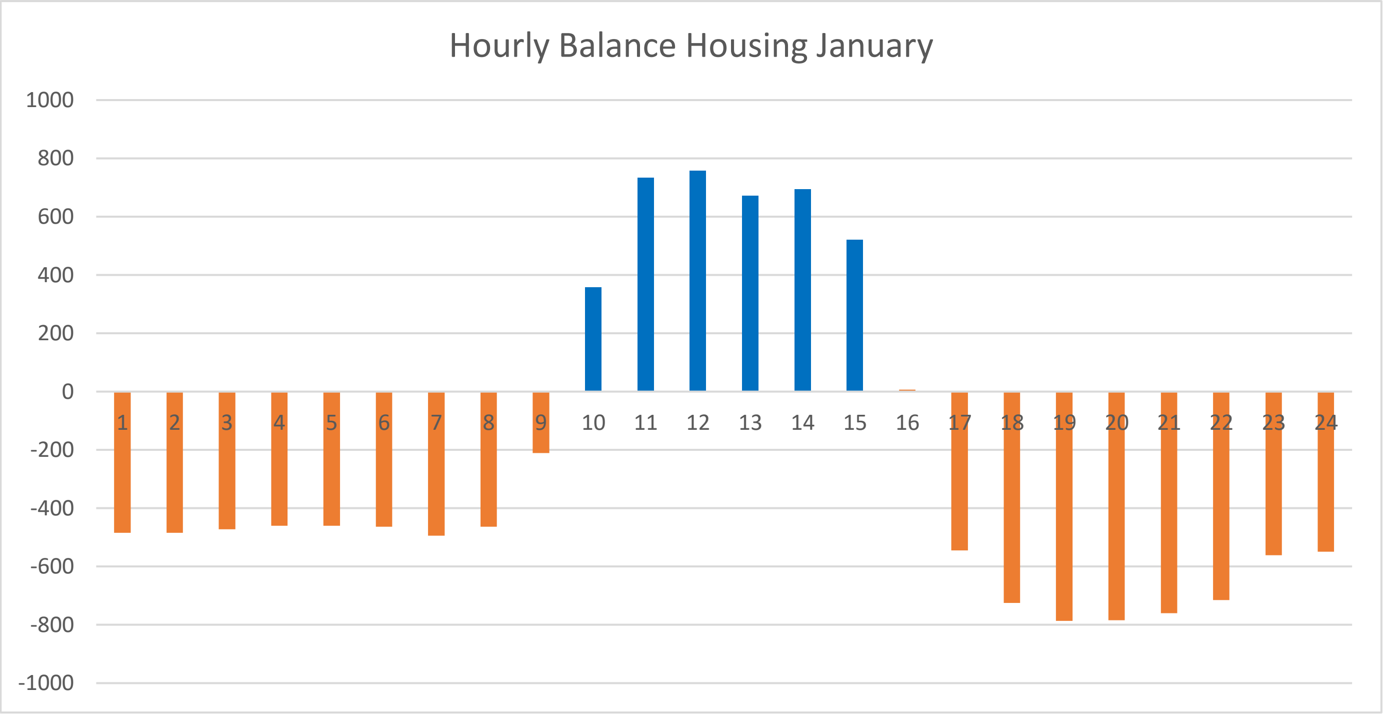
Table A.2. Effective areas of transparent and opaque surfaces by orientation

Total transparent area per function (wall = 50% because of façade ratio)				
	Housing	**Hotel**	**office**	**Courthouse**
ZW	1259,28	2175,12	0	2594,88
ZO	1473,12	861,84	2125,44	3035,52
NO	1259,28	1313,28	1088,64	2594,88
NW	1475,298	865,602	2125,44	3040,008
total	**5466,978**	**5215,842**	**5339,52**	**11265,288**
Agl*Ugl=	4373,5824	4172,6736	4271,616	9012,2304
Awall*Uwal=	606,834558	578,958462	592,68672	1250,446968
Transmission sum	**4980,416958**	**4751,632062**	**4864,30272**	**10262,67737**

Tables A.3. Hourly Balances and energy demand profiles for the housing function

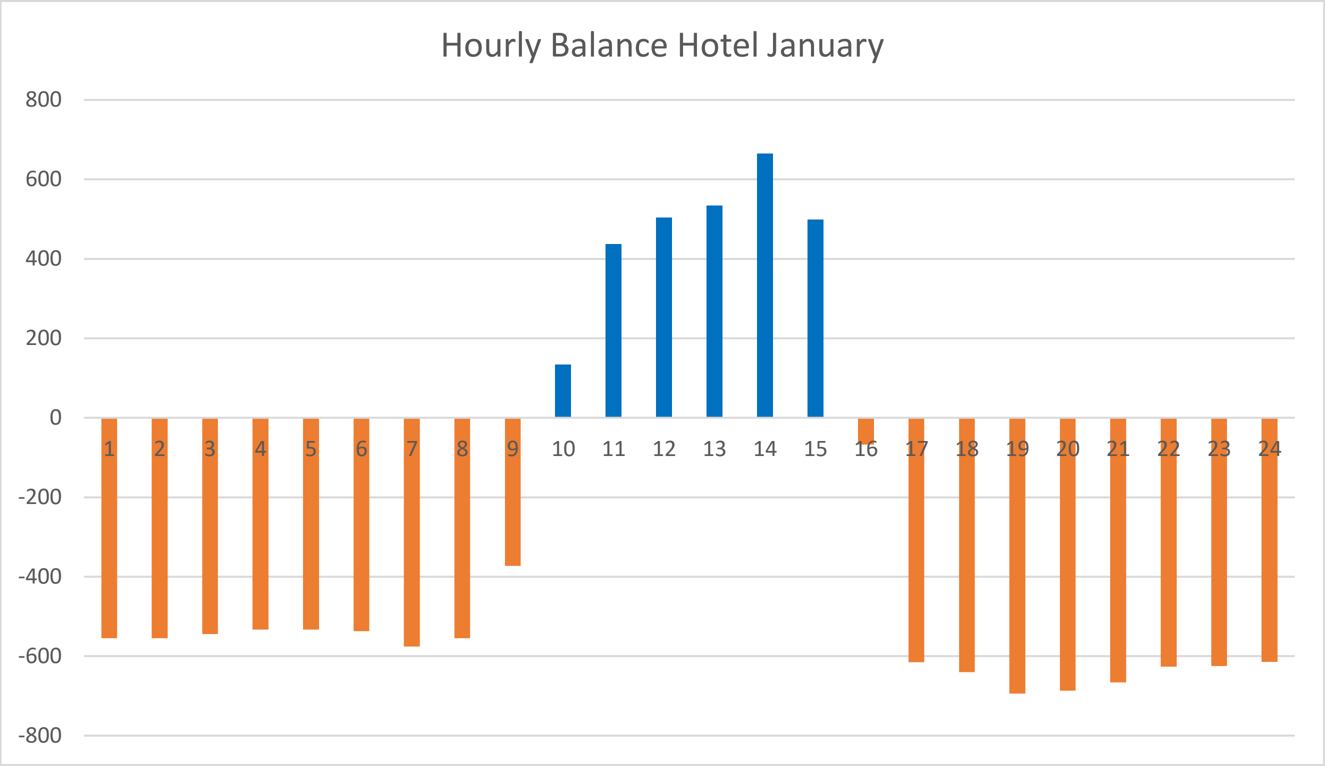
						July					
hour	T,out	T,internal	Qsun	Qpeople	Qappl	Occupancy (people)	Occupancy appl	Internal gain	Transmission	Ventilation	Energy Demand (KWh)
1	17,6	17,6	0	59880	89820	1,0	0,50	104790	0	0	104,8
2	16,6	16,6	0	59880	89820	1,0	0,50	104790	0	0	104,8
3	16	16	0	59880	89820	1,0	0,50	104790	0	0	104,8
4	15,9	15,9	0	59880	89820	1,0	0,50	104790	0	0	104,8
5	16,9	16,9	207736,452	59880	89820	1,0	0,50	104790	0	0	312,5
6	18,4	18,4	921072,537	59880	89820	1,0	0,50	104790	0	0	1025,9
7	20,2	20,2	1265363,649	59880	89820	0,5	0,50	74850	0	0	1340,2
8	21,6	21,6	1324047,087	59880	89820	0,5	0,70	92814	0	0	1416,9
9	22,9	22,9	1464804,891	59880	89820	0,5	0,70	92814	0	0	1557,6
10	23,7	23,7	1798191,45	59880	89820	0,1	0,50	50898	0	0	1849,1
11	24,7	24	1904781,186	59880	89820	0,1	0,50	50898	-3486	-25150	1984,3
12	25	24	1809168,966	59880	89820	0,1	0,60	59880	-4980	-35928	1910,0
13	26	24	1735484,553	59880	89820	0,1	0,60	59880	-9961	-71856	1877,2
14	25,9	24	1895561,91	59880	89820	0,2	0,60	65868	-9463	-68263	2039,2
15	25,8	24	1861593,129	59880	89820	0,2	0,60	65868	-8965	-64670	2001,1
16	25,7	24	1598034,141	59880	89820	0,2	0,50	56886	-8467	-61078	1724,5
17	25,4	24	1356248,322	59880	89820	0,5	0,50	74850	-6973	-50299	1488,4
18	24,6	24	1304316,387	59880	89820	0,5	0,70	92814	-2988	-21557	1421,7
19	23,3	23,3	1080107,127	59880	89820	0,5	0,70	92814	0	0	1172,9
20	21,3	21,3	485365,815	59880	89820	0,8	0,80	119760	0	0	605,1
21	20,4	20,4	0	59880	89820	0,8	0,80	119760	0	0	119,8
22	18,7	18,7	0	59880	89820	0,8	0,80	119760	0	0	119,8
23	18,4	18,4	0	59880	89820	1,0	0,60	113772	0	0	113,8
24	17,3	17,3	0	59880	89820	1,0	0,60	113772	0	0	113,8
								89446	**-2303**	**-16617**	



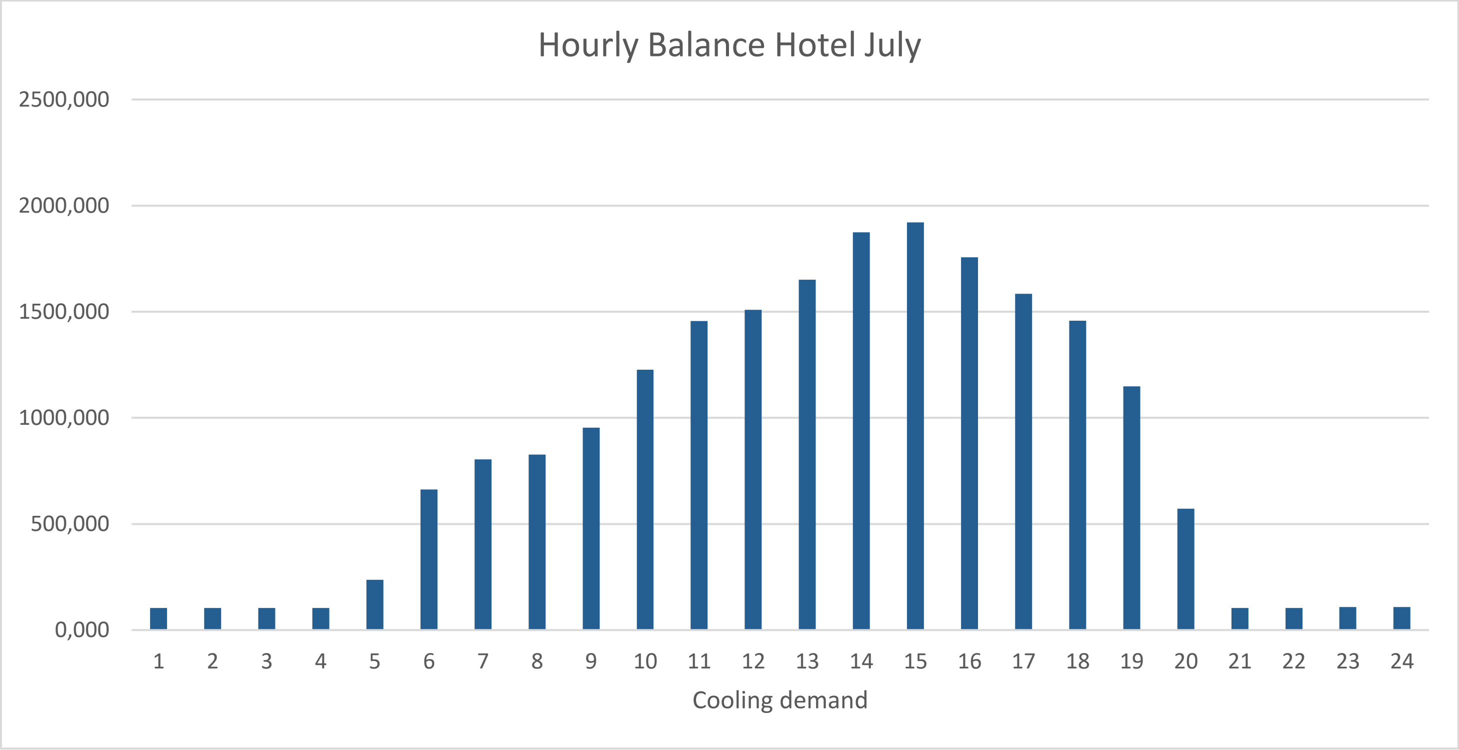


Tables A.4. Hourly Balances and energy demand profiles for the hotel function

January											
hour	Tout	T,internal	Q,sun	Qpeople	Qappl	Occupancy (people)	Occupancy appl	Internal gain	Transmission	Ventilation	Energy Demand (kWh)
1	3,6	22	0	77550	51700	1,0	0,50	103400	87430	570768	-554,7980299
2	3,6	22	0	77550	51700	1,0	0,50	103400	87430	570768	-554,7980299
3	3,9	22	0	77550	51700	1,0	0,50	103400	86005	561462	-544,0665403
4	4,2	22	0	77550	51700	1,0	0,50	103400	84579	552156	-533,3350507
5	4,2	22	0	77550	51700	1,0	0,50	103400	84579	552156	-533,3350507
6	4,1	22	0	77550	51700	1,0	0,50	103400	85054	555258	-536,9122139
7	4,1	22	0	77550	51700	0,5	0,50	64625	85054	555258	-575,6872139
8	4,4	22	0	77550	51700	0,5	0,70	74965	83629	545952	-554,6157243
9	4,7	22	170890,902	77550	51700	0,5	0,70	74965	82203	536646	-372,9933327
10	5	22	708579,027	77550	51700	0,1	0,50	33605	80778	527340	134,0662819
11	5,8	22	982825,578	77550	51700	0,1	0,50	33605	76976	502524	436,9301386
12	5,6	22	1051704,04	77550	51700	0,1	0,60	38775	77927	508728	503,8242702
13	5,3	22	1093313,98	77550	51700	0,1	0,60	38775	79352	518034	534,7027236
14	5,6	22	1205178,08	77550	51700	0,2	0,60	46530	77927	508728	665,0533092
15	4,8	22	1067735,8	77550	51700	0,2	0,60	46530	81728	533544	498,9937275
16	4,1	22	531725,013	77550	51700	0,2	0,50	41360	85054	555258	-67,22720091
17	3	22	0	77550	51700	0,5	0,50	64625	90281	589380	-615,0360092
18	2	22	0	77550	51700	0,5	0,70	74965	95033	620400	-640,4676412
19	0,5	22	0	77550	51700	0,5	0,70	74965	102160	666930	-694,1250893
20	-0,1	22	0	77550	51700	0,8	0,80	103400	105011	685542	-687,1530686
21	0,5	22	0	77550	51700	0,8	0,80	103400	102160	666930	-665,6900893
22	1,6	22	0	77550	51700	0,8	0,80	103400	96933	632808	-626,3412941
23	1,5	22	0	77550	51700	1,0	0,60	108570	97408	635910	-624,7484573
24	1,8	22	0	77550	51700	1,0	0,60	108570	95983	626604	-614,0169677
								77335	**87945**	**574129**	

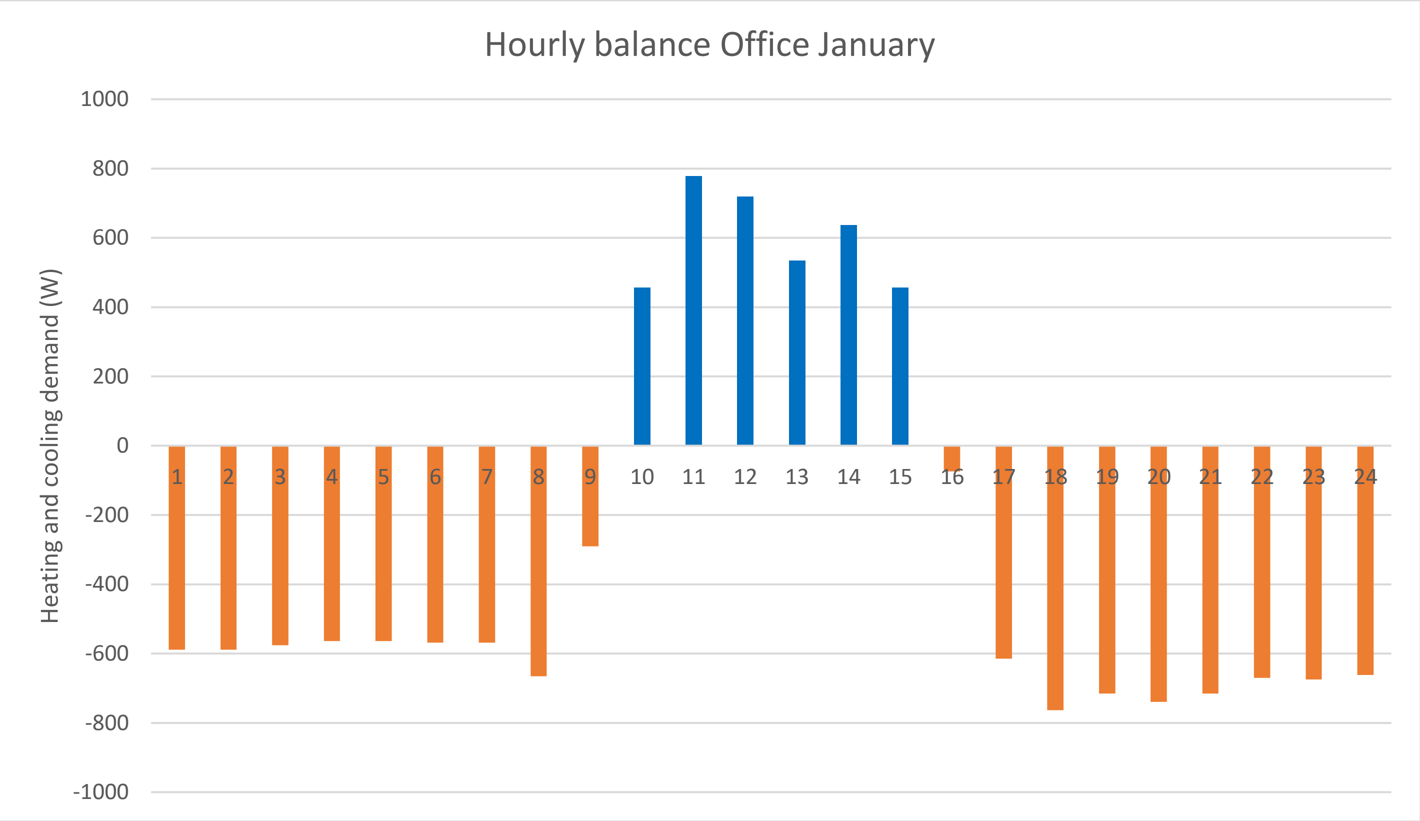


July											
hour	T,out	T,internal	Qsun	Qpeople	Qappl	Occupancy (people)	Occupancy appl	Internal gain	Transmission	Ventilation	Energy Demand (kWh)
1	17,6	17,6	0	77550	51700	1,0	0,50	103400	0	0	103,400
2	16,6	16,6	0	77550	51700	1,0	0,50	103400	0	0	103,400
3	16	16	0	77550	51700	1,0	0,50	103400	0	0	103,400
4	15,9	15,9	0	77550	51700	1,0	0,50	103400	0	0	103,400
5	16,9	16,9	133979,868	77550	51700	1,0	0,50	103400	0	0	237,380
6	18,4	18,4	559792,953	77550	51700	1,0	0,50	103400	0	0	663,193
7	20,2	20,2	739501,641	77550	51700	0,5	0,50	64625	0	0	804,127
8	21,6	21,6	752545,863	77550	51700	0,5	0,70	74965	0	0	827,511
9	22,9	22,9	877990,779	77550	51700	0,5	0,70	74965	0	0	952,956
10	23,7	23,7	1192969,53	77550	51700	0,1	0,50	33605	0	0	1226,575
11	24,7	24	1354548,114	77550	51700	0,1	0,50	33605	-3326	-65142	1456,621
12	25	24	1372397,094	77550	51700	0,1	0,60	38775	-4752	-93060	1508,984
13	26	24	1415953,017	77550	51700	0,1	0,60	38775	-9503	-186120	1650,351
14	25,9	24	1642278,87	77550	51700	0,2	0,60	46530	-9028	-176814	1874,651
15	25,8	24	1698148,161	77550	51700	0,2	0,60	46530	-8553	-167508	1920,739
16	25,7	24	1548350,109	77550	51700	0,2	0,50	41360	-8078	-158202	1755,990
17	25,4	24	1382623,578	77550	51700	0,5	0,50	64625	-6652	-130284	1584,185
18	24,6	24	1324462,203	77550	51700	0,5	0,70	74965	-2851	-55836	1458,114
19	23,3	23,3	1073013,543	77550	51700	0,5	0,70	74965	0	0	1147,979
20	21,3	21,3	469019,655	77550	51700	0,8	0,80	103400	0	0	572,420
21	20,4	20,4	0	77550	51700	0,8	0,80	103400	0	0	103,400
22	18,7	18,7	0	77550	51700	0,8	0,80	103400	0	0	103,400
23	18,4	18,4	0	77550	51700	1,0	0,60	108570	0	0	108,570
24	17,3	17,3	0	77550	51700	1,0	0,60	108570	0	0	108,570
								77335	-2198	-43040	

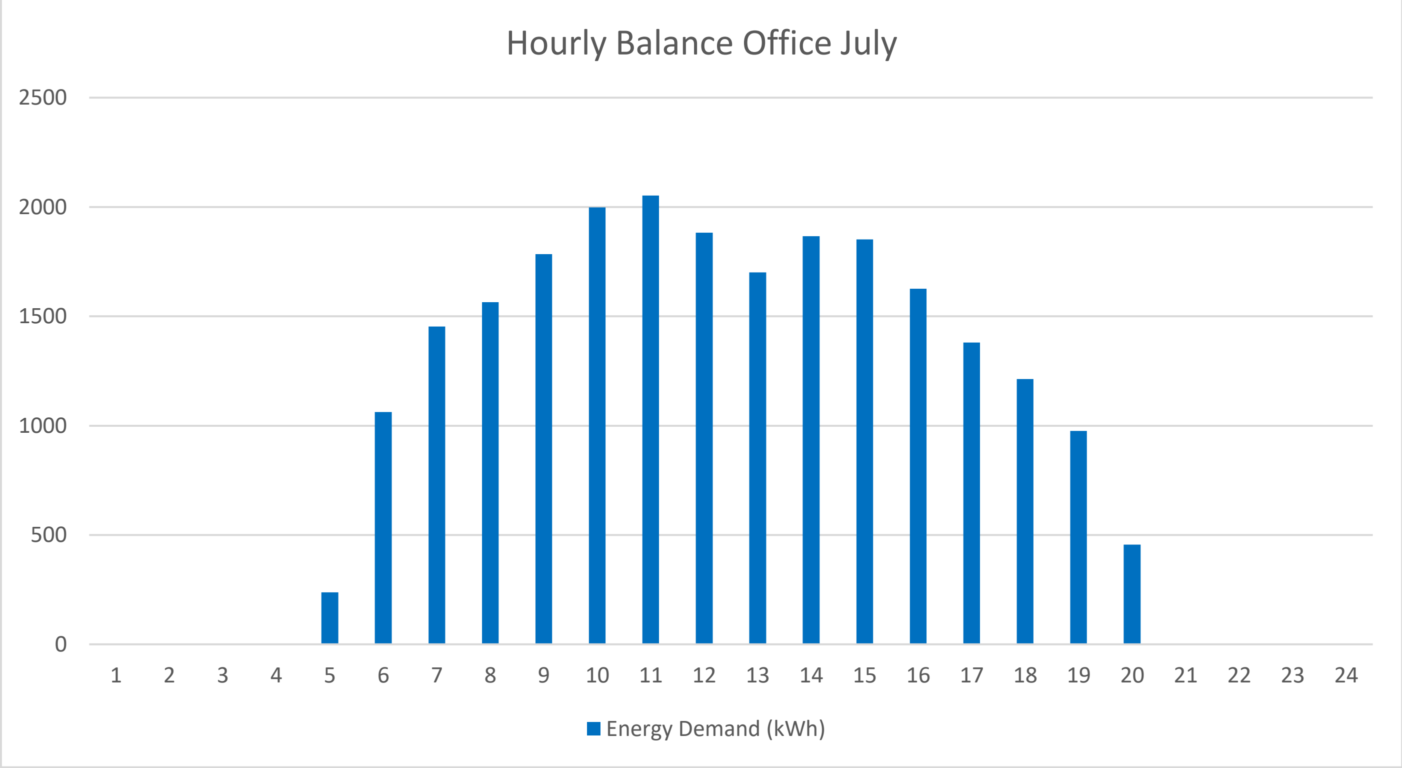


Tables A.5. Hourly Balances and energy demand profiles for the office function

January											
hour	Tout	T,internal	Q,sun	Qpeople	Qappl	Occupancy (people)	Occupancy appl	Internal gain	Transmission	Ventilation	Energy Demand (kWh)
1	3,6	18	0	150000	120000	0,0	0,0	0	70046	518400	-588,4459592
2	3,6	18	0	150000	120000	0,0	0,0	0	70046	518400	-588,4459592
3	3,9	18	0	150000	120000	0,0	0,0	0	68587	507600	-576,1866684
4	4,2	18	0	150000	120000	0,0	0,0	0	67127	496800	-563,9273775
5	4,2	18	0	150000	120000	0,0	0,0	0	67127	496800	-563,9273775
6	4,1	18	0	150000	120000	0,0	0,0	0	67614	500400	-568,0138078
7	4,1	18	0	150000	120000	0,0	0,0	0	67614	500400	-568,0138078
8	4,4	22	0	150000	120000	0,2	0,2	54000	85612	633600	-665,2117279
9	4,7	22	254223,36	150000	120000	0,6	0,6	162000	84152	622800	-290,7290771
10	5	22	988433,28	150000	120000	0,6	0,6	162000	82693	612000	455,7401338
11	5,8	22	1251028,8	150000	120000	0,7	0,7	189000	78802	583200	778,0270959
12	5,6	22	1200666,24	150000	120000	0,7	0,7	189000	79775	590400	719,4916754
13	5,3	22	1109453,76	150000	120000	0,4	0,4	108000	81234	601200	535,0199046
14	5,6	22	1144834,56	150000	120000	0,6	0,6	162000	79775	590400	636,6599954
15	4,8	22	969719,04	150000	120000	0,7	0,7	189000	83666	619200	455,8530332
16	4,1	22	468115,2	150000	120000	0,7	0,7	189000	87071	644400	-74,35581869
17	3	22	0	150000	120000	0,6	0,6	162000	92422	684000	-614,4217517
18	2	22	0	150000	120000	0,2	0,2	54000	97286	720000	-763,2860544
19	0,5	18	0	150000	120000	0,0	0,0	0	85125	630000	-715,1252976
20	-0,1	18	0	150000	120000	0,0	0,0	0	88044	651600	-739,6438792
21	0,5	18	0	150000	120000	0,0	0,0	0	85125	630000	-715,1252976
22	1,6	18	0	150000	120000	0,0	0,0	0	79775	590400	-670,1745646
23	1,5	18	0	150000	120000	0,0	0,0	0	80261	594000	-674,2609949
24	1,8	18	0	150000	120000	0,0	0,0	0	78802	583200	-662,0017041
								67500			



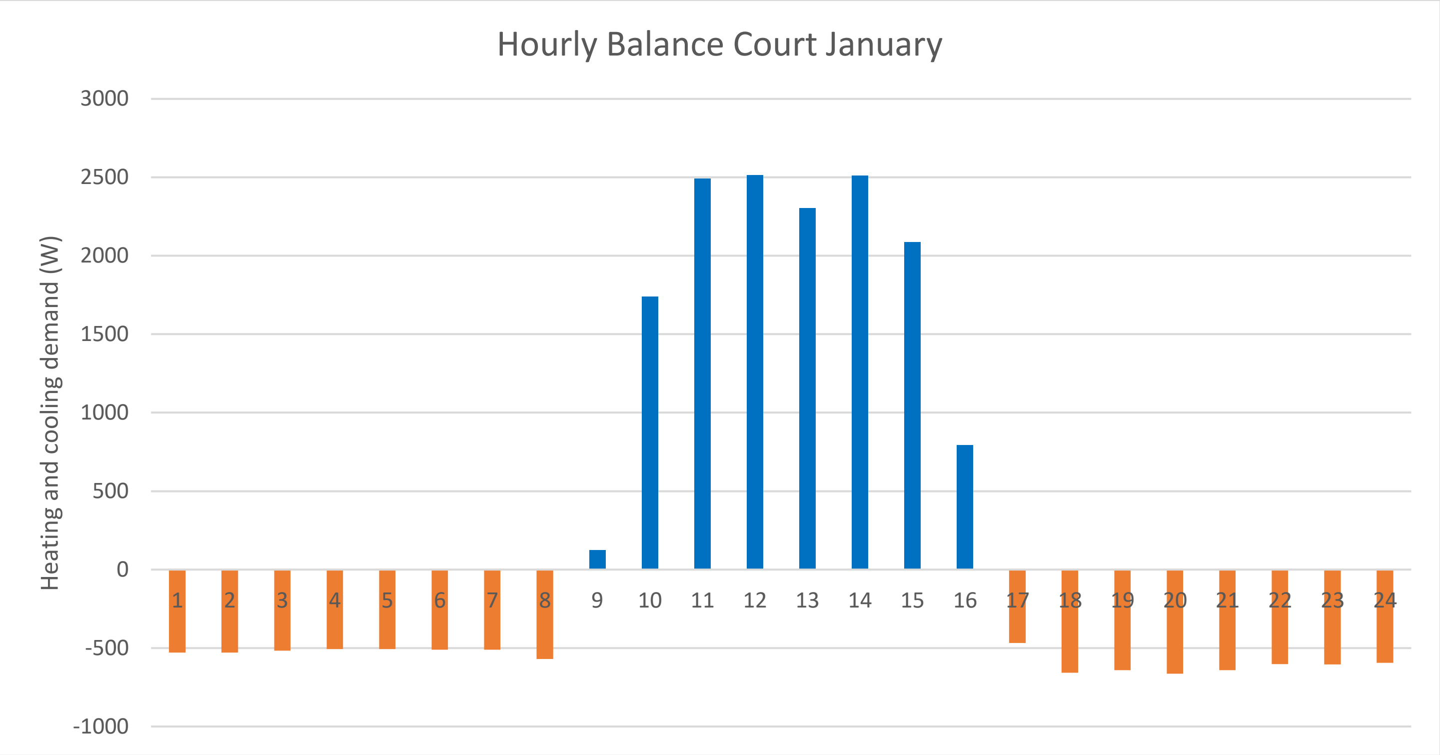
July											
hour	T,out	T,internal	Qsun	Qpeople	Qappl	Occupancy (people)	Occupancy appl	Internal gain	Transmission	Ventilation	Energy Demand (kWh)
1	17,6	17,6	0	150000	120000	0,0	0,0	0	0	0	0
2	16,6	16,6	0	150000	120000	0,0	0,0	0	0	0	0
3	16	16	0	150000	120000	0,0	0,0	0	0	0	0
4	15,9	15,9	0	150000	120000	0,0	0,0	0	0	0	0
5	16,9	16,9	238282,56	150000	120000	0,0	0,0	0	0	0	238
6	18,4	18,4	1062460,8	150000	120000	0,0	0,0	0	0	0	1062
7	20,2	20,2	1453826,88	150000	120000	0,0	0,0	0	0	0	1454
8	21,6	21,6	1510410,24	150000	120000	0,2	0,2	54000	0	0	1564
9	22,9	22,9	1622592	150000	120000	0,6	0,6	162000	0	0	1785
10	23,7	23,7	1836172,8	150000	120000	0,6	0,6	162000	0	0	1998
11	24,7	24	1835239,68	150000	120000	0,7	0,7	189000	-3405	-25200	2053
12	25	24	1653073,92	150000	120000	0,7	0,7	189000	-4864	-36000	1883
13	26	24	1511861,76	150000	120000	0,4	0,4	108000	-9729	-72000	1702
14	25,9	24	1627490,88	150000	120000	0,6	0,6	162000	-9242	-68400	1867
15	25,8	24	1589492,16	150000	120000	0,7	0,7	189000	-8756	-64800	1852
16	25,7	24	1367513,28	150000	120000	0,7	0,7	189000	-8269	-61200	1626
17	25,4	24	1161449,28	150000	120000	0,6	0,6	162000	-6810	-50400	1381
18	24,6	24	1134129,6	150000	120000	0,2	0,2	54000	-2919	-21600	1213
19	23,3	23,3	975628,8	150000	120000	0,0	0,0	0	0	0	976
20	21,3	21,3	455647,68	150000	120000	0,0	0,0	0	0	0	456
21	20,4	20,4	0	150000	120000	0,0	0,0	0	0	0	0
22	18,7	18,7	0	150000	120000	0,0	0,0	0	0	0	0
23	18,4	18,4	0	150000	120000	0,0	0,0	0	0	0	0
24	17,3	17,3	0	150000	120000	0,0	0,0	0	0	0	0



Tables A.6. Hourly Balances and energy demand profiles for the courthouse function

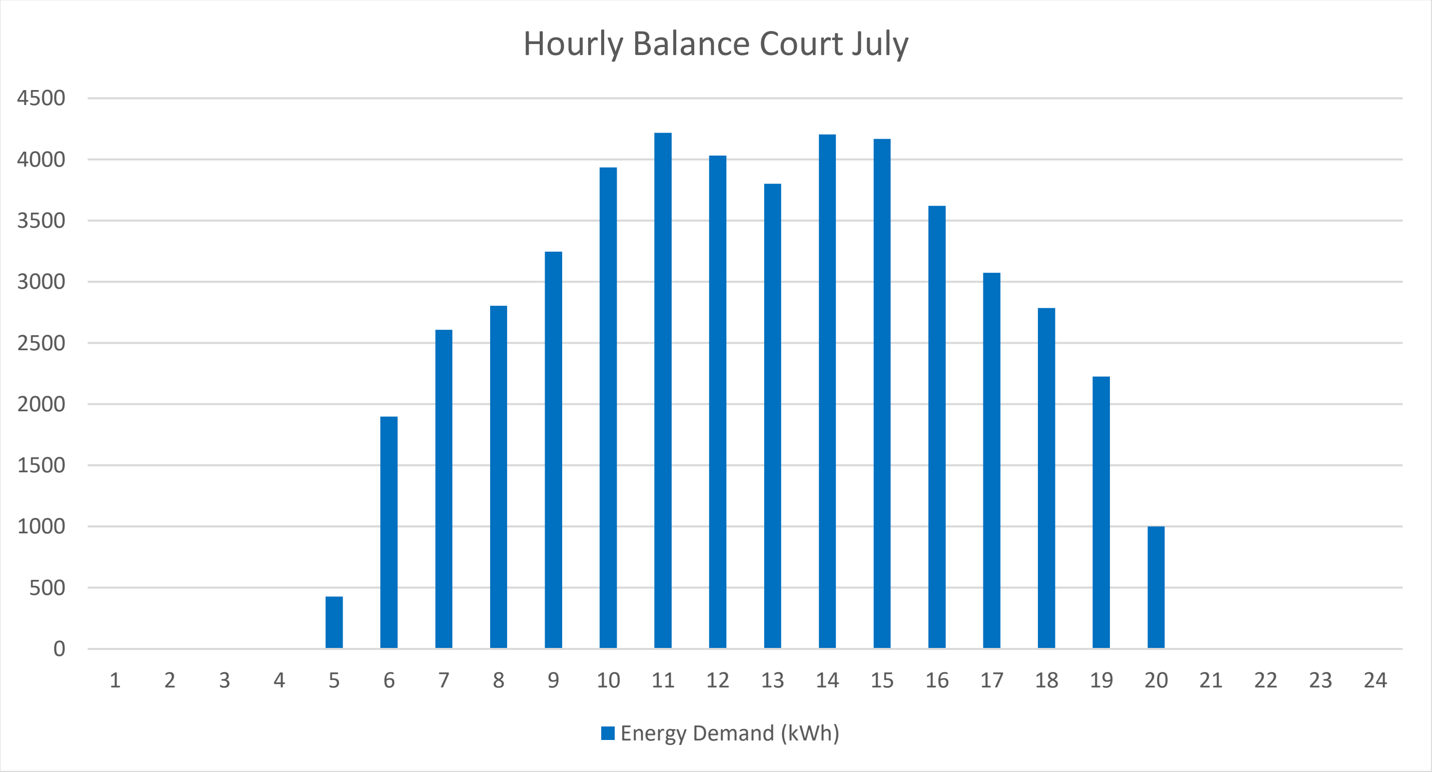
January

hour	Tout	T,internal	Q,sun	Qpeople	Qappl	Occupancy (people)	Occupancy appl	Internal gain	Transmission	Ventilation	Energy Demand (kWh)
1	3,6	18	0	116150	264240	0,0	0,0	0	147783	380506	-528,2881541
2	3,6	18	0	116150	264240	0,0	0,0	0	147783	380506	-528,2881541
3	3,9	18	0	116150	264240	0,0	0,0	0	144704	372578	-517,2821509
4	4,2	18	0	116150	264240	0,0	0,0	0	141625	364651	-506,2761477
5	4,2	18	0	116150	264240	0,0	0,0	0	141625	364651	-506,2761477
6	4,1	18	0	116150	264240	0,0	0,0	0	142651	367294	-509,9448154
7	4,1	18	0	116150	264240	0,0	0,0	0	142651	367294	-509,9448154
8	4,4	22	0	116150	264240	0,2	0,2	76078	180623	465062	-569,6075217
9	4,7	22	529306,968	116150	264240	0,6	0,6	228234	177544	457135	122,8614495
10	5	22	2134071,95	116150	264240	0,6	0,6	228234	174466	449208	1738,632433
11	5,8	22	2818235,11	116150	264240	0,7	0,7	266273	166255	428069	2490,183939
12	5,6	22	2849242,7	116150	264240	0,7	0,7	266273	168308	433354	2513,854195
13	5,3	22	2764928,08	116150	264240	0,4	0,4	152156	171387	441281	2304,416564
14	5,6	22	2883471,66	116150	264240	0,6	0,6	228234	168308	433354	2510,044151
15	4,8	22	2452844,8	116150	264240	0,7	0,7	266273	176518	454493	2088,106945
16	4,1	22	1182861,97	116150	264240	0,7	0,7	266273	183702	472990	792,4434471
17	3	22	0	116150	264240	0,6	0,6	228234	194991	502056	-468,81287
18	2	22	0	116150	264240	0,2	0,2	76078	205254	528480	-657,6555474
19	0,5	18	0	116150	264240	0,0	0,0	0	179597	462420	-642,0168539
20	-0,1	18	0	116150	264240	0,0	0,0	0	185754	478274	-664,0288604
21	0,5	18	0	116150	264240	0,0	0,0	0	179597	462420	-642,0168539
22	1,6	18	0	116150	264240	0,0	0,0	0	168308	433354	-601,6615088
23	1,5	18	0	116150	264240	0,0	0,0	0	169334	435996	-605,3301766
24	1,8	18	0	116150	264240	0,0	0,0	0	166255	428069	-594,3241734
								95098			


Hourly Balance Court January

July

hour	T,out	T,internal	Qsun	Qpeople	Qappl	Occupancy (people)	Occupancy appl	Internal gain	Transmission	Ventilation	Energy Demand (kWh)
1	17,6	17,6	0	116150	264240	0,0	0,0	0	0	0	0
2	16,6	16,6	0	116150	264240	0,0	0,0	0	0	0	0
3	16	16	0	116150	264240	0,0	0,0	0	0	0	0
4	15,9	15,9	0	116150	264240	0,0	0,0	0	0	0	0
5	16,9	16,9	428062,992	116150	264240	0,0	0,0	0	0	0	428,062992
6	18,4	18,4	1897967,652	116150	264240	0,0	0,0	0	0	0	1897,967652
7	20,2	20,2	2607416,004	116150	264240	0,0	0,0	0	0	0	2607,416004
8	21,6	21,6	2728339,452	116150	264240	0,2	0,2	76078	0	0	2804,417452
9	22,9	22,9	3018385,836	116150	264240	0,6	0,6	228234	0	0	3246,619836
10	23,7	23,7	3705364,2	116150	264240	0,6	0,6	228234	0	0	3933,5982
11	24,7	24	3925003,656	116150	264240	0,7	0,7	266273	-7184	-18497	4216,95733
12	25	24	3727984,536	116150	264240	0,7	0,7	266273	-10263	-26424	4030,944213
13	26	24	3576149,988	116150	264240	0,4	0,4	152156	-20525	-52848	3801,679343
14	25,9	24	3906006,36	116150	264240	0,6	0,6	228234	-19499	-50206	4203,945047
15	25,8	24	3836010,084	116150	264240	0,7	0,7	266273	-18473	-47563	4168,319103
16	25,7	24	3292918,836	116150	264240	0,7	0,7	266273	-17447	-44921	3621,559188
17	25,4	24	2794693,512	116150	264240	0,6	0,6	228234	-14368	-36994	3074,28886
18	24,6	24	2687682,252	116150	264240	0,2	0,2	76078	-6158	-15854	2785,772258
19	23,3	23,3	2225675,292	116150	264240	0,0	0,0	0	0	0	2225,675292
20	21,3	21,3	1000147,74	116150	264240	0,0	0,0	0	0	0	1000,14774
21	20,4	20,4	0	116150	264240	0,0	0,0	0	0	0	0
22	18,7	18,7	0	116150	264240	0,0	0,0	0	0	0	0
23	18,4	18,4	0	116150	264240	0,0	0,0	0	0	0	0
24	17,3	17,3	0	116150	264240	0,0	0,0	0	0	0	0


Hourly Balance Court July

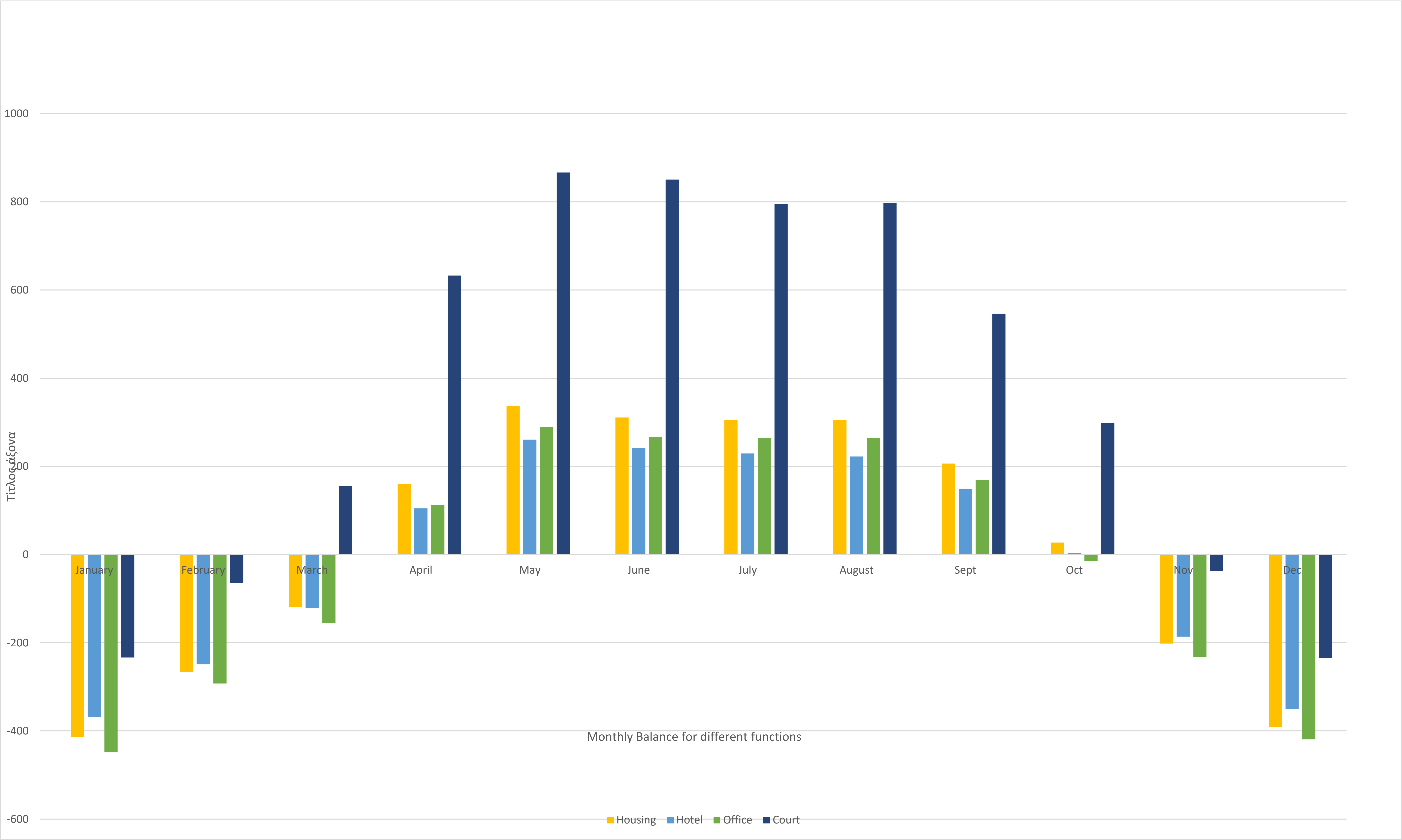

1000
800
600
400
200
0
-200
-400
-600
Τίτλος άξονα
January
February
March
April
May
June
July
August
Sept
Oct
Nov
Dec
Monthly Balance for different functions
Housing
Hotel
Office
Court

Table A.7. – Monthly balances for the different functions

			Total energy demand (MWh)			
Month	Avg. Outdoor Temp.(o C)	Hours per month	Housing	Hotel	Office	Court
January	2,6	744	-414,49	-368,54	-448,31	-233,31
February	5	672	-265,81	-248,64	-292,56	-63,79
March	6,8	744	-119,19	-121,00	-155,78	155,58
April	9,3	720	160,32	105,04	112,92	632,90
May	13,3	744	337,58	260,87	289,82	866,57
June	16	720	310,96	241,26	267,22	850,77
July	17,4	744	304,62	229,30	265,07	795,10
August	17,4	744	305,59	222,62	265,09	797,10
Sept	14,6	720	206,41	149,17	168,94	546,20
Oct	11,3	744	27,32	3,51	-14,09	298,08
Nov	7,1	720	-201,72	-185,95	-231,76	-37,70
Dec	4	744	-390,85	-350,29	-419,15	-234,18

Housing

Month	Avg. Outdoor Temp.(o C)	Indoor temperature	Hours per month	Solar Gains	Int gains	Transmission	Ventilation	Energy Demand (MWh)
January	2,6	22	744	147062,50	89446	96620,09	697003,2	-414,49
February	5	22	672	210448,74	89446	84667,09	610776	-265,81
March	6,8	20	744	290339,62	89446	65741,50	474249,6	-119,19
April	9,3	20	720	570940,94	89446	53290,46	384429,6	160,32
May	13,3	20	744	638380,69	89446	33368,79	240717,6	337,58
June	16	24	720	669716,49	89446	39843,34	287424	310,96
July	17,4	24	744	589980,50	89446	32870,75	237124,8	304,62
August	17,4	24	744	591287,82	89446	32870,75	237124,8	305,59
Sept	14,6	20	720	418139,96	89446	26894,25	194011,2	206,41
Oct	11,3	20	744	303172,71	89446	43329,63	312573,6	27,32
Nov	7,1	20	720	158109,65	89446	64247,38	463471,2	-201,72
Dec	4	22	744	121569,92	89446	89647,51	646704	-390,85

Hotel

Month	Avg. Outdoor Temp.(o C)	Indoor temperature	Hours per month	Solar Gains	Int gains	Transmission	Ventilation	Energy Demand (MWh)
January	2,6	22	744	121281,37	77335	92181,66	601788	-368,54
February	5	22	672	160781,18	77335	80777,75	527340	-248,64
March	6,8	20	744	232211,74	77335	62721,54	409464	-121,00
April	9,3	20	720	451312,81	77335	50842,46	331914	105,04
May	13,3	20	744	512970,21	77335	31835,93	207834	260,87
June	16	24	720	543920,39	77335	38013,06	248160	241,26
July	17,4	24	744	466958,42	77335	31360,77	204732	229,30
August	17,4	24	744	457983,86	77335	31360,77	204732	222,62
Sept	14,6	20	720	323016,95	77335	25658,81	167508	149,17
Oct	11,3	20	744	238589,90	77335	41339,20	269874	3,51
Nov	7,1	20	720	125859,28	77335	61296,05	400158	-185,95
Dec	4	22	744	95737,26	77335	85529,38	558360	-350,29

Office

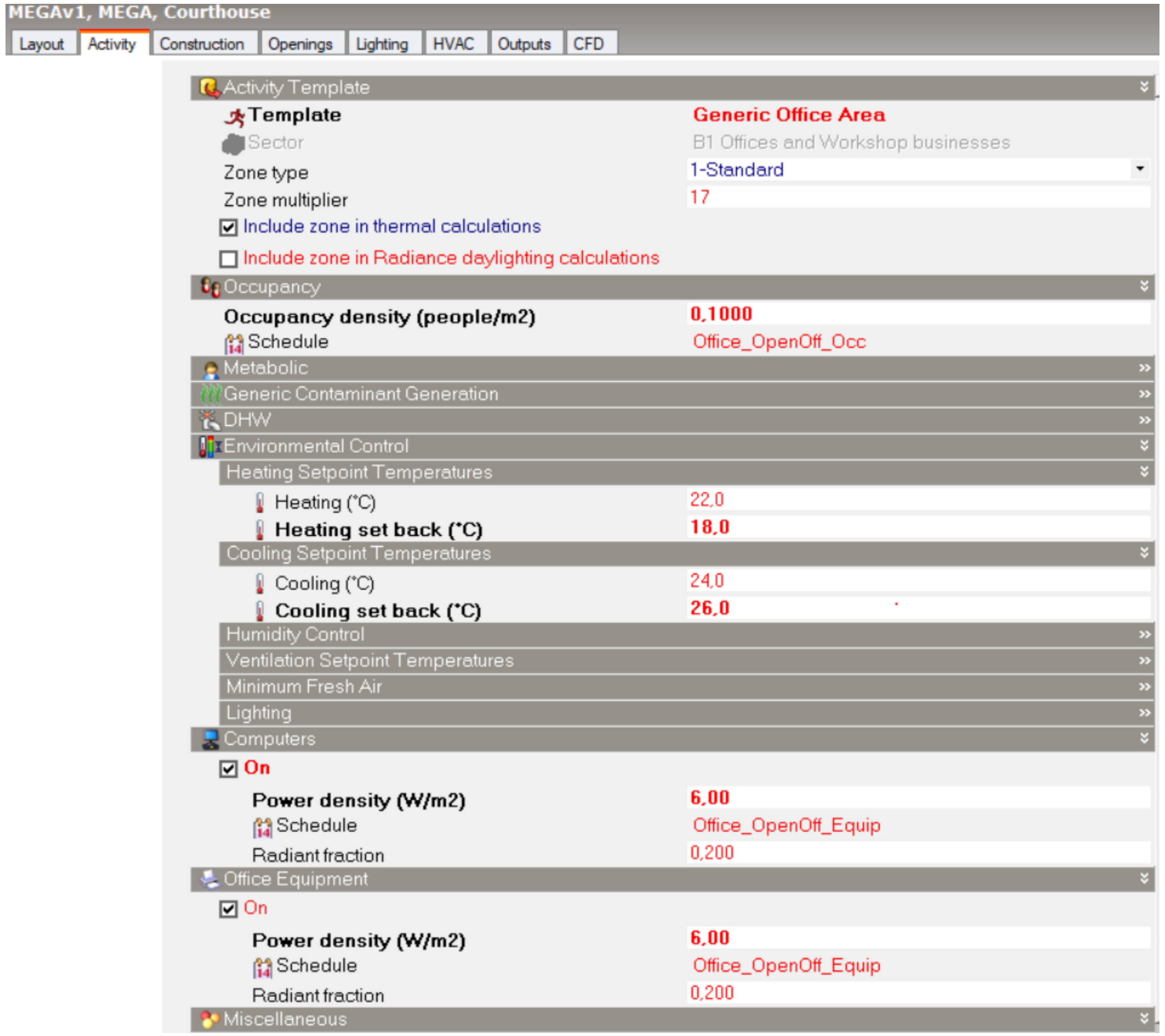
Month	Avg. Outdoor Temp.(o C)	Indoor temperature	Hours per month	Solar Gains	Int gains	Transmission	Ventilation	Energy Demand (MWh)
January	2,6	22	744	122705,28	67500	94367,47	698400	-448,31
February	5	22	672	191839,10	67500	82693,15	612000	-292,56
March	6,8	20	744	262528,13	67500	64208,80	475200	-155,78
April	9,3	20	720	526575,17	67500	52048,04	385200	112,92
May	13,3	20	744	595833,41	67500	32590,83	241200	289,82
June	16	24	720	630550,66	67500	38914,42	288000	267,22
July	17,4	24	744	558477,50	67500	32104,40	237600	265,07
August	17,4	24	744	558513,79	67500	32104,40	237600	265,09
Sept	14,6	20	720	387799,49	67500	26267,23	194400	168,94
Oct	11,3	20	744	269080,70	67500	42319,43	313200	-14,09
Nov	7,1	20	720	137759,62	67500	62749,51	464400	-231,76
Dec	4	22	744	104685,70	67500	87557,45	648000	-419,15

Courthouse

Month	Avg. Outdoor Temp.(o C)	Indoor temperature	Hours per month	Solar Gains	Int gains	Transmission	Ventilation	Energy Demand (MWh)
January	2,6	22	744	303037,88	95098	199095,94	512625,6	-233,31
February	5	22	672	433651,94	95098	174465,52	449208	-63,79
March	6,8	20	744	598275,57	95098	135467,34	348796,8	155,58
April	9,3	20	720	1176484,36	95098	109810,65	282736,8	632,90
May	13,3	20	744	1315451,12	95098	68759,94	177040,8	866,57
June	16	24	720	1380021,85	95098	82101,42	211392	850,77
July	17,4	24	744	1215717,40	95098	67733,67	174398,4	795,10
August	17,4	24	744	1218411,26	95098	67733,67	174398,4	797,10
Sept	14,6	20	720	861621,74	95098	55418,46	142689,6	546,20
Oct	11,3	20	744	624719,52	95098	89285,29	229888,8	298,08
Nov	7,1	20	720	325801,71	95098	132388,54	340869,6	-37,70
Dec	4	22	744	250507,72	95098	184728,19	475632	-234,18

9.2. APPENDIX 2: Design Builder Simulation

MEGA Building



MEGAv1, MEGA, Courthouse

Activity Template

Template	**Generic Office Area**
Sector	B1 Offices and Workshop businesses
Zone type	1-Standard
Zone multiplier	17

☑ Include zone in thermal calculations

☐ Include zone in Radiance daylighting calculations

Occupancy

Occupancy density (people/m2)	**0,1000**
Schedule	Office_OpenOff_Occ

Metabolic

Generic Contaminant Generation

DHW

Environmental Control

Heating Setpoint Temperatures

Heating (°C)	22,0
Heating set back (°C)	**18,0**

Cooling Setpoint Temperatures

Cooling (°C)	24,0
Cooling set back (°C)	**26,0**

Humidity Control

Ventilation Setpoint Temperatures

Minimum Fresh Air

Lighting

Computers

☑ **On**

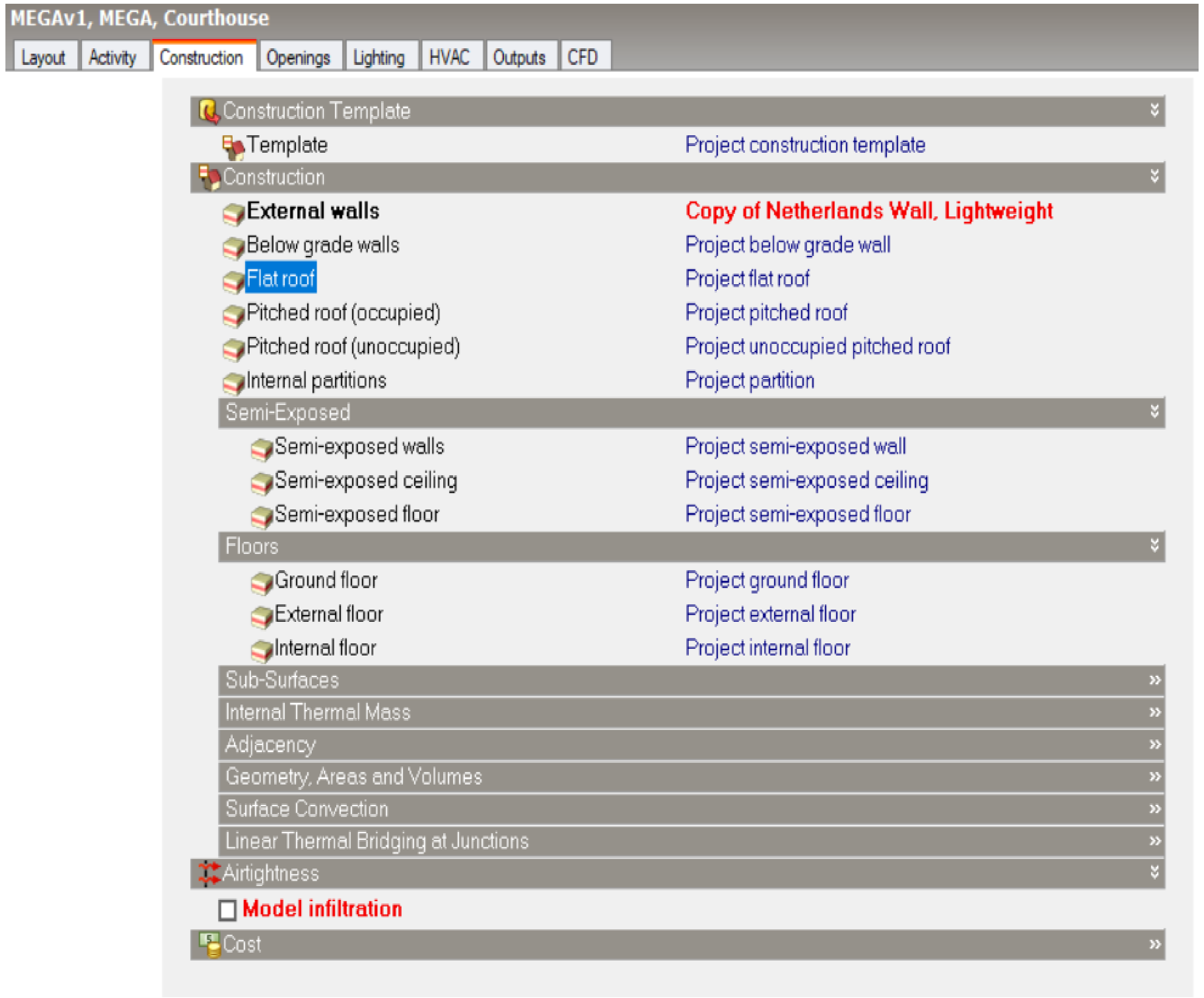
Power density (W/m2)	**6,00**
Schedule	Office_OpenOff_Equip
Radiant fraction	0,200

Office Equipment

☑ On

Power density (W/m2)	**6,00**
Schedule	Office_OpenOff_Equip
Radiant fraction	0,200

Miscellaneous



MEGAv1, MEGA, Courthouse

Construction Template

Template	Project construction template

Construction

External walls	**Copy of Netherlands Wall, Lightweight**
Below grade walls	Project below grade wall
Flat roof	Project flat roof
Pitched roof (occupied)	Project pitched roof
Pitched roof (unoccupied)	Project unoccupied pitched roof
Internal partitions	Project partition

Semi-Exposed

Semi-exposed walls	Project semi-exposed wall
Semi-exposed ceiling	Project semi-exposed ceiling
Semi-exposed floor	Project semi-exposed floor

Floors

Ground floor	Project ground floor
External floor	Project external floor
Internal floor	Project internal floor

Sub-Surfaces

Internal Thermal Mass

Adjacency

Geometry, Areas and Volumes

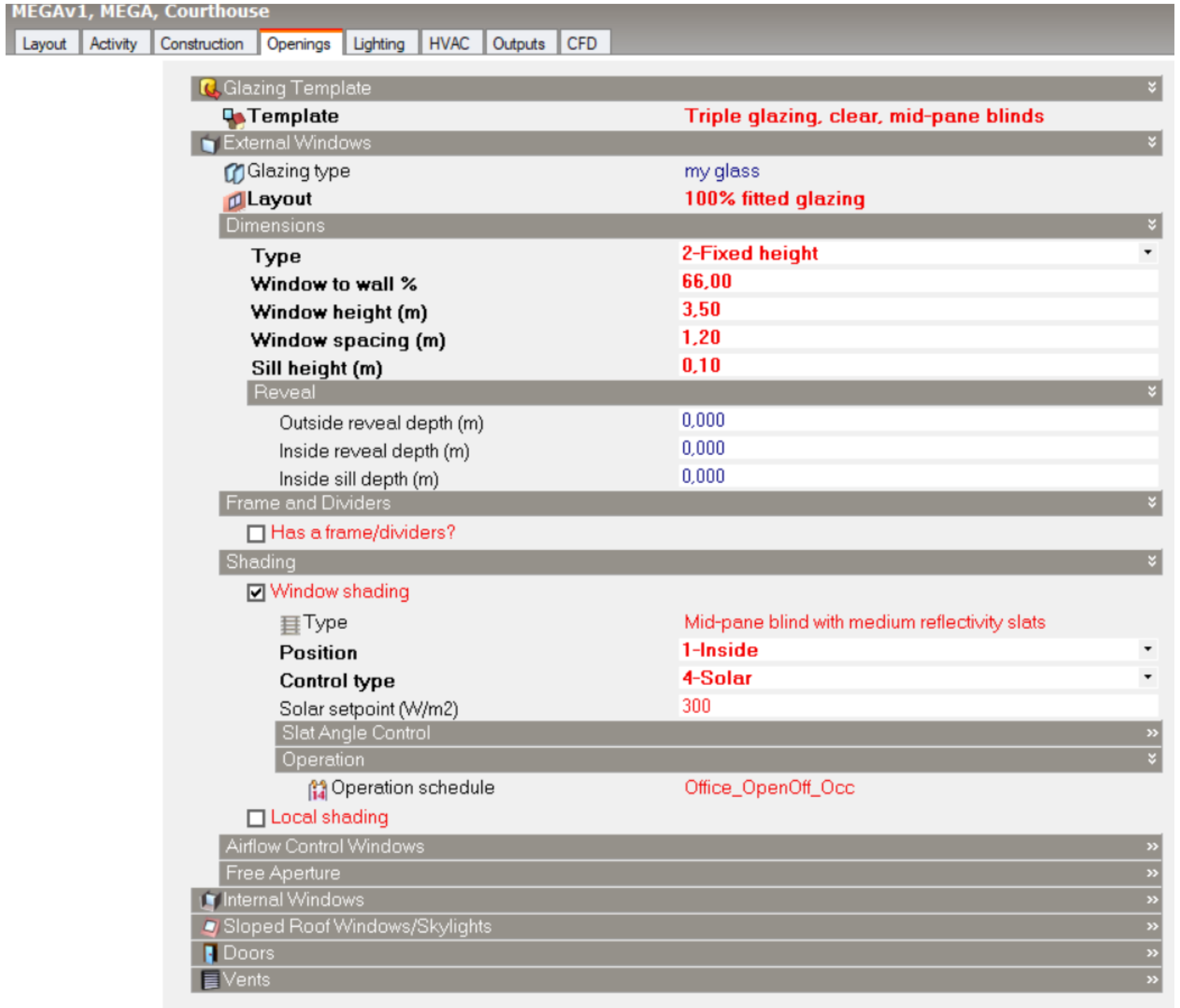
Surface Convection

Linear Thermal Bridging at Junctions

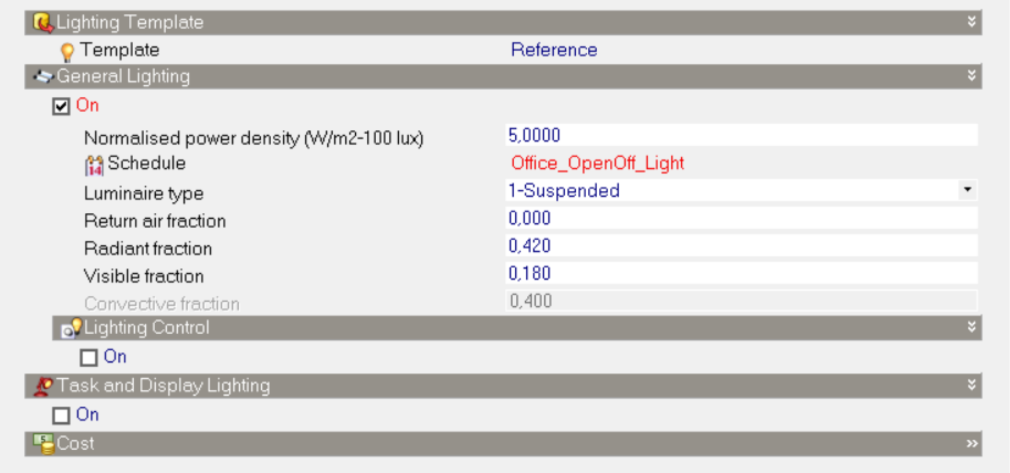
Airtightness

☐ **Model infiltration**

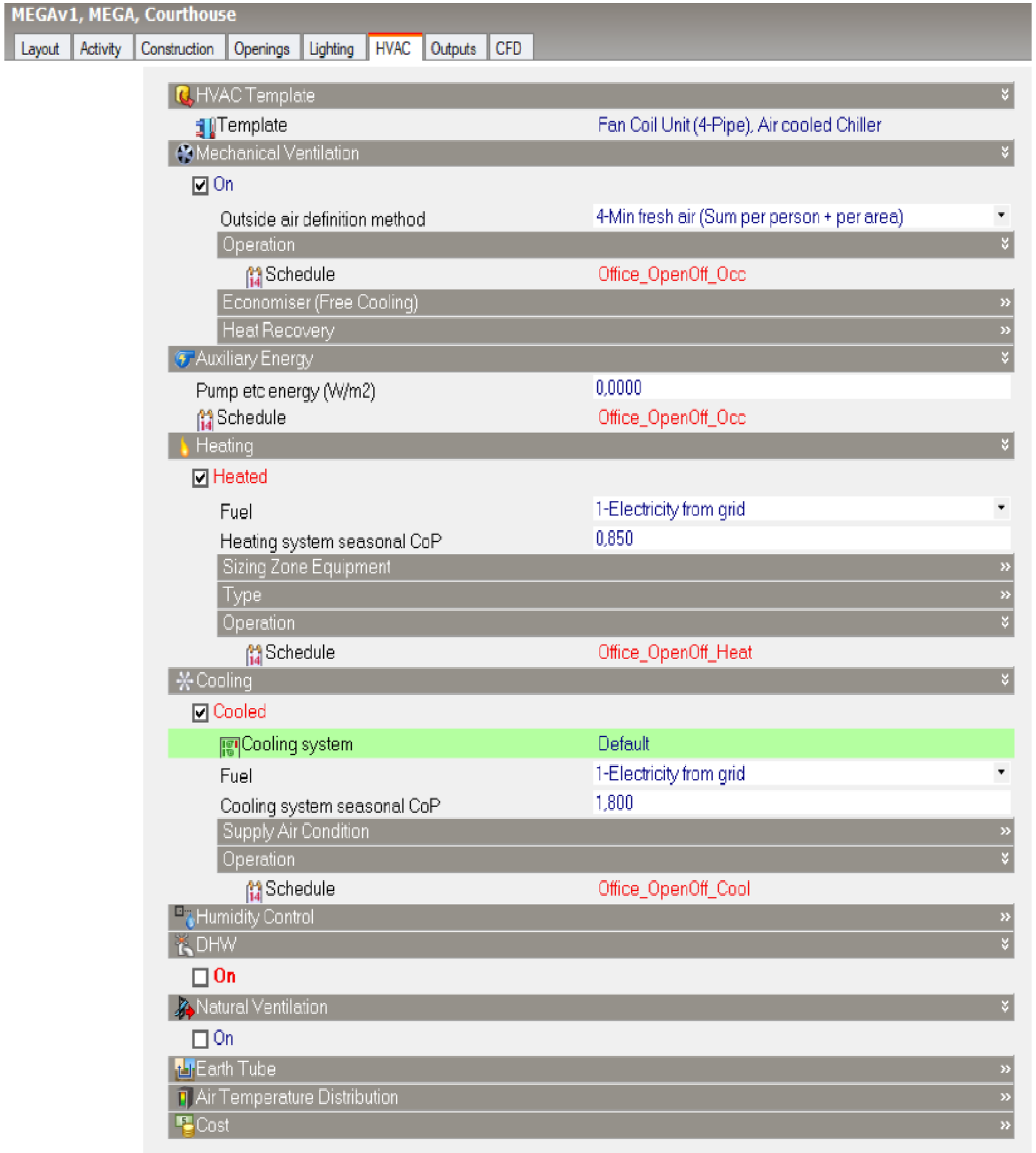
Cost



Glazing Template	
Template	**Triple glazing, clear, mid-pane blinds**
External Windows	
Glazing type	my glass
Layout	**100% fitted glazing**
Dimensions	
Type	**2-Fixed height**
Window to wall %	**66,00**
Window height (m)	**3,50**
Window spacing (m)	**1,20**
Sill height (m)	**0,10**
Reveal	
Outside reveal depth (m)	0,000
Inside reveal depth (m)	0,000
Inside sill depth (m)	0,000
Frame and Dividers	
☐ Has a frame/dividers?	
Shading	
☑ Window shading	
Type	Mid-pane blind with medium reflectivity slats
Position	**1-Inside**
Control type	**4-Solar**
Solar setpoint (W/m2)	300
Slat Angle Control	
Operation	
Operation schedule	Office_OpenOff_Occ
☐ Local shading	
Airflow Control Windows	
Free Aperture	
Internal Windows	
Sloped Roof Windows/Skylights	
Doors	
Vents	

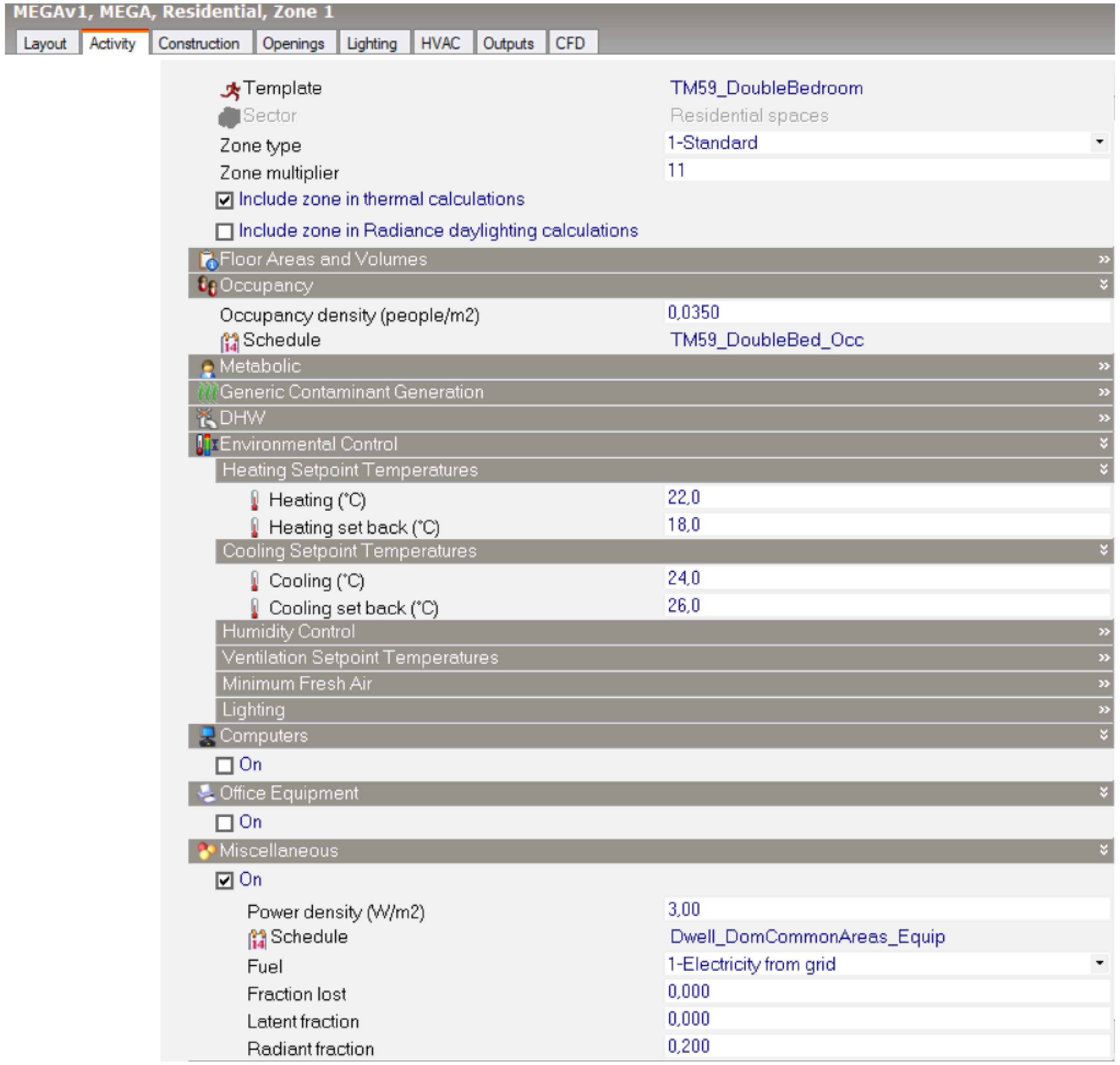


Lighting Template	
Template	Reference
General Lighting	
☑ On	
Normalised power density (W/m2-100 lux)	5,0000
Schedule	Office_OpenOff_Light
Luminaire type	1-Suspended
Return air fraction	0,000
Radiant fraction	0,420
Visible fraction	0,180
Convective fraction	0,400
Lighting Control	
☐ On	
Task and Display Lighting	
☐ On	
Cost	



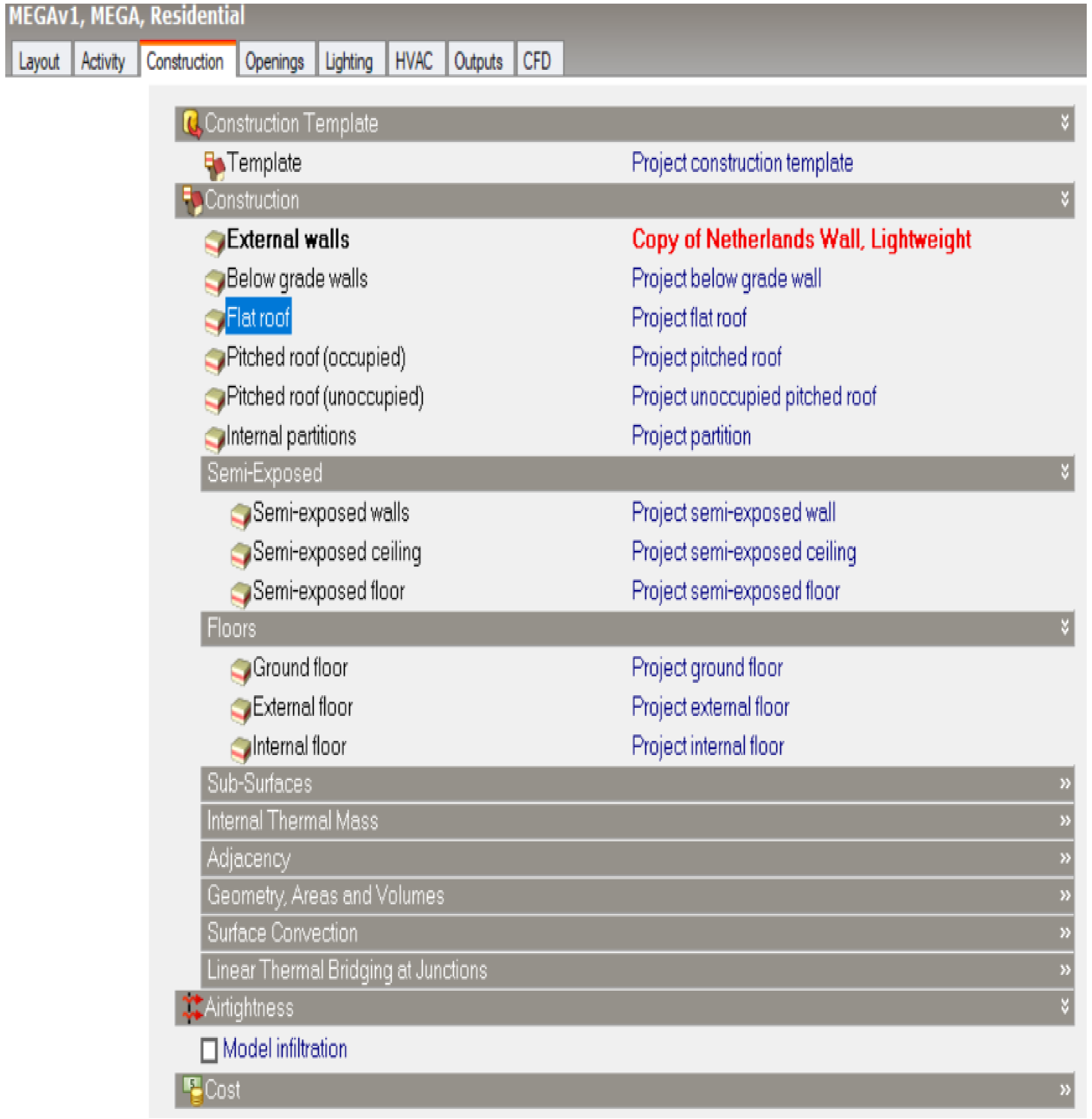
HVAC Template	
Template	Fan Coil Unit (4-Pipe), Air cooled Chiller
Mechanical Ventilation	
☑ On	
Outside air definition method	4-Min fresh air (Sum per person + per area)
Operation	
Schedule	Office_OpenOff_Occ
Economiser (Free Cooling)	
Heat Recovery	
Auxiliary Energy	
Pump etc energy (W/m2)	0,0000
Schedule	Office_OpenOff_Occ
Heating	
☑ Heated	
Fuel	1-Electricity from grid
Heating system seasonal CoP	0,850
Sizing Zone Equipment	
Type	
Operation	
Schedule	Office_OpenOff_Heat
Cooling	
☑ Cooled	
Cooling system	Default
Fuel	1-Electricity from grid
Cooling system seasonal CoP	1,800
Supply Air Condition	
Operation	
Schedule	Office_OpenOff_Cool
Humidity Control	
DHW	
☐ **On**	
Natural Ventilation	
☐ On	
Earth Tube	
Air Temperature Distribution	
Cost	

Residential function = Hotel function



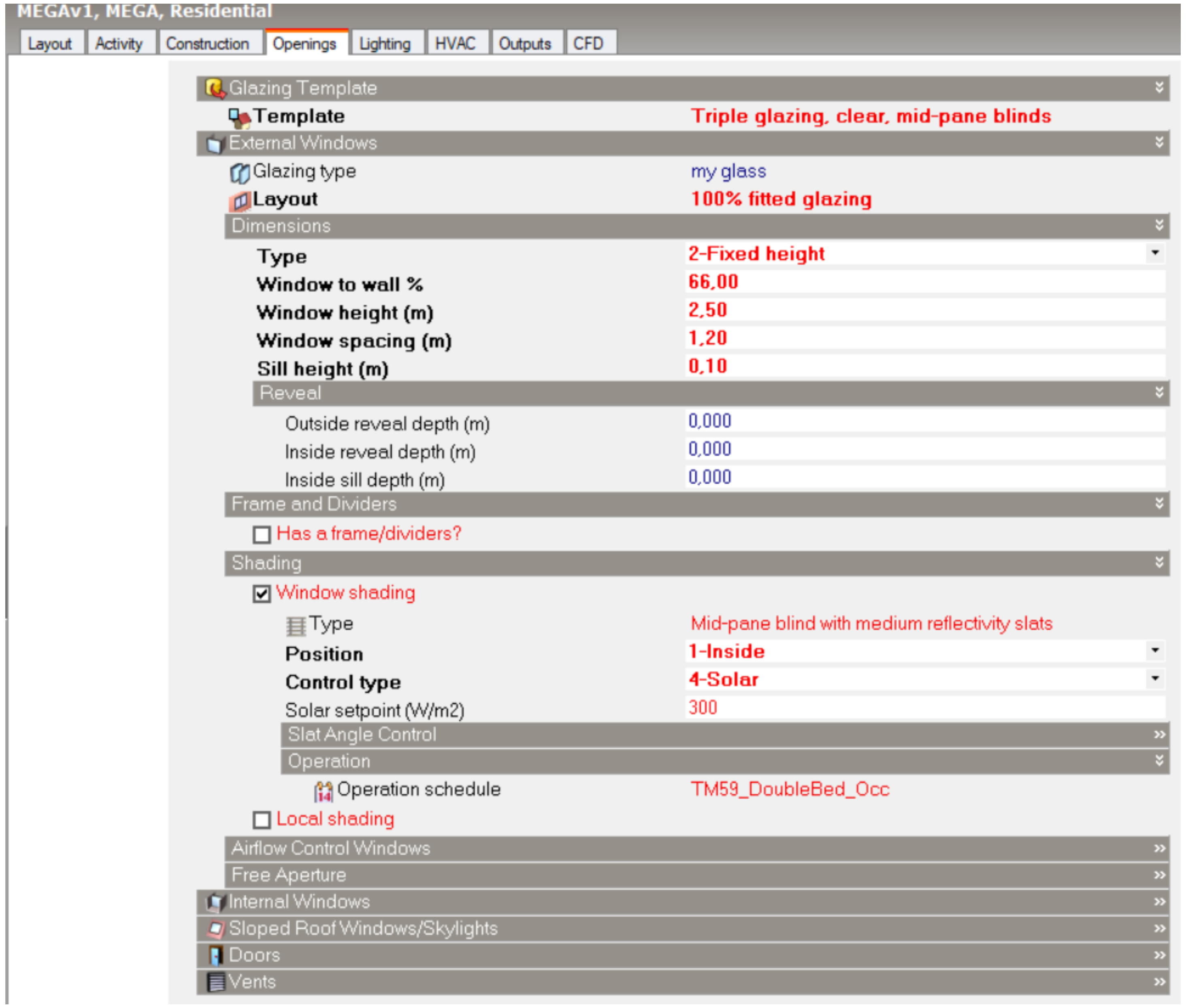
MEGAv1, MEGA, Residential, Zone 1

Template	TM59_DoubleBedroom
Sector	Residential spaces
Zone type	1-Standard
Zone multiplier	11
☑ Include zone in thermal calculations	
☐ Include zone in Radiance daylighting calculations	
Floor Areas and Volumes	
Occupancy	
Occupancy density (people/m2)	0,0350
Schedule	TM59_DoubleBed_Occ
Metabolic	
Generic Contaminant Generation	
DHW	
Environmental Control	
Heating Setpoint Temperatures	
Heating (°C)	22,0
Heating set back (°C)	18,0
Cooling Setpoint Temperatures	
Cooling (°C)	24,0
Cooling set back (°C)	26,0
Humidity Control	
Ventilation Setpoint Temperatures	
Minimum Fresh Air	
Lighting	
Computers	
☐ On	
Office Equipment	
☐ On	
Miscellaneous	
☑ On	
Power density (W/m2)	3,00
Schedule	Dwell_DomCommonAreas_Equip
Fuel	1-Electricity from grid
Fraction lost	0,000
Latent fraction	0,000
Radiant fraction	0,200



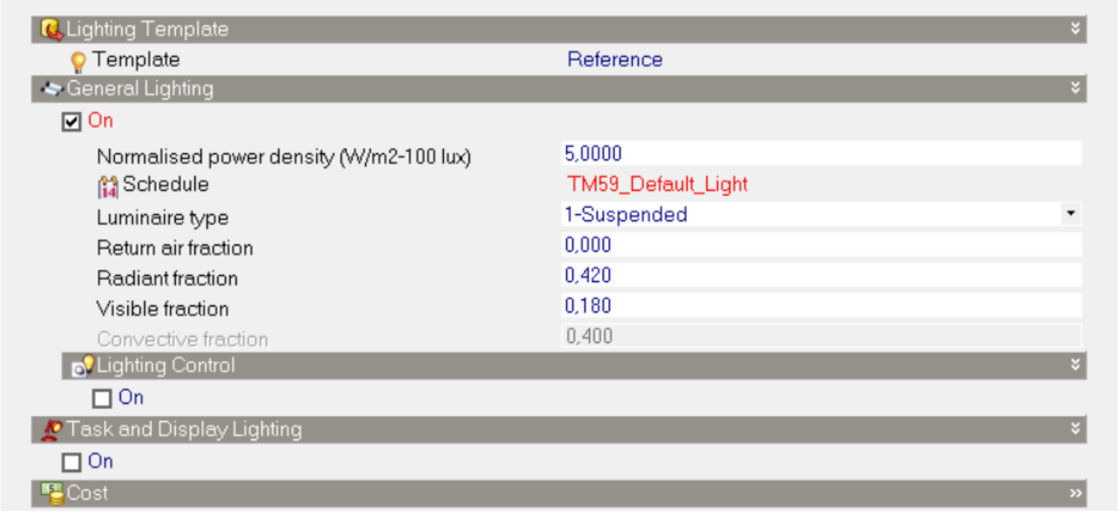
MEGAv1, MEGA, Residential

Construction Template	
Template	Project construction template
Construction	
External walls	Copy of Netherlands Wall, Lightweight
Below grade walls	Project below grade wall
Flat roof	Project flat roof
Pitched roof (occupied)	Project pitched roof
Pitched roof (unoccupied)	Project unoccupied pitched roof
Internal partitions	Project partition
Semi-Exposed	
Semi-exposed walls	Project semi-exposed wall
Semi-exposed ceiling	Project semi-exposed ceiling
Semi-exposed floor	Project semi-exposed floor
Floors	
Ground floor	Project ground floor
External floor	Project external floor
Internal floor	Project internal floor
Sub-Surfaces	
Internal Thermal Mass	
Adjacency	
Geometry, Areas and Volumes	
Surface Convection	
Linear Thermal Bridging at Junctions	
Airtightness	
☐ Model infiltration	
Cost	

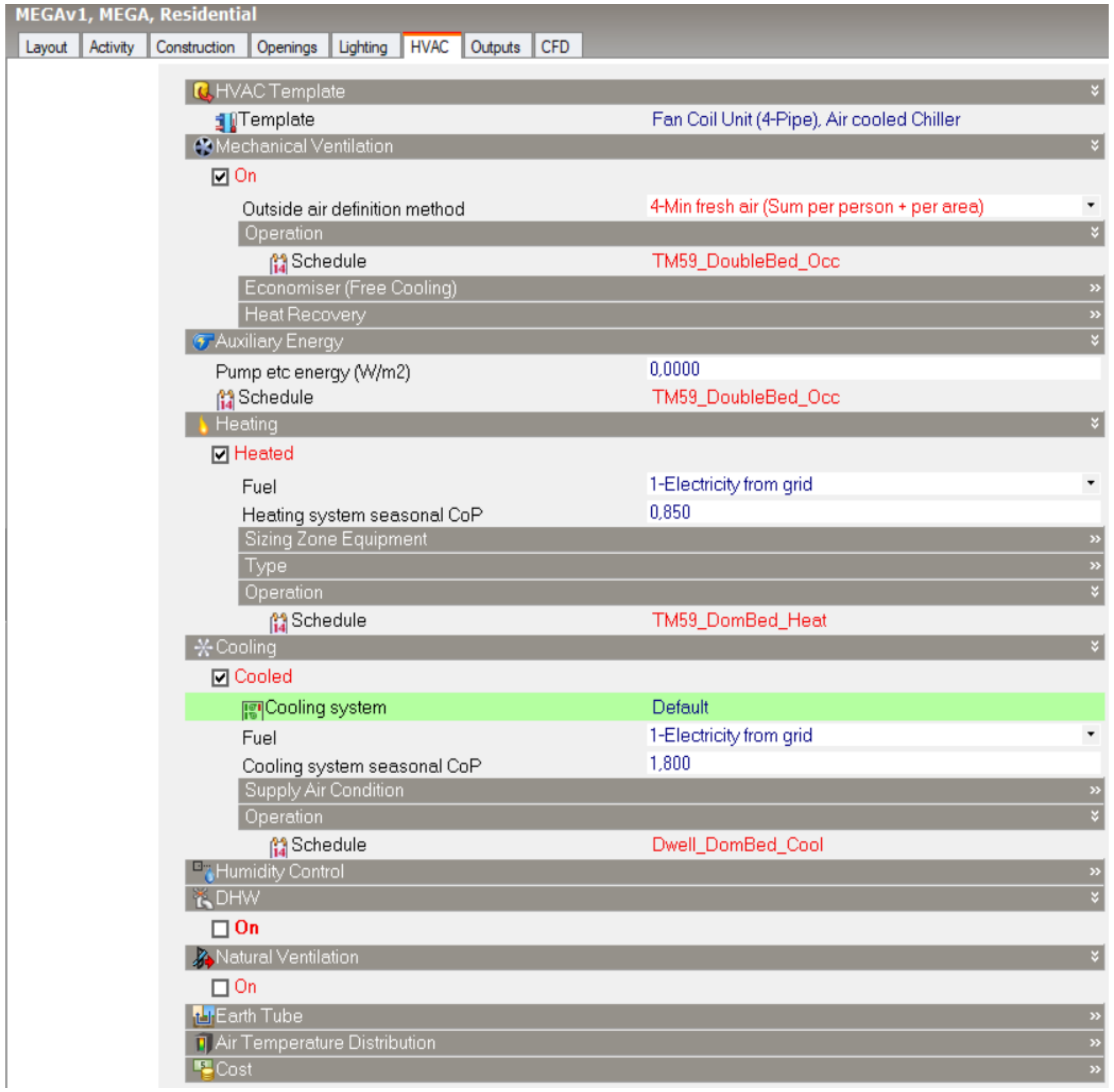


MEGAv1, MEGA, Residential

Glazing Template	
Template	**Triple glazing, clear, mid-pane blinds**
External Windows	
Glazing type	my glass
Layout	**100% fitted glazing**
Dimensions	
Type	**2-Fixed height**
Window to wall %	**66,00**
Window height (m)	**2,50**
Window spacing (m)	**1,20**
Sill height (m)	**0,10**
Reveal	
Outside reveal depth (m)	0,000
Inside reveal depth (m)	0,000
Inside sill depth (m)	0,000
Frame and Dividers	
☐ Has a frame/dividers?	
Shading	
☑ Window shading	
Type	Mid-pane blind with medium reflectivity slats
Position	**1-Inside**
Control type	**4-Solar**
Solar setpoint (W/m2)	300
Slat Angle Control	
Operation	
Operation schedule	TM59_DoubleBed_Occ
☐ Local shading	
Airflow Control Windows	
Free Aperture	
Internal Windows	
Sloped Roof Windows/Skylights	
Doors	
Vents	



Lighting Template	
Template	Reference
General Lighting	
☑ On	
Normalised power density (W/m2-100 lux)	5,0000
Schedule	TM59_Default_Light
Luminaire type	1-Suspended
Return air fraction	0,000
Radiant fraction	0,420
Visible fraction	0,180
Convective fraction	0,400
Lighting Control	
☐ On	
Task and Display Lighting	
☐ On	
Cost	

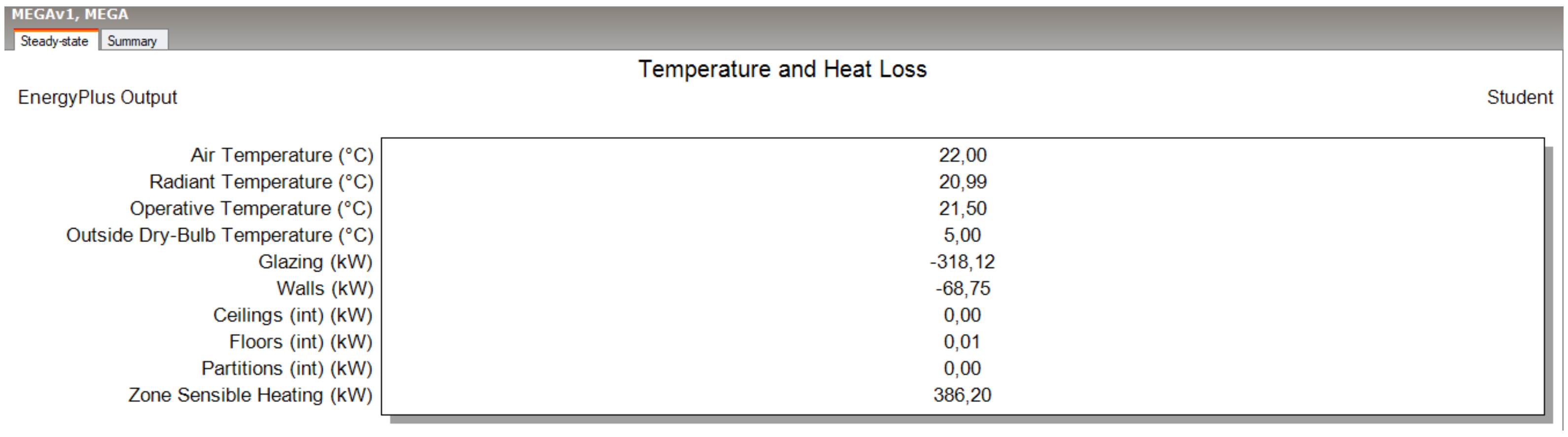


MEGAv1, MEGA, Residential

HVAC Template	
Template	Fan Coil Unit (4-Pipe), Air cooled Chiller
Mechanical Ventilation	
☑ On	
Outside air definition method	4-Min fresh air (Sum per person + per area)
Operation	
Schedule	TM59_DoubleBed_Occ
Economiser (Free Cooling)	
Heat Recovery	
Auxiliary Energy	
Pump etc energy (W/m2)	0,0000
Schedule	TM59_DoubleBed_Occ
Heating	
☑ Heated	
Fuel	1-Electricity from grid
Heating system seasonal CoP	0,850
Sizing Zone Equipment	
Type	
Operation	
Schedule	TM59_DomBed_Heat
Cooling	
☑ Cooled	
Cooling system	Default
Fuel	1-Electricity from grid
Cooling system seasonal CoP	1,800
Supply Air Condition	
Operation	
Schedule	Dwell_DomBed_Cool
Humidity Control	
DHW	
☐ **On**	
Natural Ventilation	
☐ On	
Earth Tube	
Air Temperature Distribution	
Cost	

Energy simulation results

MEGA Building

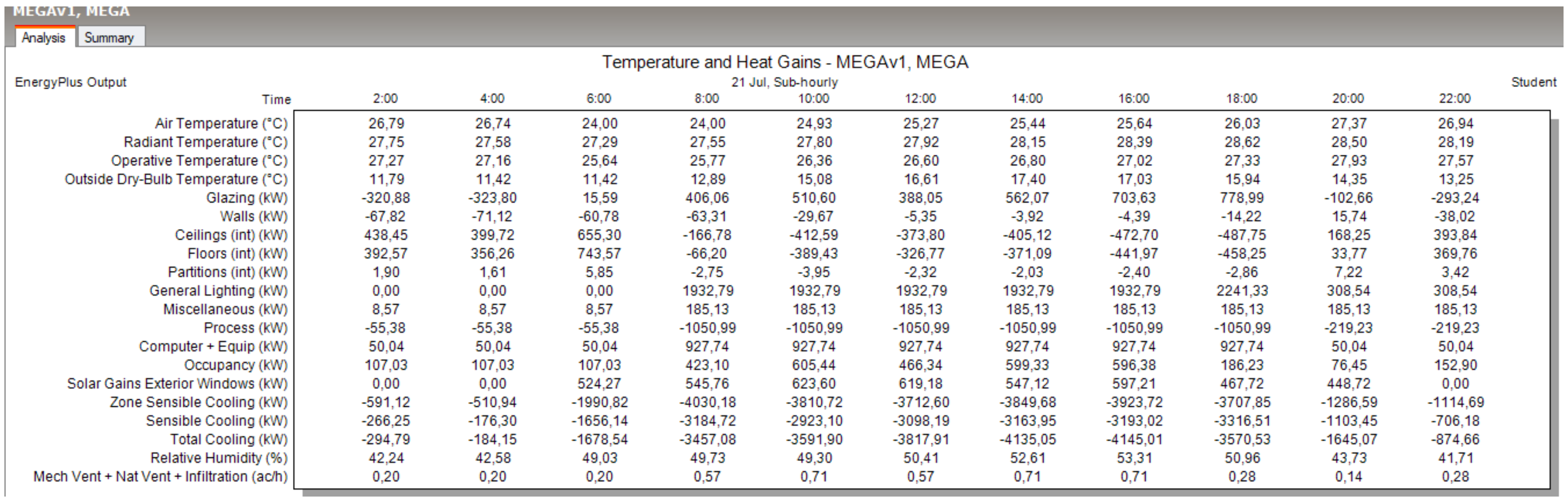


Temperature and Heat Loss

EnergyPlus Output

Student

Air Temperature (°C)	22,00
Radiant Temperature (°C)	20,99
Operative Temperature (°C)	21,50
Outside Dry-Bulb Temperature (°C)	5,00
Glazing (kW)	-318,12
Walls (kW)	-68,75
Ceilings (int) (kW)	0,00
Floors (int) (kW)	0,01
Partitions (int) (kW)	0,00
Zone Sensible Heating (kW)	386,20



Temperature and Heat Gains - MEGAv1, MEGA

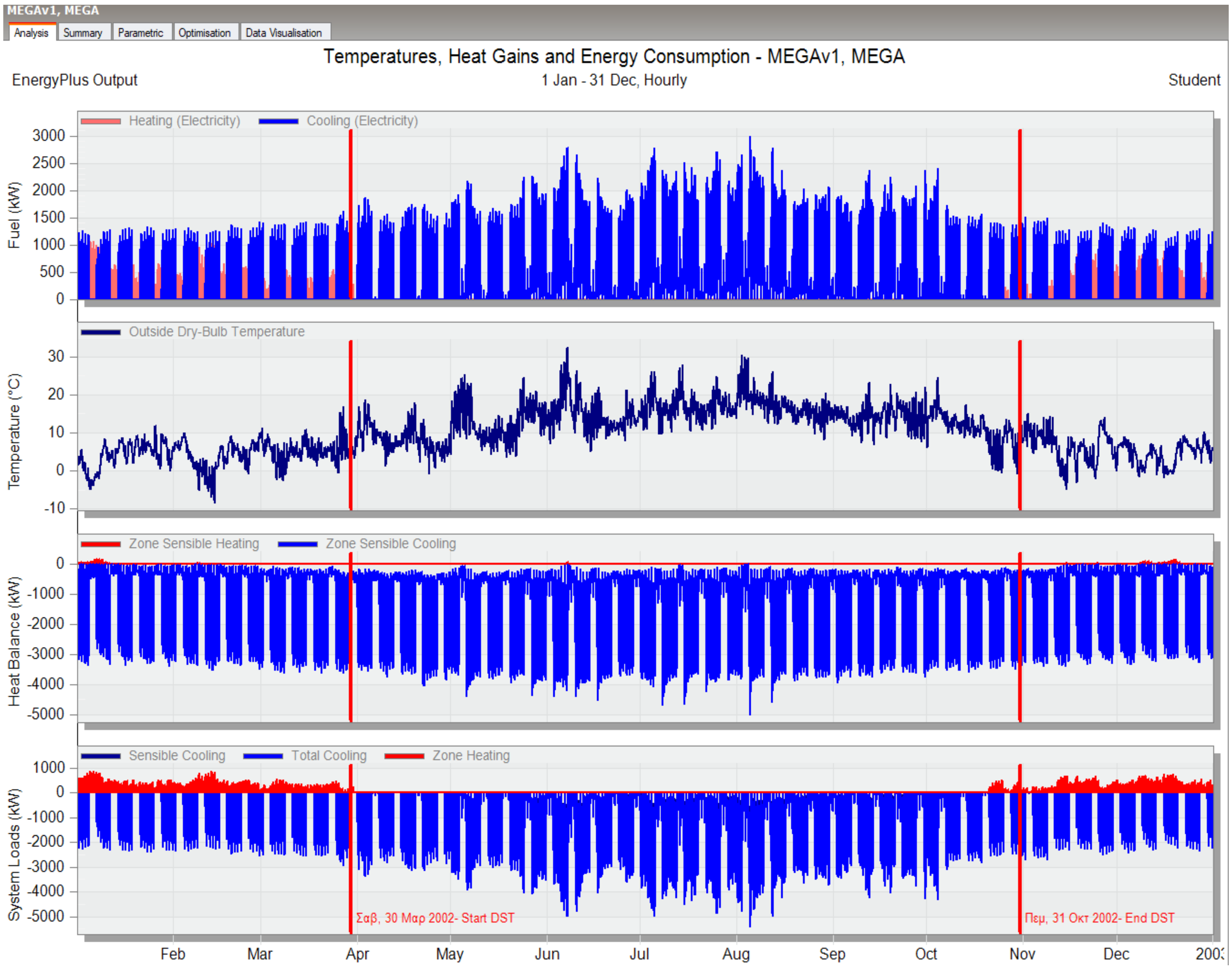
21 Jul, Sub-hourly

EnergyPlus Output

Student

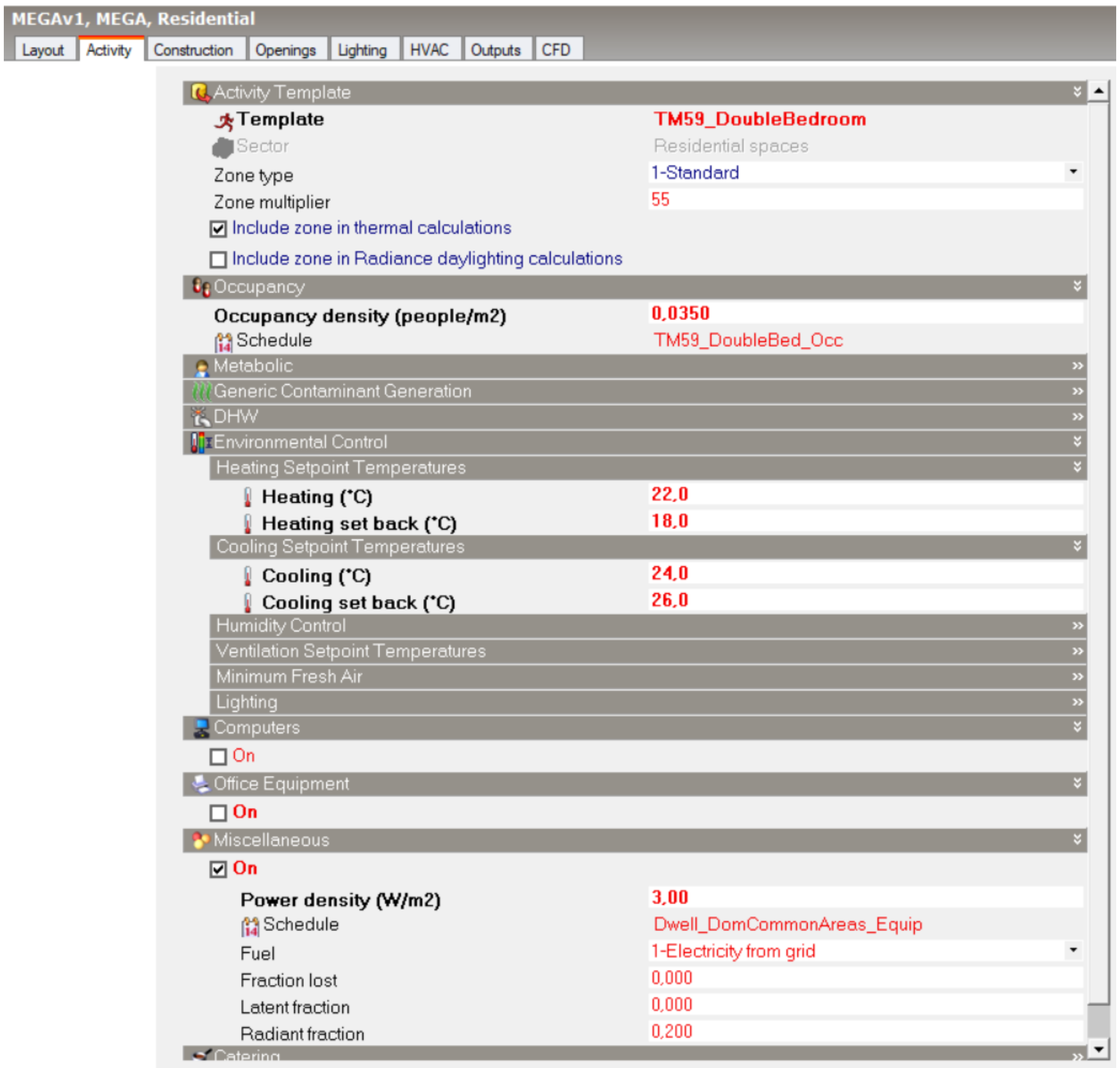
Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	26,79	26,74	24,00	24,00	24,93	25,27	25,44	25,64	26,03	27,37	26,94
Radiant Temperature (°C)	27,75	27,58	27,29	27,55	27,80	27,92	28,15	28,39	28,62	28,50	28,19
Operative Temperature (°C)	27,27	27,16	25,64	25,77	26,36	26,60	26,80	27,02	27,33	27,93	27,57
Outside Dry-Bulb Temperature (°C)	11,79	11,42	11,42	12,89	15,08	16,61	17,40	17,03	15,94	14,35	13,25
Glazing (kW)	-320,88	-323,80	15,59	406,06	510,60	388,05	562,07	703,63	778,99	-102,66	-293,24
Walls (kW)	-67,82	-71,12	-60,78	-63,31	-29,67	-5,35	-3,92	-4,39	-14,22	15,74	-38,02
Ceilings (int) (kW)	438,45	399,72	655,30	-166,78	-412,59	-373,80	-405,12	-472,70	-487,75	168,25	393,84
Floors (int) (kW)	392,57	356,26	743,57	-66,20	-389,43	-326,77	-371,09	-441,97	-458,25	33,77	369,76
Partitions (int) (kW)	1,90	1,61	5,85	-2,75	-3,95	-2,32	-2,03	-2,40	-2,86	7,22	3,42
General Lighting (kW)	0,00	0,00	0,00	1932,79	1932,79	1932,79	1932,79	1932,79	2241,33	308,54	308,54
Miscellaneous (kW)	8,57	8,57	8,57	185,13	185,13	185,13	185,13	185,13	185,13	185,13	185,13
Process (kW)	-55,38	-55,38	-55,38	-1050,99	-1050,99	-1050,99	-1050,99	-1050,99	-1050,99	-219,23	-219,23
Computer + Equip (kW)	50,04	50,04	50,04	927,74	927,74	927,74	927,74	927,74	927,74	50,04	50,04
Occupancy (kW)	107,03	107,03	107,03	423,10	605,44	466,34	599,33	596,38	186,23	76,45	152,90
Solar Gains Exterior Windows (kW)	0,00	0,00	524,27	545,76	623,60	619,18	547,12	597,21	467,72	448,72	0,00
Zone Sensible Cooling (kW)	-591,12	-510,94	-1990,82	-4030,18	-3810,72	-3712,60	-3849,68	-3923,72	-3707,85	-1286,59	-1114,69
Sensible Cooling (kW)	-266,25	-176,30	-1656,14	-3184,72	-2923,10	-3098,19	-3163,95	-3193,02	-3316,51	-1103,45	-706,18
Total Cooling (kW)	-294,79	-184,15	-1678,54	-3457,08	-3591,90	-3817,91	-4135,05	-4145,01	-3570,53	-1645,07	-874,66
Relative Humidity (%)	42,24	42,58	49,03	49,73	49,30	50,41	52,61	53,31	50,96	43,73	41,71
Mech Vent + Nat Vent + Infiltration (ac/h)	0,20	0,20	0,20	0,57	0,71	0,57	0,71	0,71	0,28	0,14	0,28

Hourly Data Profile



9.3. APPENDIX 3 – Additional cases of energy demand distribution

Case 1 – 0% mixed-use – 100% Residential Function



Activity Template

Template	**TM59_DoubleBedroom**
Sector	Residential spaces
Zone type	1-Standard
Zone multiplier	55

☑ Include zone in thermal calculations

☐ Include zone in Radiance daylighting calculations

Occupancy

Occupancy density (people/m2)	**0.0350**
Schedule	TM59_DoubleBed_Occ

Metabolic

Generic Contaminant Generation

DHW

Environmental Control

Heating Setpoint Temperatures

Heating (°C)	**22.0**
Heating set back (°C)	**18.0**

Cooling Setpoint Temperatures

Cooling (°C)	**24.0**
Cooling set back (°C)	**26.0**

Humidity Control

Ventilation Setpoint Temperatures

Minimum Fresh Air

Lighting

Computers

☐ On

Office Equipment

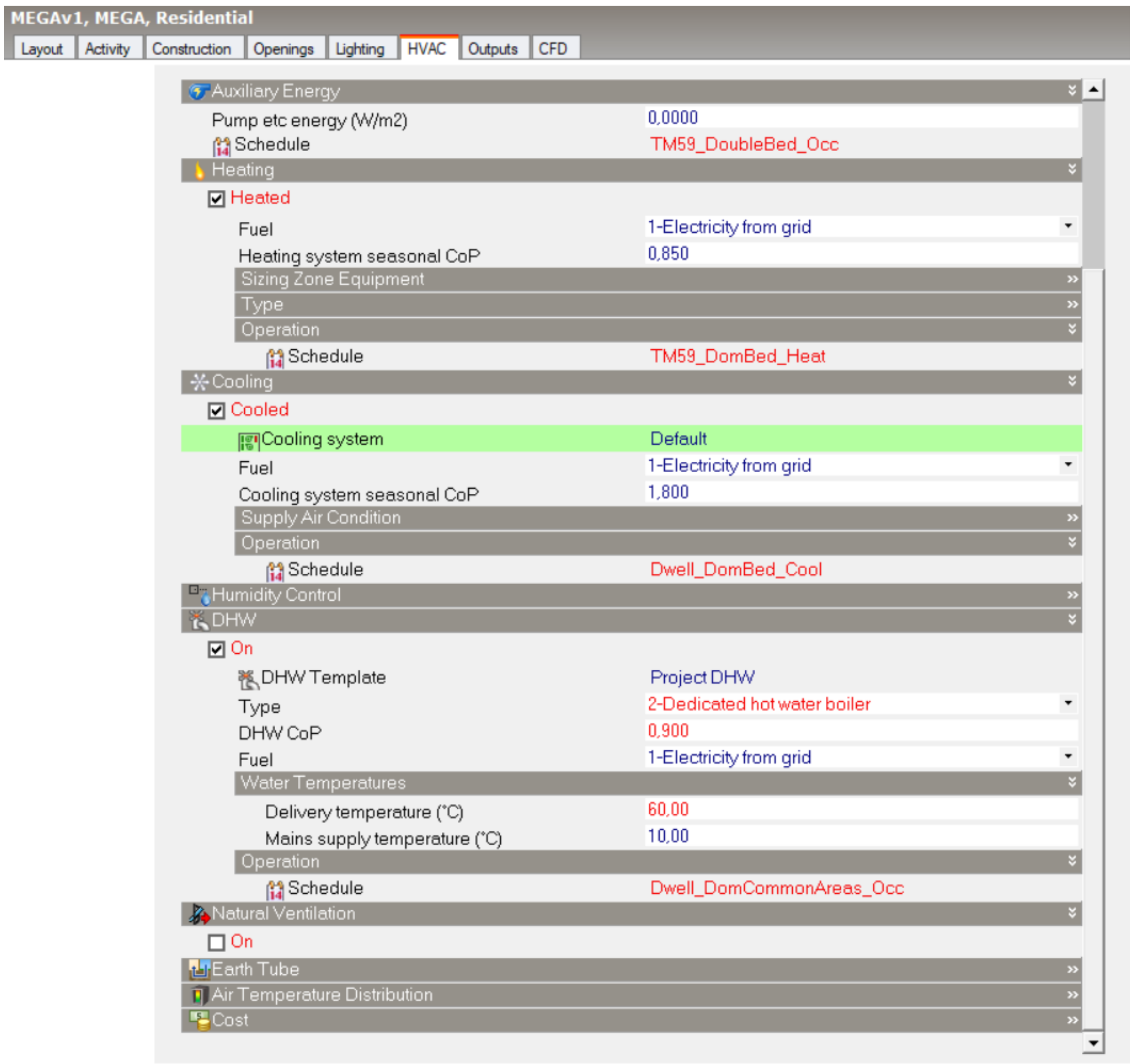
☐ **On**

Miscellaneous

☑ **On**

Power density (W/m2)	**3.00**
Schedule	Dwell_DomCommonAreas_Equip
Fuel	1-Electricity from grid
Fraction lost	0.000
Latent fraction	0.000
Radiant fraction	0.200

Catering



Auxiliary Energy

Pump etc energy (W/m2)	0.0000
Schedule	TM59_DoubleBed_Occ

Heating

☑ Heated

Fuel	1-Electricity from grid
Heating system seasonal CoP	0.850

Sizing Zone Equipment

Type

Operation

Schedule	TM59_DomBed_Heat

Cooling

☑ Cooled

Cooling system	Default
Fuel	1-Electricity from grid
Cooling system seasonal CoP	1.800

Supply Air Condition

Operation

Schedule	Dwell_DomBed_Cool

Humidity Control

DHW

☑ On

DHW Template	Project DHW
Type	2-Dedicated hot water boiler
DHW CoP	0.900
Fuel	1-Electricity from grid

Water Temperatures

Delivery temperature (°C)	60.00
Mains supply temperature (°C)	10.00

Operation

Schedule	Dwell_DomCommonAreas_Occ

Natural Ventilation

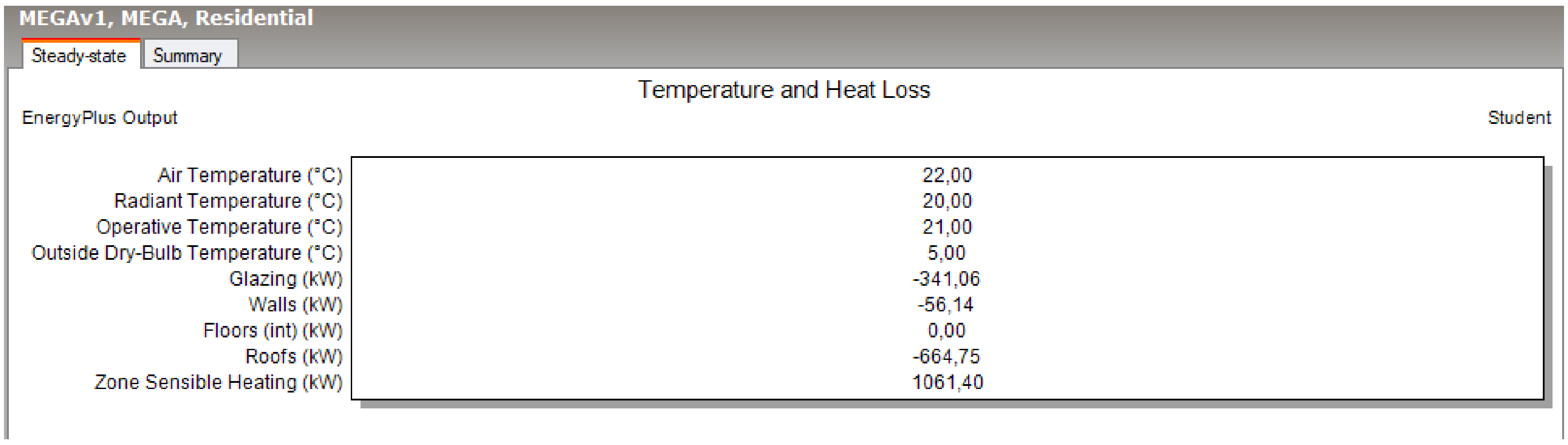
☐ On

Earth Tube

Air Temperature Distribution

Cost

Energy Simulation Results

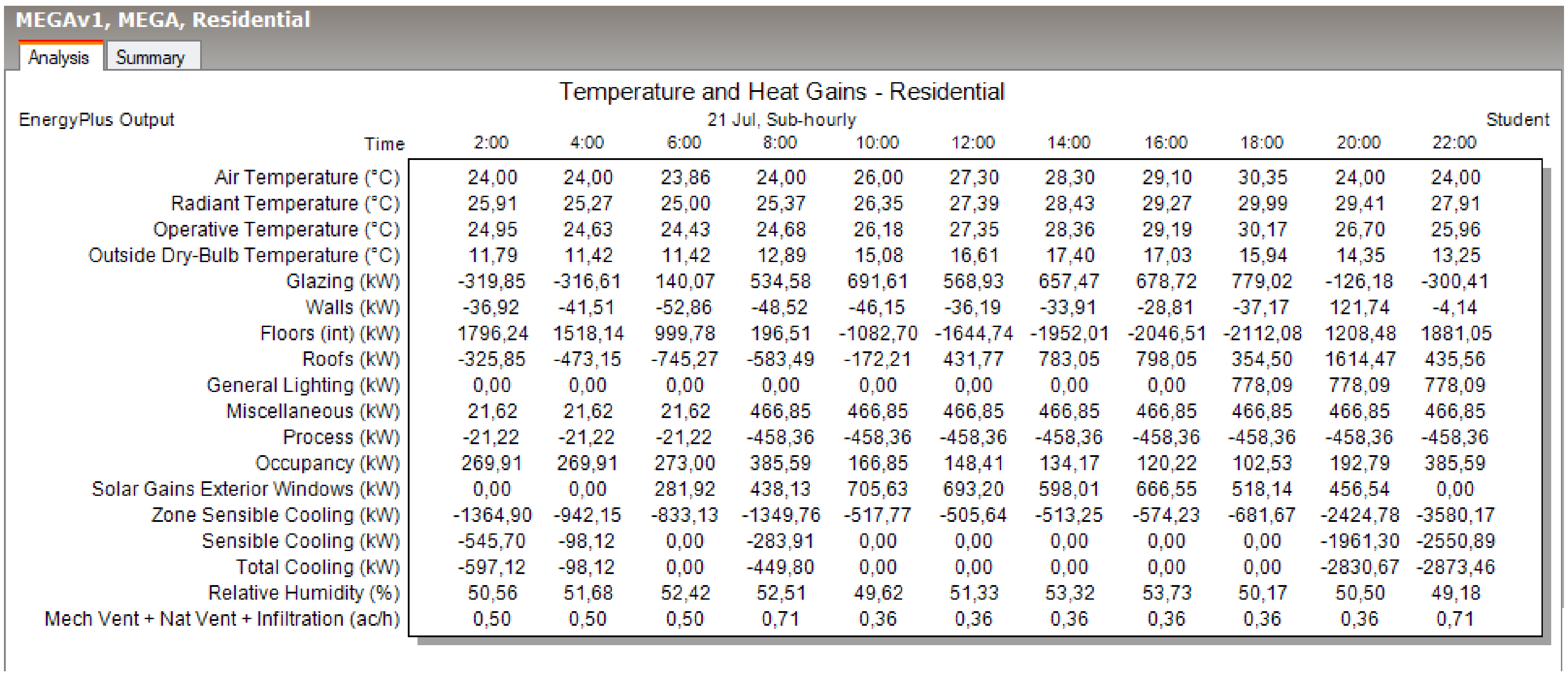


Temperature and Heat Loss

EnergyPlus Output

Student

Air Temperature (°C)	22,00
Radiant Temperature (°C)	20,00
Operative Temperature (°C)	21,00
Outside Dry-Bulb Temperature (°C)	5,00
Glazing (kW)	-341,06
Walls (kW)	-56,14
Floors (int) (kW)	0,00
Roofs (kW)	-664,75
Zone Sensible Heating (kW)	1061,40



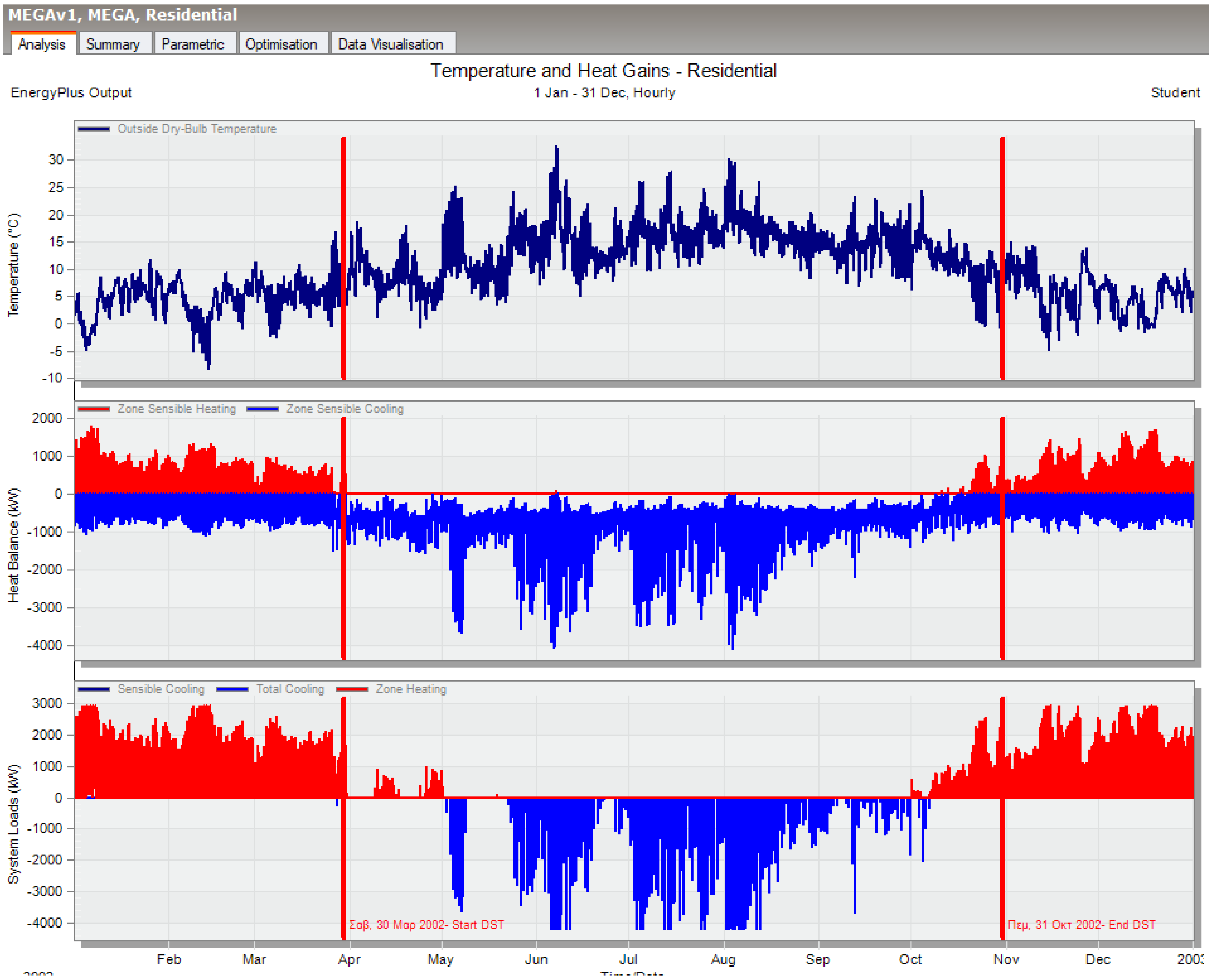
Temperature and Heat Gains - Residential

EnergyPlus Output

21 Jul, Sub-hourly

Student

Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	24,00	24,00	23,86	24,00	26,00	27,30	28,30	29,10	30,35	24,00	24,00
Radiant Temperature (°C)	25,91	25,27	25,00	25,37	26,35	27,39	28,43	29,27	29,99	29,41	27,91
Operative Temperature (°C)	24,95	24,63	24,43	24,68	26,18	27,35	28,36	29,19	30,17	26,70	25,96
Outside Dry-Bulb Temperature (°C)	11,79	11,42	11,42	12,89	15,08	16,61	17,40	17,03	15,94	14,35	13,25
Glazing (kW)	-319,85	-316,61	140,07	534,58	691,61	568,93	657,47	678,72	779,02	-126,18	-300,41
Walls (kW)	-36,92	-41,51	-52,86	-48,52	-46,15	-36,19	-33,91	-28,81	-37,17	121,74	-4,14
Floors (int) (kW)	1796,24	1518,14	999,78	196,51	-1082,70	-1644,74	-1952,01	-2046,51	-2112,08	1208,48	1881,05
Roofs (kW)	-325,85	-473,15	-745,27	-583,49	-172,21	431,77	783,05	798,05	354,50	1614,47	435,56
General Lighting (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	778,09	778,09	778,09
Miscellaneous (kW)	21,62	21,62	21,62	466,85	466,85	466,85	466,85	466,85	466,85	466,85	466,85
Process (kW)	-21,22	-21,22	-21,22	-458,36	-458,36	-458,36	-458,36	-458,36	-458,36	-458,36	-458,36
Occupancy (kW)	269,91	269,91	273,00	385,59	166,85	148,41	134,17	120,22	102,53	192,79	385,59
Solar Gains Exterior Windows (kW)	0,00	0,00	281,92	438,13	705,63	693,20	598,01	666,55	518,14	456,54	0,00
Zone Sensible Cooling (kW)	-1364,90	-942,15	-833,13	-1349,76	-517,77	-505,64	-513,25	-574,23	-681,67	-2424,78	-3580,17
Sensible Cooling (kW)	-545,70	-98,12	0,00	-283,91	0,00	0,00	0,00	0,00	0,00	-1961,30	-2550,89
Total Cooling (kW)	-597,12	-98,12	0,00	-449,80	0,00	0,00	0,00	0,00	0,00	-2830,67	-2873,46
Relative Humidity (%)	50,56	51,68	52,42	52,51	49,62	51,33	53,32	53,73	50,17	50,50	49,18
Mech Vent + Nat Vent + Infiltration (ac/h)	0,50	0,50	0,50	0,71	0,36	0,36	0,36	0,36	0,36	0,36	0,71



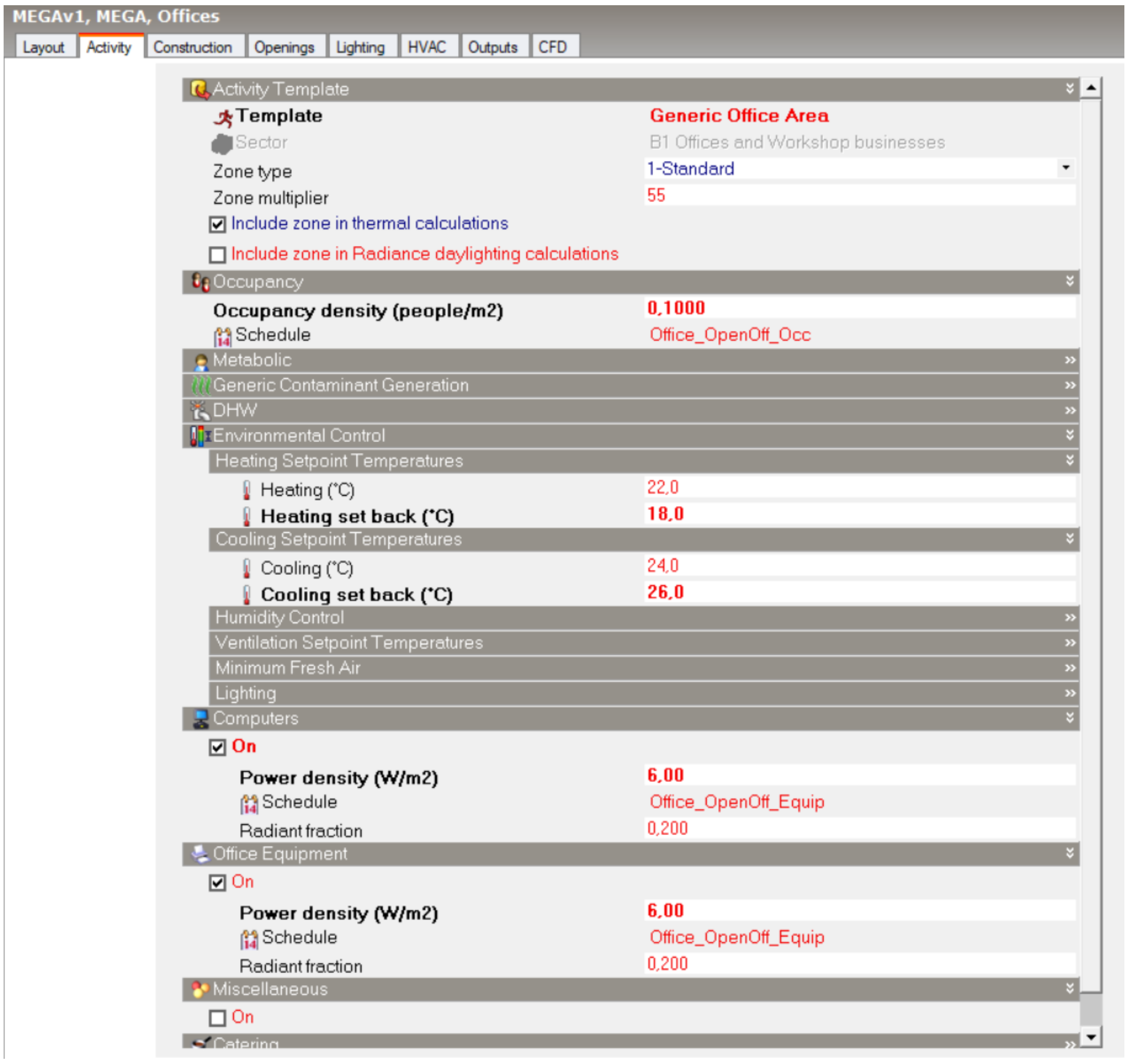
Temperature and Heat Gains - Residential

EnergyPlus Output

1 Jan - 31 Dec, Hourly

Student

Case 5 - 0% Mixed-use – 100% Office function



Activity Template
Template Generic Office Area
Sector B1 Offices and Workshop businesses
Zone type 1-Standard
Zone multiplier 55
☑ Include zone in thermal calculations
☐ Include zone in Radiance daylighting calculations

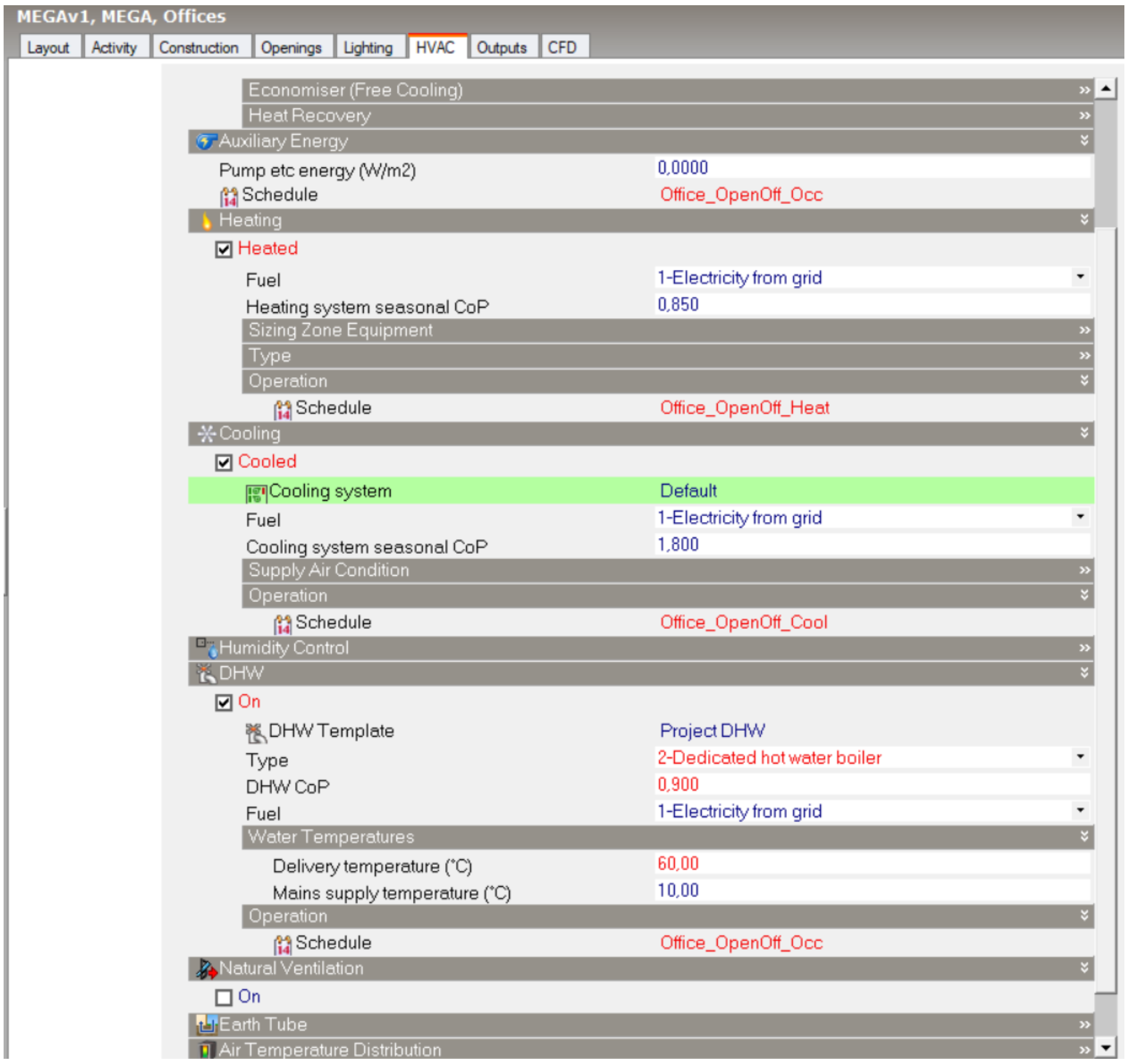
Occupancy
Occupancy density (people/m2) 0,1000
Schedule Office_OpenOff_Occ

Metabolic
Generic Contaminant Generation
DHW
Environmental Control
Heating Setpoint Temperatures
Heating (°C) 22,0
Heating set back (°C) 18,0
Cooling Setpoint Temperatures
Cooling (°C) 24,0
Cooling set back (°C) 26,0
Humidity Control
Ventilation Setpoint Temperatures
Minimum Fresh Air
Lighting

Computers
☑ On
Power density (W/m2) 6,00
Schedule Office_OpenOff_Equip
Radiant fraction 0,200

Office Equipment
☑ On
Power density (W/m2) 6,00
Schedule Office_OpenOff_Equip
Radiant fraction 0,200

Miscellaneous
☐ On
Catering



Economiser (Free Cooling)
Heat Recovery
Auxiliary Energy
Pump etc energy (W/m2) 0,0000
Schedule Office_OpenOff_Occ

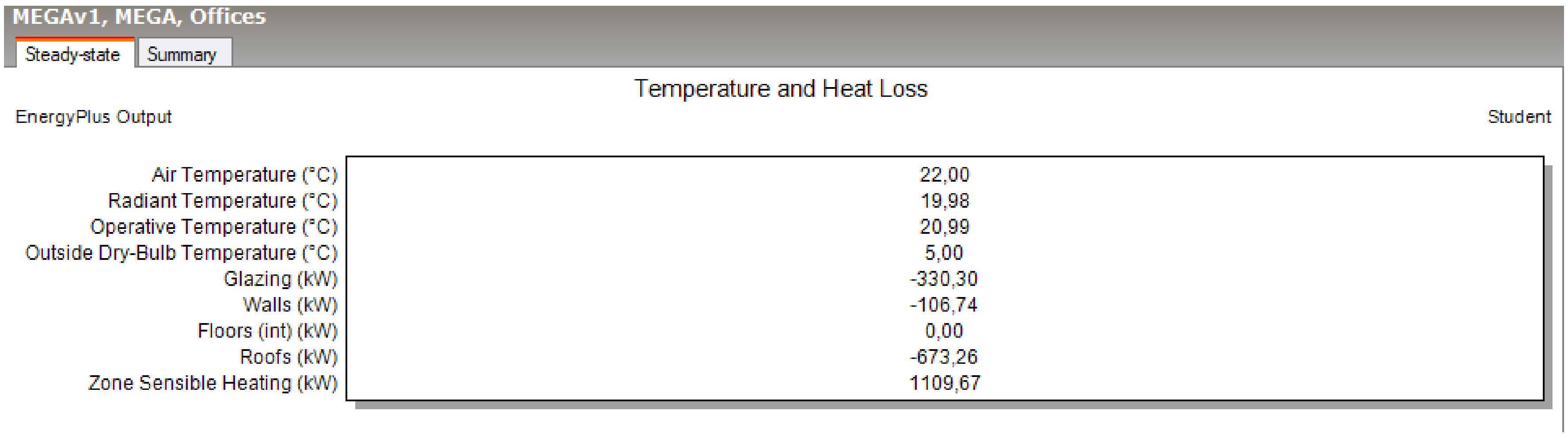
Heating
☑ Heated
Fuel 1-Electricity from grid
Heating system seasonal CoP 0,850
Sizing Zone Equipment
Type
Operation
Schedule Office_OpenOff_Heat

Cooling
☑ Cooled
Cooling system Default
Fuel 1-Electricity from grid
Cooling system seasonal CoP 1,800
Supply Air Condition
Operation
Schedule Office_OpenOff_Cool

Humidity Control
DHW
☑ On
DHW Template Project DHW
Type 2-Dedicated hot water boiler
DHW CoP 0,900
Fuel 1-Electricity from grid
Water Temperatures
Delivery temperature (°C) 60,00
Mains supply temperature (°C) 10,00
Operation
Schedule Office_OpenOff_Occ

Natural Ventilation
☐ On
Earth Tube
Air Temperature Distribution

Energy Simulation Results

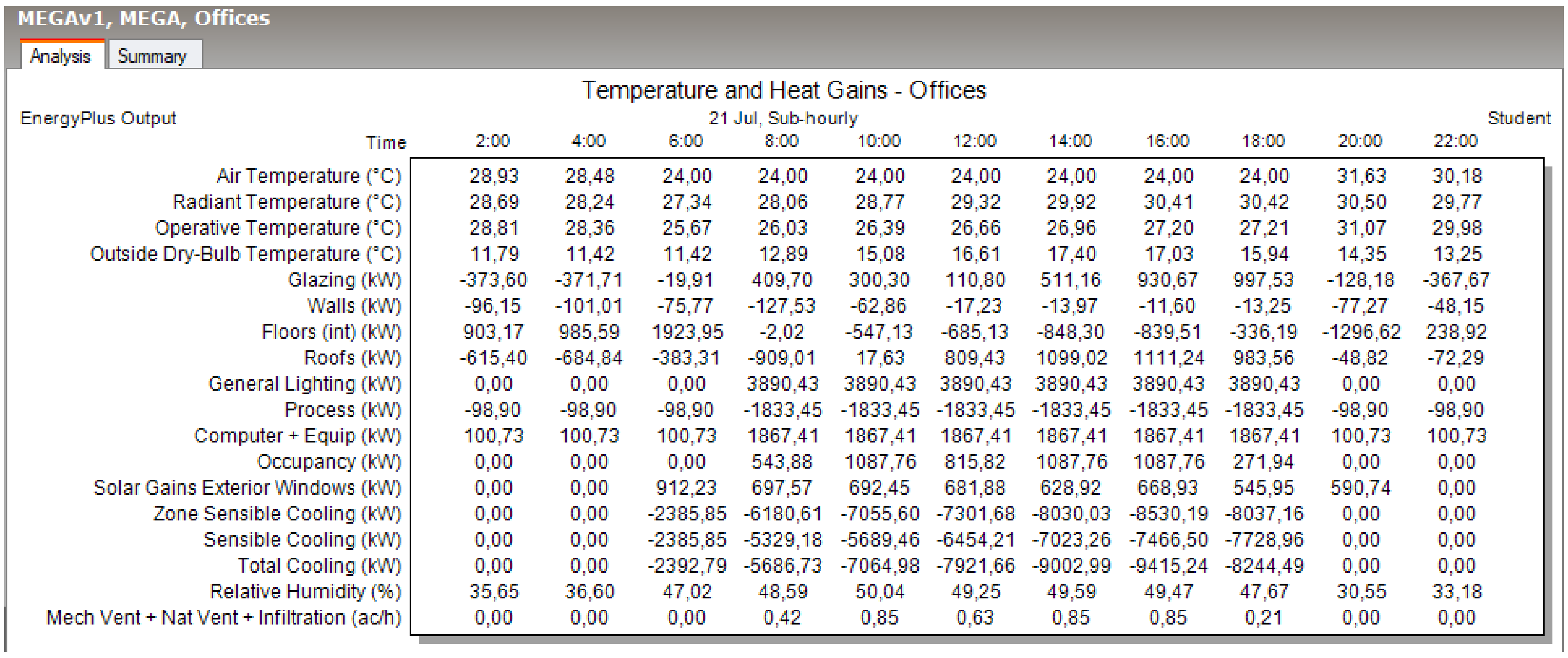


Temperature and Heat Loss

EnergyPlus Output

Student

Air Temperature (°C)	22,00
Radiant Temperature (°C)	19,98
Operative Temperature (°C)	20,99
Outside Dry-Bulb Temperature (°C)	5,00
Glazing (kW)	-330,30
Walls (kW)	-106,74
Floors (int) (kW)	0,00
Roofs (kW)	-673,26
Zone Sensible Heating (kW)	1109,67



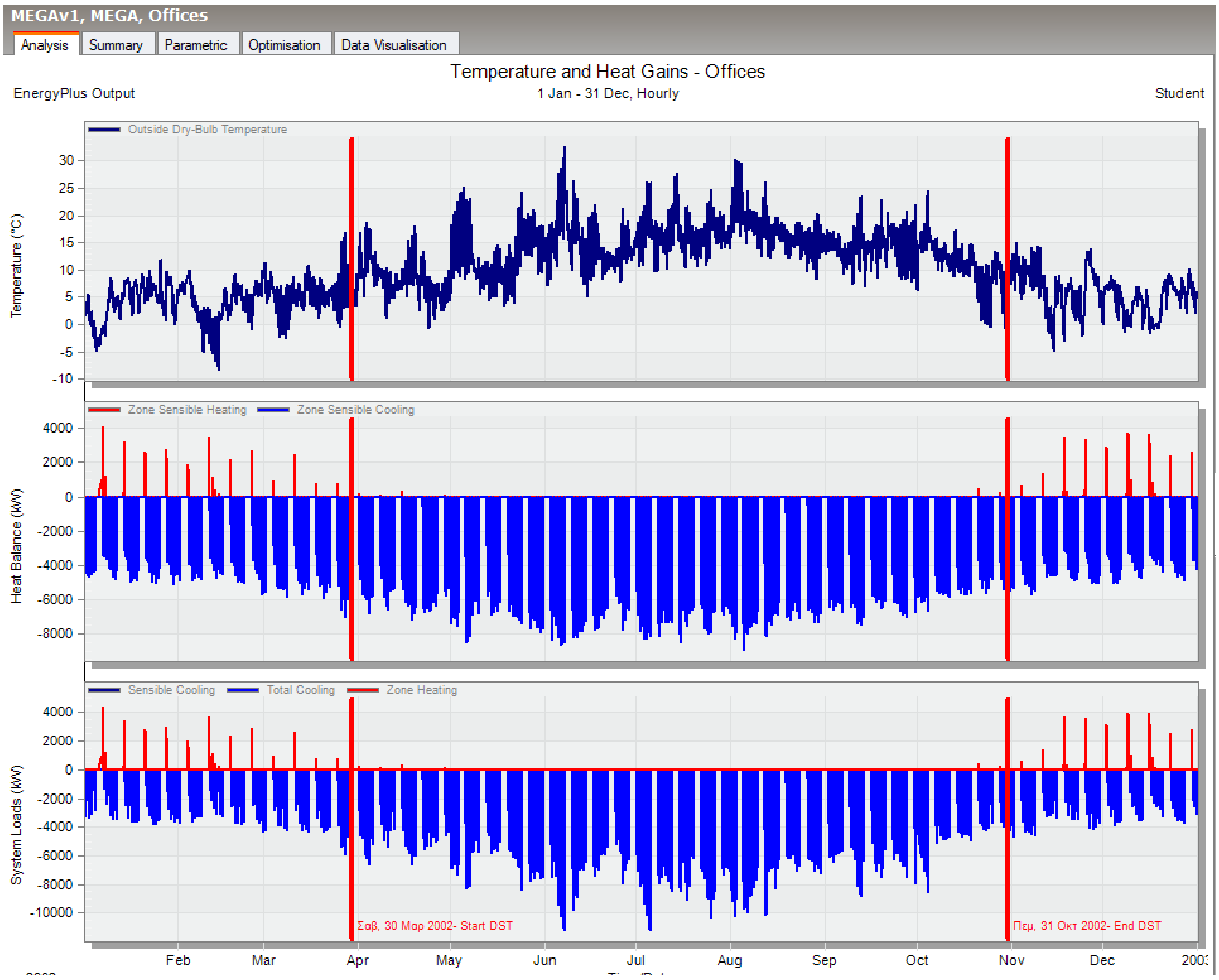
Temperature and Heat Gains - Offices

EnergyPlus Output

21 Jul, Sub-hourly

Student

Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	28,93	28,48	24,00	24,00	24,00	24,00	24,00	24,00	24,00	31,63	30,18
Radiant Temperature (°C)	28,69	28,24	27,34	28,06	28,77	29,32	29,92	30,41	30,42	30,50	29,77
Operative Temperature (°C)	28,81	28,36	25,67	26,03	26,39	26,66	26,96	27,20	27,21	31,07	29,98
Outside Dry-Bulb Temperature (°C)	11,79	11,42	11,42	12,89	15,08	16,61	17,40	17,03	15,94	14,35	13,25
Glazing (kW)	-373,60	-371,71	-19,91	409,70	300,30	110,80	511,16	930,67	997,53	-128,18	-367,67
Walls (kW)	-96,15	-101,01	-75,77	-127,53	-62,86	-17,23	-13,97	-11,60	-13,25	-77,27	-48,15
Floors (int) (kW)	903,17	985,59	1923,95	-2,02	-547,13	-685,13	-848,30	-839,51	-336,19	-1296,62	238,92
Roofs (kW)	-615,40	-684,84	-383,31	-909,01	17,63	809,43	1099,02	1111,24	983,56	-48,82	-72,29
General Lighting (kW)	0,00	0,00	0,00	3890,43	3890,43	3890,43	3890,43	3890,43	3890,43	0,00	0,00
Process (kW)	-98,90	-98,90	-98,90	-1833,45	-1833,45	-1833,45	-1833,45	-1833,45	-1833,45	-98,90	-98,90
Computer + Equip (kW)	100,73	100,73	100,73	1867,41	1867,41	1867,41	1867,41	1867,41	1867,41	100,73	100,73
Occupancy (kW)	0,00	0,00	0,00	543,88	1087,76	815,82	1087,76	1087,76	271,94	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	912,23	697,57	692,45	681,88	628,92	668,93	545,95	590,74	0,00
Zone Sensible Cooling (kW)	0,00	0,00	-2385,85	-6180,61	-7055,60	-7301,68	-8030,03	-8530,19	-8037,16	0,00	0,00
Sensible Cooling (kW)	0,00	0,00	-2385,85	-5329,18	-5689,46	-6454,21	-7023,26	-7466,50	-7728,96	0,00	0,00
Total Cooling (kW)	0,00	0,00	-2392,79	-5686,73	-7064,98	-7921,66	-9002,99	-9415,24	-8244,49	0,00	0,00
Relative Humidity (%)	35,65	36,60	47,02	48,59	50,04	49,25	49,59	49,47	47,67	30,55	33,18
Mech Vent + Nat Vent + Infiltration (ac/h)	0,00	0,00	0,00	0,42	0,85	0,63	0,85	0,85	0,21	0,00	0,00



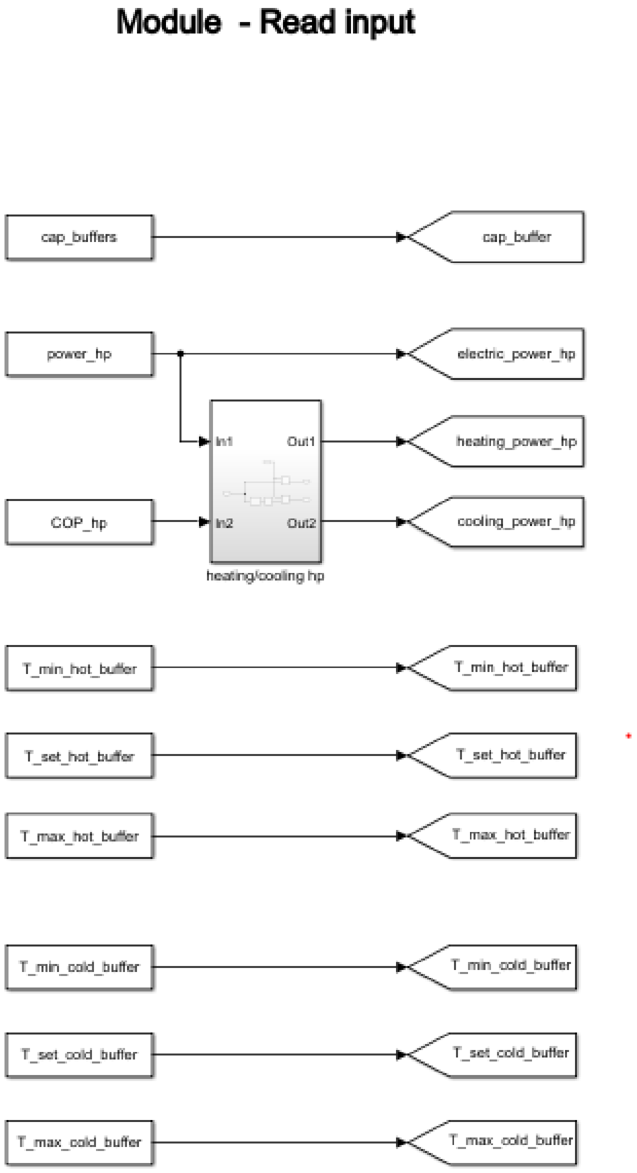
9.4. APPENDIX 4: MATLAB / SIMULINK Model

MATLAB parameter value input

```
% Script file Georgios Germanos
clear;

T_min_hot_buffer = 45;  % minimum allowed temperature
T_set_hot_buffer = 47;  % setpoint temperature
T_max_hot_buffer = 55;  % minimum allowed temperature

T_min_cold_buffer = 7;  % minimum allowed temperature
T_set_cold_buffer = 11; % setpoint temperature
T_max_cold_buffer = 15; % minimum allowed temperature

cap_buffers =7e9;       % thermal capacity in J/K of both the heat and cold buffer11

COP_hp = 4;             % COP heat pump for heating. For is cooling it is
automatically COP_hp-1

power_hp = 2e6;         % Electric power (capacity) of the heat pump in W.

start_time = 0;
stop_time = 365*86400;

%  --- END of INPUT ----
```

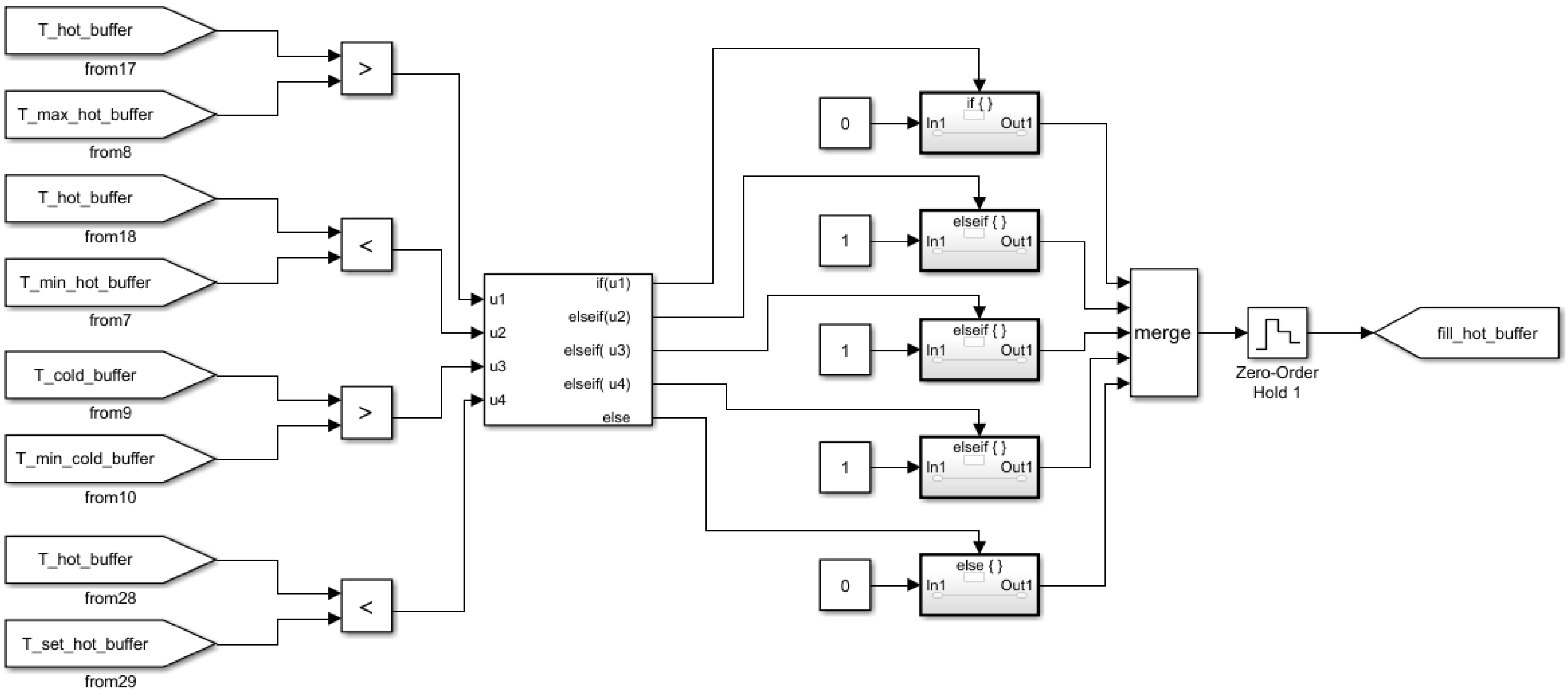
SIMULINK Model

Module 1 – Input variables

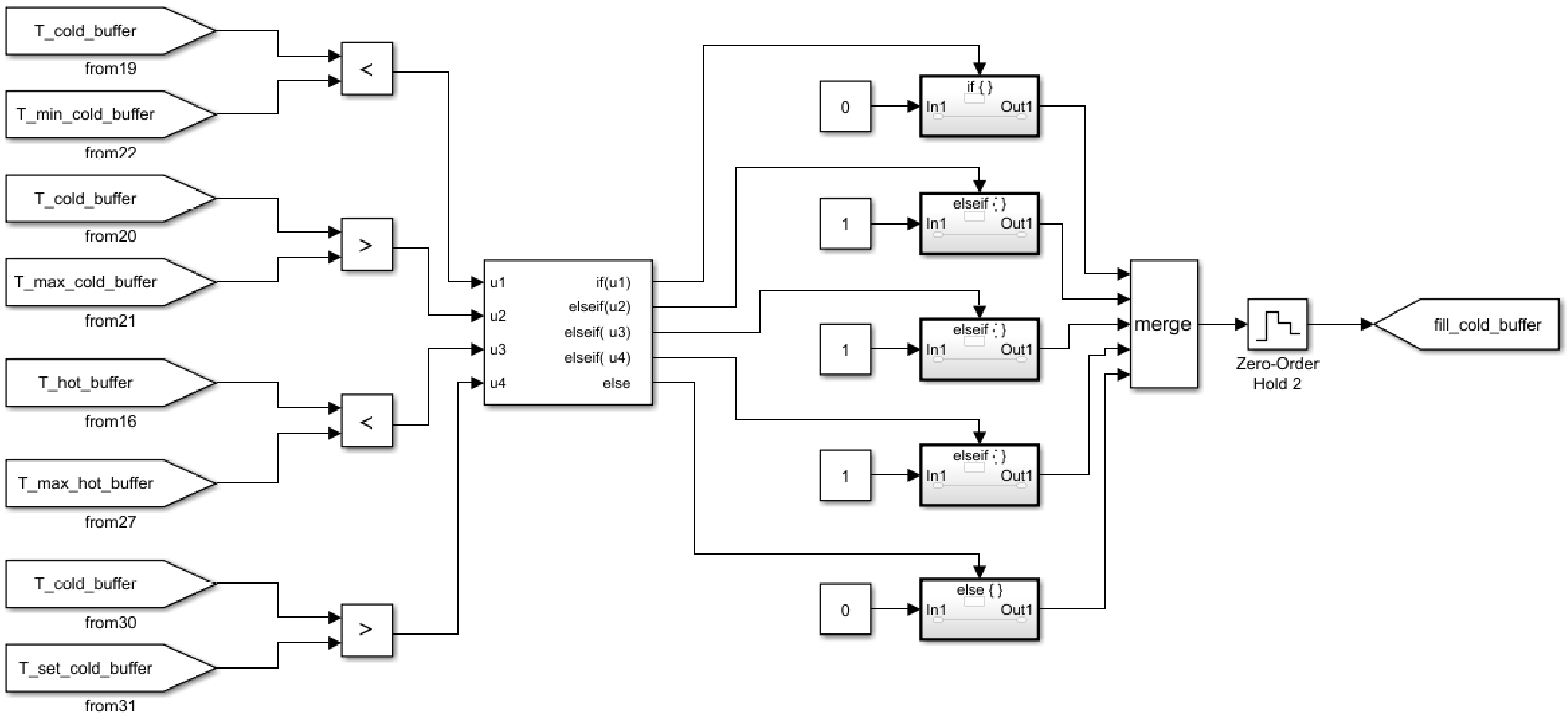


Module 2 – Calculation charging hot or cold storage tanks until filling

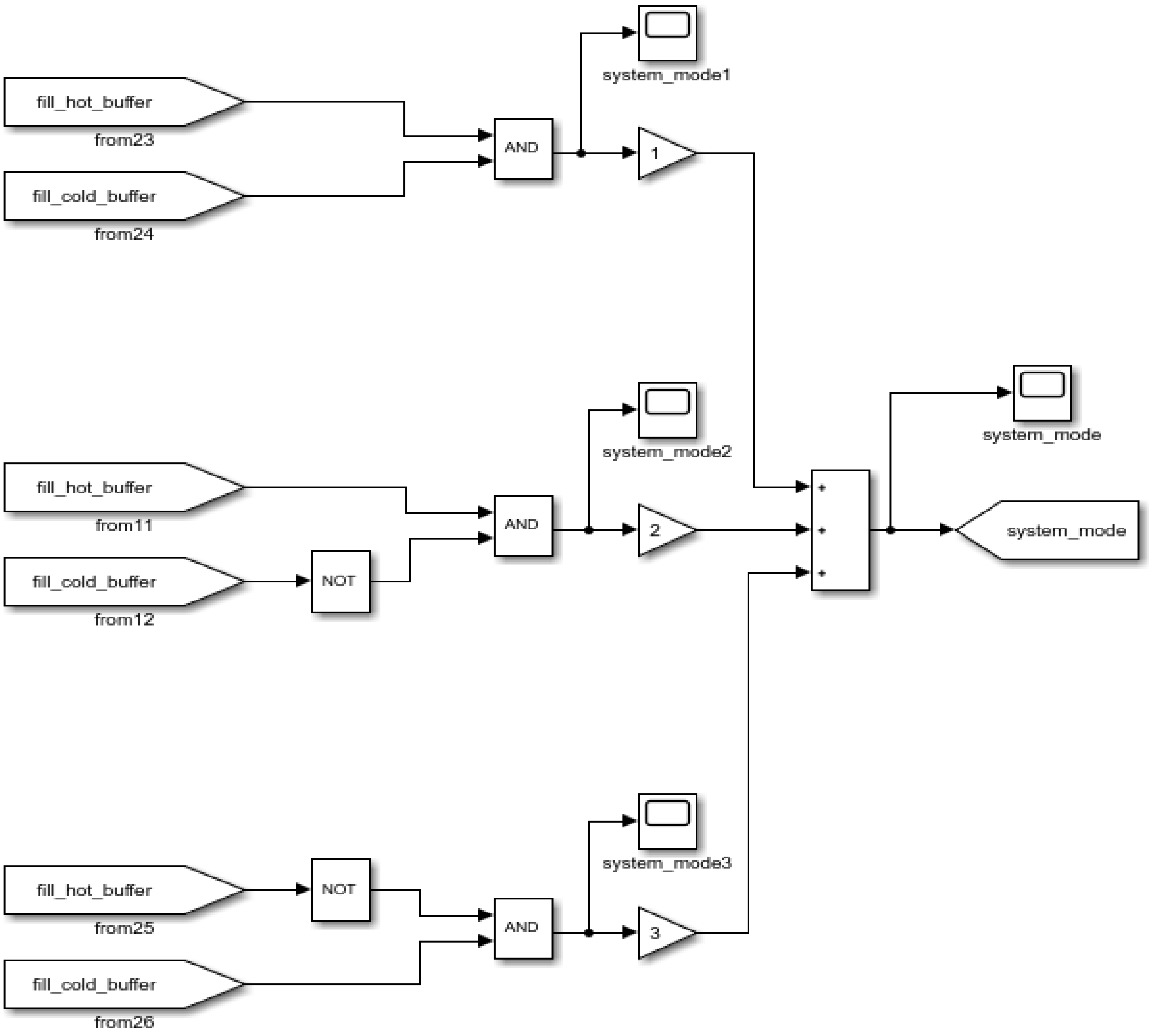
Hot Storage Tank



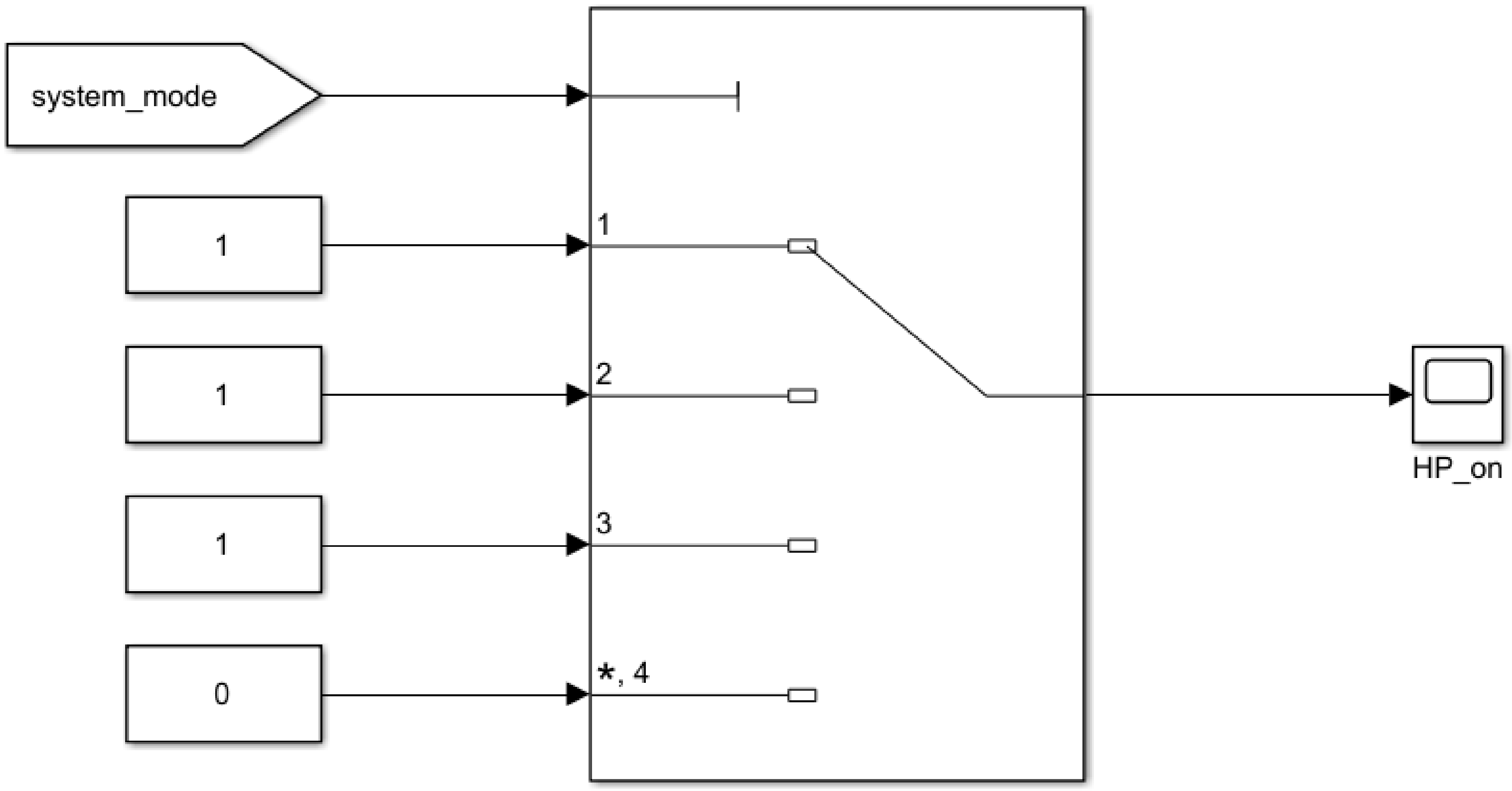
Cold Storage Tank



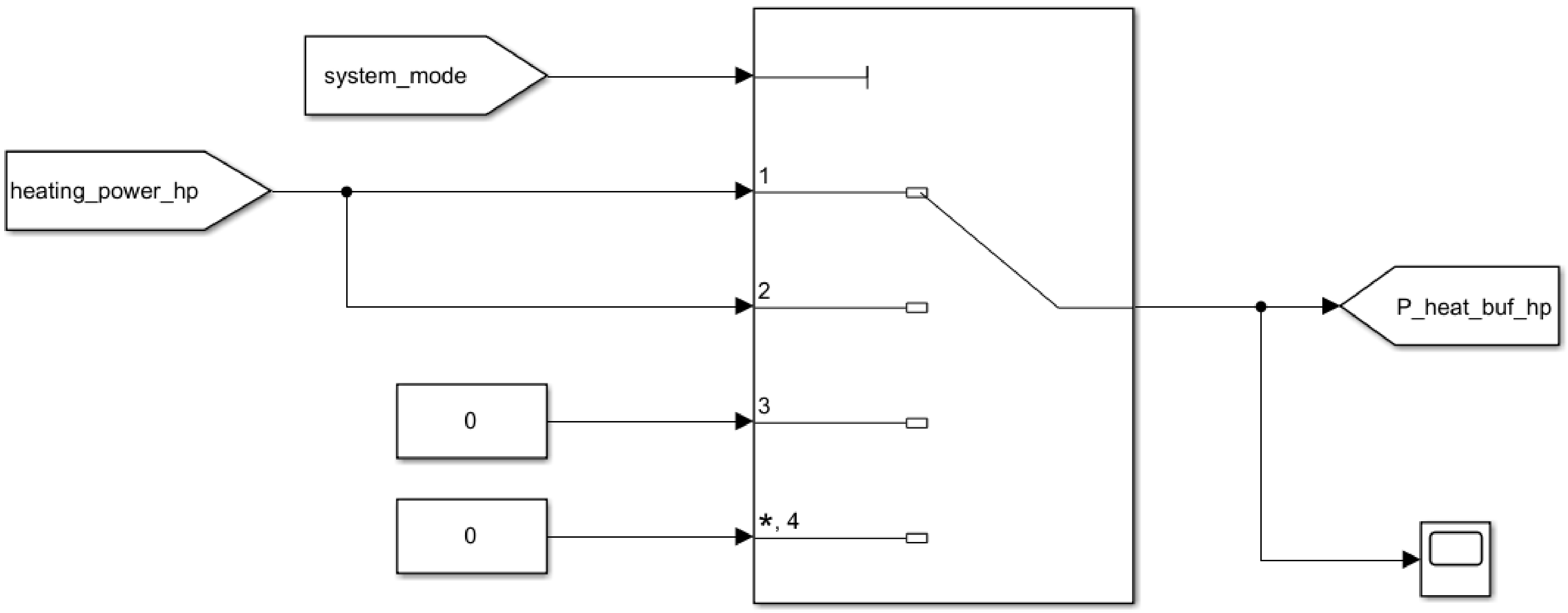
Module 3 – Determining the system mode of the heat pump installation



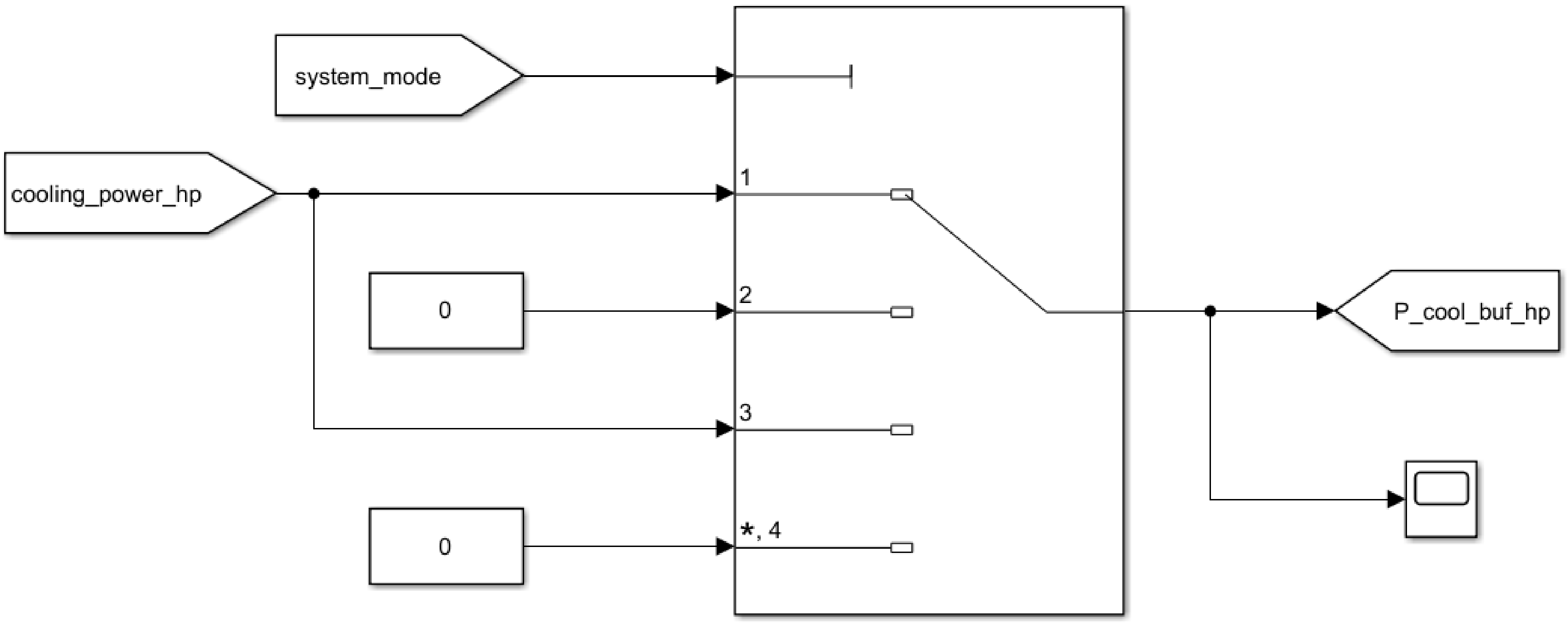
Module 4 – Operation mode of the heat pump



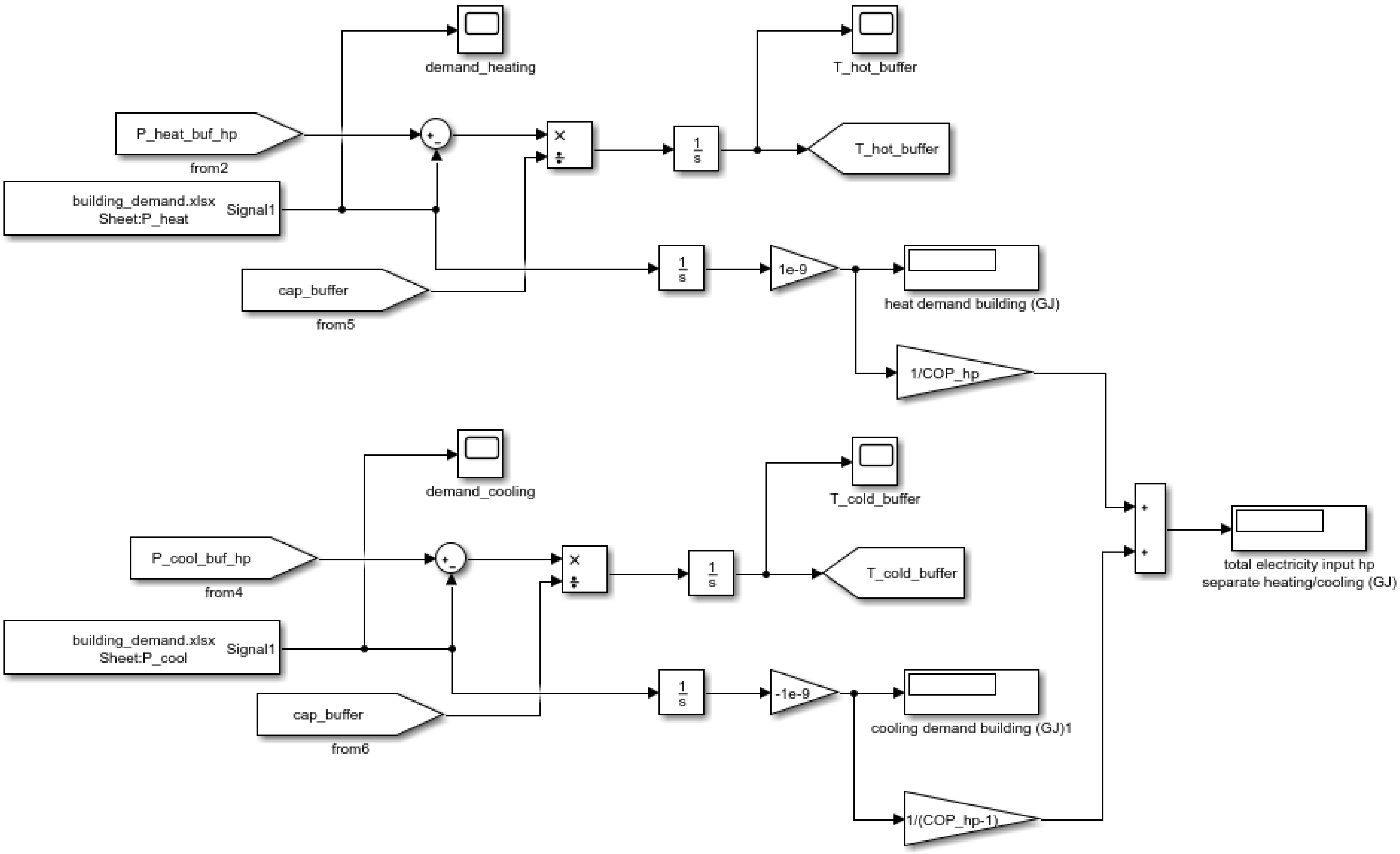
Module 5.2. – Heating mode and heat pump capacity selector



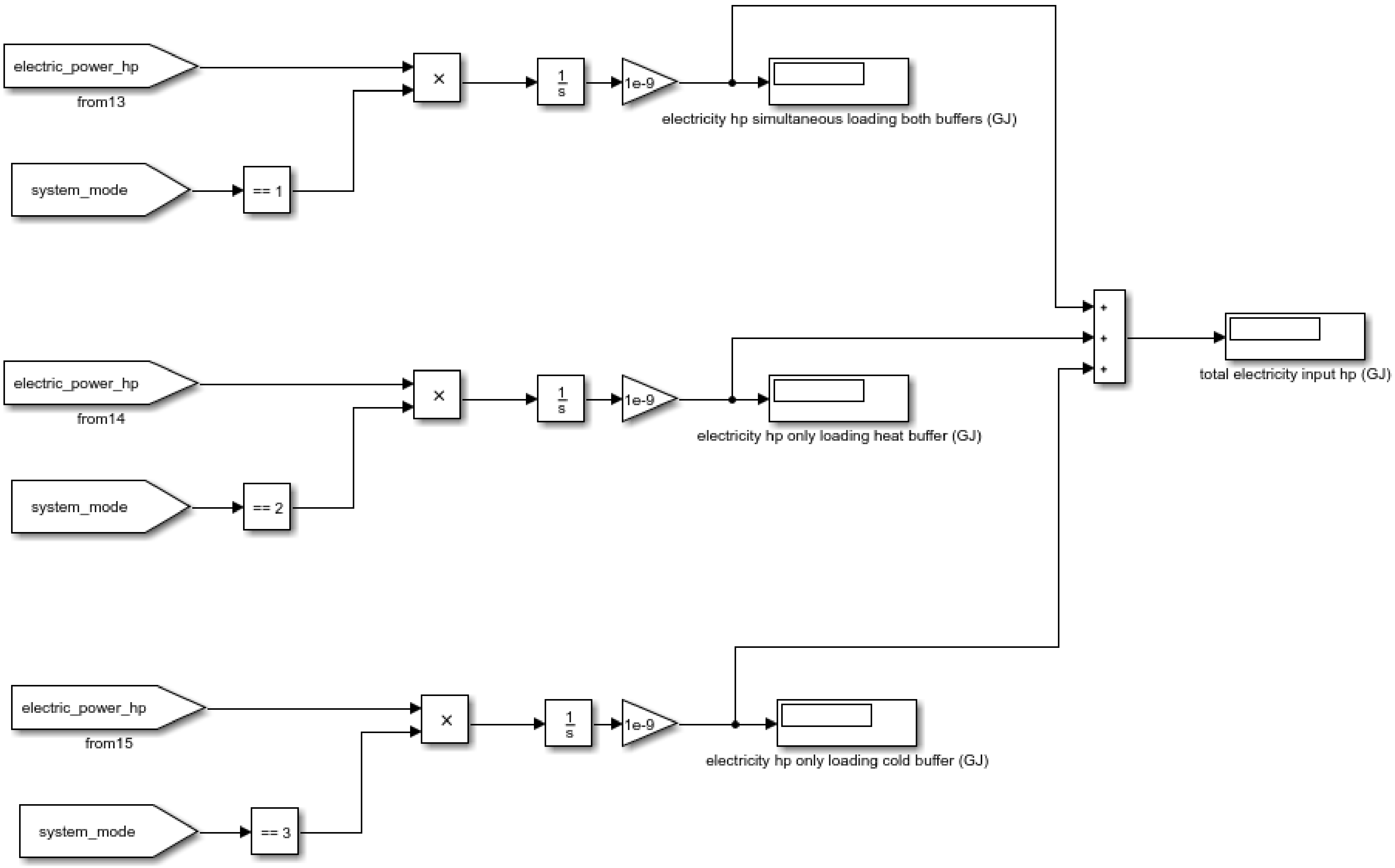
Module 5.3. – Cooling mode and heat pump capacity selector



Module 6 – Building demand and thermal buffering energy balance / calculation of electricity consumption for individual heating and cooling during reference case



Module 7 – Calculation of energy savings during synergetic heating / cooling, output of results



10. References

Past relevant graduation projects from TU Delft:

1. Ten Caat N. "Towards Energetic Circularity: greenhouse – supermarket -dwelling energy exchange.", 2018
2. Giouri E. – "Zero energy potential of a high-rise office building in a Mediterranean climate", 2017
3. Sillem E. – "Exchanging and storing energy: Reducing Energy Demand through heat exchange between functions and temporary storage.", 2011
4. Alexandri Ch. – "Towards zero energy office modules through parametric analysis of Building Envelope Strategies: Recommendations for the Green Village.", 2014
5. Leeuw, A. – "The potential for high-rise envelopes as energy production units",2016

Journal articles and reports

1. Sustainable high-rise buildings in urban zones: Advantages, Challenges and Global Case Studies, Springer, ISBN 978-3-319-17756-4 (eBook)
2. Ali, M. M. and Armstrong, P. J. (2008) 'Overview of Sustainable Design Factors in High-Rise Buildings', CTBUH 8th World Congress, Dubai. March 3 - 5, 2008., pp. 1–10.
3. Ali, M. *et al.* (2010) 'Title: Sustainability and the Tall Building: Recent Developments and Future Trends'.
4. ALwaer, H. and Clements-Croome, D. J. (2010) 'Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings', Building and Environment. Elsevier Ltd, 45(4), pp. 799–807. doi: 10.1016/j.buildenv.2009.08.019.
5. Alyami, S. H. and Rezgui, Y. (2012) 'Sustainable building assessment tool development approach', *Sustainable Cities and Society*. Elsevier B.V., 5(1), pp. 52–62. doi: 10.1016/j.scs.2012.05.004.
6. Azhar, S. *et al.* (2011) 'Building information modeling for sustainable design and LEED rating analysis', *Automation in Construction*. Elsevier B.V., 20(2), pp. 217–224. doi: 10.1016/j.autcon.2010.09.019.
7. Bojic, M., Yik, F. and Sat, P. (2001) 'Influence of thermal insulation position in building envelope on the space cooling of high-rise residential buildings in Hong Kong', Energy and Buildings, 33(6), pp. 569–581
8. BREEAM (2016) 'Technical Manual (2016), BREEAM International New Construction', *Building Research Establishment Group*, p. 454. doi: 10.1017/CBO9781107415324.004.
9. Chambers, N. (2014) 'Is Net-Zero Tall Possible?', *CTBUH Journal*, (2), pp. 18–24.
10. Cho, S. and Kim, J. (2015) 'Zero Energy Potential of High-Rise Residential Buildings', (September), pp. 641–648.
11. Choi, I. Y., Cho, S. H. and Kim, J. T. (2012) 'Energy consumption characteristics of high-rise apartment buildings according to building shape and mixed-use development', *Energy and Buildings*. Elsevier B.V., 46, pp. 123–131. doi: 10.1016/j.enbuil
12. Ding, G. K. C. (2008) 'Sustainable construction-The role of environmental assessment tools', *Journal of Environmental Management*, 86(3), pp. 451–464. doi: 10.1016/j.jenvman.2006.12.025.
13. Generalova, E. M. *et al.* (2018) 'Mixed-use development in a high-rise context', https://doi.org/10.1051/e3sconf/20183301021
14. Ha, P. T. H. (2016) 'A concept for energy-efficient high-rise buildings in Hanoi and a calculation method for building energy efficiency factor', *Procedia Engineering*. Elsevier B.V., 142, pp. 153–159. doi: 10.1016/j.proeng.2016.02.026.
15. Hachem, C. (2015) 'Design of a base case mixed-use community and its energy performance', *Energy Procedia*. Elsevier B.V., 78, pp. 663–668. doi: 10.1016/j.egypro.2015.11.056.
16. Hubers, J. C. C. (2012) 'Collaborative design of parametric sustainable architecture', *Journal of Civil Engineering and Architecture*, 6(7), pp. 812–821. doi: 10.1061/41182(416)51.
17. Jian, Z., Boranian, A. and Griego, D. (2013) 'Energy Saving Potential for Retroffiting Mixed-Use Buildings in Singapore : Developing Best Practices At Ntu Campus', pp. 978–981.

18. Jin, X.-H. *et al.* (2013) ‘Sustainable High-rise Design Trends – Dubai’s Strategy’, *Civil Engineering and Architecture*, 1(2), pp. 33–41. doi: 10.13189/cea.2013.010201.

19. Lee, W. L. (2012) ‘Benchmarking energy use of building environmental assessment schemes’, *Energy and Buildings*. Elsevier B.V., 45, pp. 326–334. doi: 10.1016/j.enbuild.2011.11.024.

20. Lee, W. L. (2013) ‘A comprehensive review of metrics of building environmental assessment schemes’, *Energy and Buildings*. Elsevier B.V., 62, pp. 403–413. doi: 10.1016/j.enbuild.2013.03.014.

21. Lotfabadi, P. (2014) ‘High-rise buildings and environmental factors’, *Renewable and Sustainable Energy Reviews*. Elsevier, 38, pp. 285–295. doi: 10.1016/j.rser.2014.05.024.

22. Lotfabadi, P. (2015) ‘Analyzing passive solar strategies in the case of high-rise building’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 52, pp. 1340–1353. doi: 10.1016/j.rser.2015.07.189.

23. Lotfabadi, P. (2015) ‘Solar considerations in high-rise buildings’, *Energy and Buildings*. Elsevier B.V., 89(72), pp. 183–195. doi: 10.1016/j.enbuild.2014.12.044.

24. Mir M. Ali, A. J. P. (2006) ‘Strategies for Integrated Design of Sustainable Tall Buildings’, *University of Illinois at Urbana-Champaign School of Architecture*, pp. 1–22.

25. Nguyen, B. K. and Altan, H. (2011) ‘TPSI - Tall-building Projects Sustainability Indicator’, *Procedia Engineering*, 21(0), pp. 387–394. doi: 10.1016/j.proeng.2011.11.2030.

26. Oldfield, P., Trabucco, D. and Wood, A. (2009) ‘Five energy generations of tall buildings: An historical analysis of energy consumption in high-rise buildings’, *Journal of Architecture*, 14(5), pp. 591–613. doi: 10.1080/13602360903119405.

27. Pan, F. and Wu, X. (2011) ‘Sustainable development of high-rise building’, *Procedia Engineering*, 21, pp. 943–947. doi: 10.1016/j.proeng.2011.11.2098.

28. Prieto, A. *et al.* (2017) ‘25 Years of cooling research in office buildings: Review for the integration of cooling strategies into the building faï¿½ade (1990–2014)’, *Renewable and Sustainable Energy Reviews*. Elsevier, 71, pp. 89–102. doi: 10.1016/j.rser.2017.01.012.

29. Raji, B., Tenpierik, M. J. and van den Dobbelsteen, A. (2017) ‘Early-stage design considerations for the energy-efficiency of high-rise office buildings’, *Sustainability (Switzerland)*, 9(4). doi: 10.3390/su9040623.