Master Thesis

TECHNO-ENVIRONMENTAL ANALYSIS OF A MODULAR HEAT PUMP SYSTEM WITH A LATENT STORAGE FOR RESIDENTIAL APPLICATIONS

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by

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List of Abbreviations and Symbols

1GDH	First Generation District Heating
2GDH	Second Generation District Heating
3GDH	Third Generation District Heating
4GDH	Fourth Generation District Heating
5GDH	Fifth Generation District Heating
5GDHC	Fifth Generation District Heating and Cooling
AC	Air Conditioner
ASHP	Air Source Heat Pump
COP	Coefficient of Performance
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
EU	European Union
FIN	Finland
FR	France
GHG	Green House Gas
GR	Greece
GSHP	Ground Source Heat Pump
HEX	Heat Exchanger
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioner
ICT	Information and Communication Technology
KPI	Key Performance Indicator
LHS	Latent Heat Storage
PCM	Phase Change Material
RES	Renewable Energy Source
RPW-HEX	Refrigerant-PCM-Water Heat Exchanger
SCOP	Seasonal Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
SHTES	Sensible Heat Storage Materials
TES	Thermal Energy Storage
WPW-HEX	Water-PCM-Water Heat Exchanger
WSHP	Water Source Heat Pump

ϑ	Temperature (°C)
χ	Liquid fraction
A	Area (m^2)
c_p	Specific heat capacity (J/(kg.K))
f_{CO2}	Emission factor CO2 (g_{CO2}/kWh)
$\dot{m}$	Mass flow rate (kg/s)
M_{CO2}	Mass of CO2 (kg)
P_{el}	Electrical input (W)
Q	Heat (J)
$\dot{Q}$	Heat transfer rate (W)
$\dot{Q}_{specific}$	Specific heat transfer rate (W/m^2)
T	Absolute Temperature (K)
V	Volume (m^3)
W	Work of the compressor (J)

Abstract

Both globally and in Europe, the energy consumption in the building stock represents a considerable share of the final energy consumption. Under this consumption, the production of space heating, space cooling and domestic hot water (DHW) constitute a large proportion, as well as being a source of greenhouse gases when the building energy system is fossil fuels based. Hence, to achieve both energy efficiency and decarbonization goals in the residential sector, the introduction and/or expansion of renewable energy sources and decarbonization-key enabling technologies are essential. Accordingly, implementation of heat pump technology arises as a key technology for the production of heating, cooling and domestic hot water.

Consequently, this work proposes a system of reversible modular heat pumps equipped with a latent heat storage. This system has the capacity to produce domestic hot water, heating in the winter season and cooling during the summer. Due to its modularity, this system further has the particularity of being able to connect the energy carrier fluid (in this case water), in serial or in parallel automatically, depending on the desired supply temperature, the demand flow rate and the acceptable pressure drop in the hydronic circuit. In addition, the use of latent heat storage technologies, allows the elimination of buffer and water storage tanks in order to avoid oversizing the heat pumps, thus increasing the performance of the system and reducing the electrical energy consumption.

This work develops a fully dynamic thermo-hydraulic model in Modelica/Dymola for a building energy system comprising of three major parts that are: a supply side (heat pumps system), building distribution system (hydronic circuit for water distribution equipped with a latent heat storage for DHW) and a demand side represented by a building with occupancy. The integration of these parts into the building distribution system, its optimization, and the investigation of the impact of connecting the heat pumps condenser side in parallel and series on the heat delivery, indoor and DHW temperatures and overall system performance will be the main focus of the present work. This system is going to be investigated based on annual simulations in three different climates (Helsinki, Strasbourg, and Athens), to determine their performance and efficiency under different conditions.

Moreover, the work then studies the technical feasibility of the system and conducts an environmental analysis focusing on the CO2 savings of such an installation compared to a conventional building energy system whereby a gas-fired boiler, hot water tank and electrical air-conditioning system are present.

Key words

Modular reversible heat pump, simulation-based analysis, phase change material.

Kurzfassung

Sowohl weltweit als auch in Europa macht der Energieverbrauch im Gebäudebestand einen beträchtlichen Teil des Endenergieverbrauchs aus. Ein großer Teil dieses Verbrauchs entfällt auf die Erzeugung von Raumwärme, Raumkühlung und Brauchwarmwasser und ist eine Quelle von Treibhausgasen, wenn das Gebäudeenergiesystem auf fossilen Brennstoffen basiert. Um sowohl die Ziele der Energieeffizienz als auch der Dekarbonisierung im Wohnbereich zu erreichen, ist daher die Einführung und/oder der Ausbau von erneuerbaren Energiequellen und Dekarbonisierung-Schlüsseltechnologien unumgänglich. Dementsprechend erweist sich die Einführung der Wärmepumpentechnologie als eine Schlüsseltechnologie für die Erzeugung von Heizung, Kühlung und Warmwasser.

Daher wird in dieser Arbeit ein System von reversiblen modularen Wärmepumpen mit einem Latentwärmespeicher vorgeschlagen. Dieses System ist in der Lage, Brauchwarmwasser zu erzeugen, im Winter zu heizen und im Sommer zu kühlen. Aufgrund seiner Modularität weist dieses System außerdem die Besonderheit auf, dass es in der Lage ist, die Energieträgerflüssigkeit (in diesem Fall Wasser) automatisch in Reihe oder parallel zu schalten, je nach der gewünschten Vorlauftemperatur, der benötigten Durchflussmenge und dem akzeptablen Druckabfall im Hydraulikkreislauf. Darüber hinaus ermöglicht der Einsatz von Latentwärmespeichertechnologien den Verzicht auf Puffer- und Wasserspeicher, um eine Überdimensionierung der Wärmepumpen zu vermeiden, wodurch die Leistung des Systems erhöht, und der Stromverbrauch gesenkt wird.

In dieser Studie wird ein volldynamisches thermohydraulisches Modell in Modelica/Dymola für ein Gebäude-Energiesystem entwickelt, das aus drei Hauptteilen besteht: einer Versorgungsseite (Wärmepumpenanlage), einem Gebäudeverteilungssystem (hydronischer Kreislauf für die Wasserverteilung mit einem Latentwärmespeicher für Warmwasser) und einer Nachfrageseite, die durch ein bewohntes Gebäude dargestellt wird. Die Integration dieser Teile in das Gebäudeverteilungssystem, seine Optimierung und die Untersuchung der Auswirkungen der Parallel- und Reihenschaltung der Wärmepumpenkondensatoren auf die Wärmeabgabe, die Innen- und Warmwassertemperaturen und die Gesamtleistung des Systems werden im Mittelpunkt der vorliegenden Arbeit stehen. Dieses System wird anhand von jährlichen Simulationen in drei verschiedenen Klimazonen (Helsinki, Straßburg und Athen) untersucht, um seine Leistung und Effizienz unter verschiedenen Bedingungen zu ermitteln.

Darüber hinaus wird die technische Machbarkeit des Systems untersucht und eine Umweltanalyse durchgeführt, die sich auf die CO2-Einsparungen einer solchen Anlage im Vergleich zu einem herkömmlichen Gebäudeenergiesystem mit einem Gaskessel, einem Warmwasserspeicher und einer elektrischen Klimaanlage konzentriert.

Schlüsselwörter

Modulare reversible Wärmepumpe, simulationsbasierte Analyse, Phasenwechselmaterial.

Chapter 1

Introduction

1.1. OBJECTIVES AND SCOPE OF THE STUDY

The European Union (EU) has set very ambitious decarbonization targets, with the aim of achieving carbon neutrality by 2050. To achieve this, a full integration of the different renewable energy sources is necessary, as improvements in the electricity grid alone are not sufficient, especially in the heating and cooling sectors, where thermal district networks (also called district heating and cooling) play an important role.

Therefore, the coupling of the electrical and thermal grids (meaning the integration of electricity and thermal), allowing the integration of renewable energy sources inside smart hybrid networks based on 4th and 5th generation district heating and cooling (DHC) is essential to achieve those decarbonization targets. This present work is included in the framework of the European HYPERGRYD project, which is one of the projects that aims for this sector coupling [1]. A description of this sector coupling and what it means to the DHC can be seen in Figure 1.

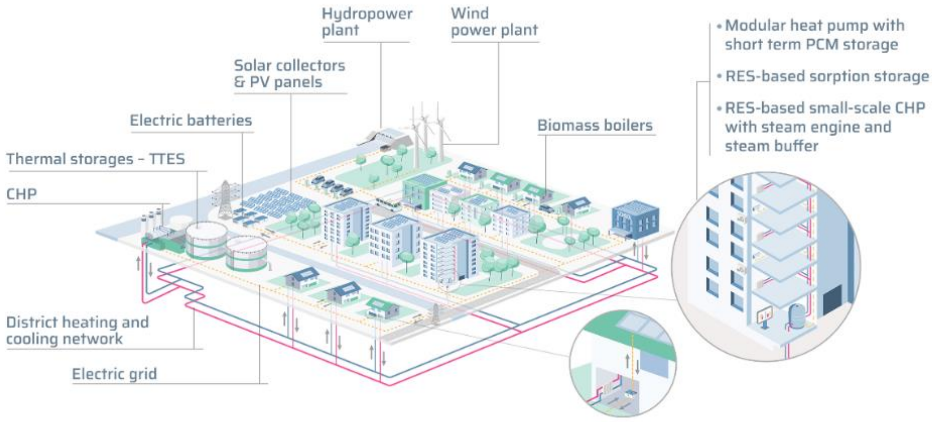


Figure 1: Hybrid coupled networks for thermal-electric integrated smart energy districts [1]

For a better understanding of the project and its objectives, it is first necessary to know the concept of DHC and its different generations so far.

District heating (DH) is an energy service based on the transmission of thermal energy in form of heat from available heat sources to consumers that demand heating (i.e. space heating, domestic hot water), distributing it by a network of subterranean pipes that supplies the demanded heat at any moment.

This kind of technology is being under improvement over the years, resulting in different generations [2]. The first generations of district heating relied on a central supply of heat at an immediately useful temperature levels (hence high heat losses) which was distributed to buildings through a network of pipes. The first generation of district heating (1GDH) was introduced in the United States of America in the 1880s, using steam as the heat carrier fluid [2].

As this technology developed, the heat transfer fluid was changed to superheated water, leading to the second generation of district heating (2GDH), with higher efficiency, reliability, and resistance. But its greatest drawback was the high pressure needed to keep that water superheated [2].

The third generation of district heating (3GDH) came with the reduction of the supply temperature below 100°C, allowing for a wider variety of heat sources, increased distribution efficiency and the economically viable utilization of high temperature waste heat, as well as the supply of heat from renewable energy sources [2].

The current generation is the fourth generation (4GDH), which is defined as a "*coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems"* [3]. The main feature of this generation is a water temperature level as close as possible to the actual demand, at a maximum of 60-70 °C. This further reduces losses in the heating network, increasing the efficiency and the flexibility of the network and enables better integration of waste heat sources, as well as emphasizing the increased use of heat pumps in DH systems [2]. Figure 2 shows the development of these DH systems over the years.

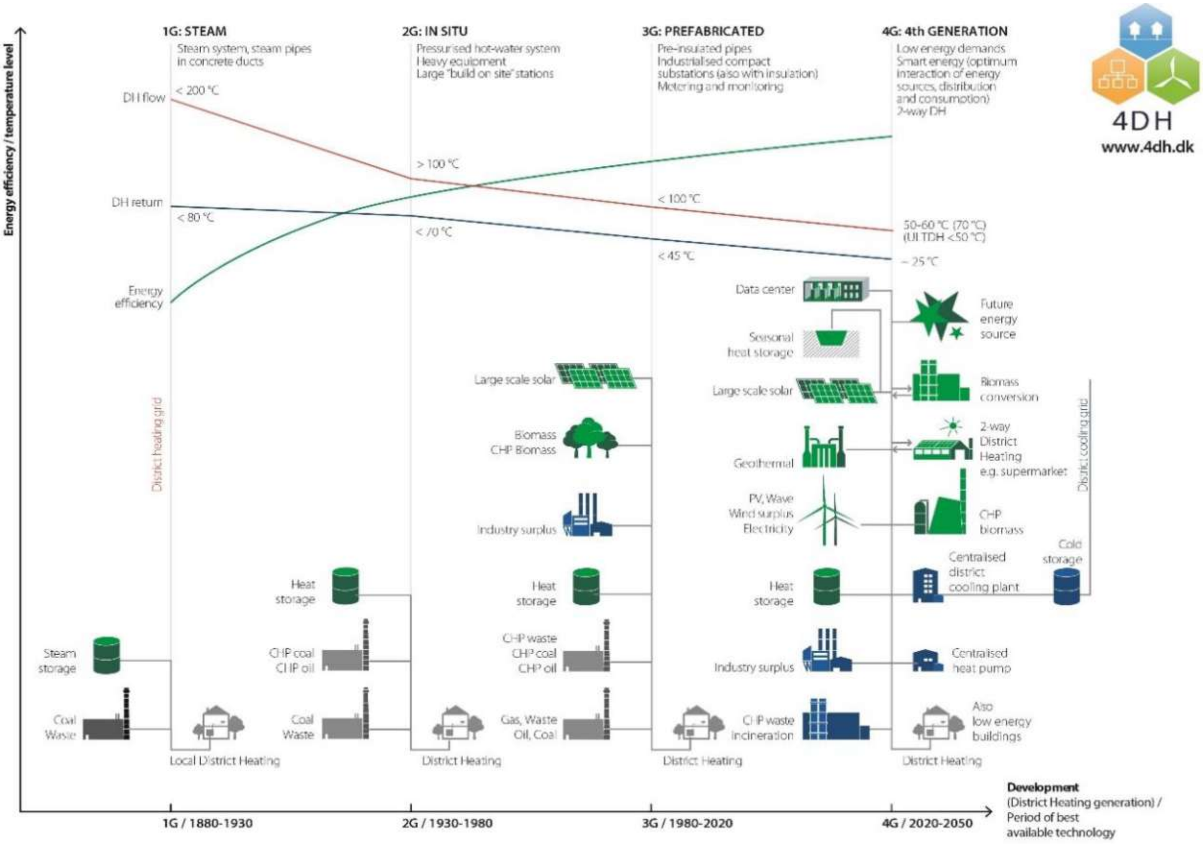


Figure 2: Progression of District Heating – 1st to 4th generation [3]

Parallel to this fourth generation, the concept and objectives of the fifth generation have been developed, so that, in addition to being considered a new technology on its own, as it shares practically the same objectives as the previous generation, it can be considered a complement that can coexist in parallel with the other 4GDH technologies [2]. The 5GDH is based on the exchange of thermal energy between buildings with different needs, where the fluid is transported at an ultra-low temperature (25-35ºC) to active and distributed substations that raise the temperature to the required level for delivery to the end user, providing both heating and cooling services simultaneously, so it can be called 5GDHC [4].

With this explained, it is clear that the integration of the thermal and electricity grids through a set of renewable energy based, digitally managed and user-centered solutions, is the main objective to accelerate the sustainable transition to the future 4th and 5th generations of DHC. This main objective can be further divided into a number of sub-objectives and challenges, including:

- The integration and development of centralized renewable energy sources (RES).
- The optimization and flexibility of the whole system, ensuring rapid deployment of the solutions.
- The development of an integrated and interconnected information and communication technology (ICT) platform between the different existing networks, enabling user participation in the management of the grid.
- The development of Live-in-Labs to simulate and validate all these solutions in 3 different climates [1].

With all of this, the impacts that are intended to have on the thermal and electrical grids are as follows:

- Ensure 60% RES penetration in DH demand for the 4th generation system and 80% for the 5th generation system, thus reducing environmental emissions in this sector.
- Reducing the temperature level to 50-60ºC in the 4th generation DHC and to 25ºC in the 5th, which minimizes losses in the grid and increases the integration of heat recovery systems, as explained above.
- Promote the sustainability of district heating and cooling networks connected to local RES, and energy storage.
- Promote user participation in the energy transition by stimulating indirect knowledge acquisition through innovative ICT solutions.
- Increasing primary energy savings compared to the current scenario [1].

In order to achieve the proposed objectives, one of the fundamental pillars is the development of RES-based technologies, being one of them, the development of a modular heat pump with short-term phase change material (PCM) storage [5].

This heat pump results in a decentralized solution with refrigeration circuit modules connected either in series or in parallel for flexible operation. The heat pump operates using the optimum amount of refrigerant per cooling circuit and is intended for decentralized installation in new buildings and to replace existing gas boilers in large residential or neighborhood buildings, thus contributing to the decarbonization of the sector [5].

In addition, it uses a short-term latent storage with higher energy density than conventional systems, using a PCM storage, which works as a WPW (Water-PCM-Water)-HEX (Heat Exchanger), meaning that it is a three-media heat exchanger, with super-heated water on one side, PCM, and with domestic hot water (DHW) on the other side.

The technical aspects of both the modular heat pump and the PCM storage will be discussed in Chapter 2, and more extensively in Chapter 3 [5]. Figure 3 shows a simple schematic diagram of the principle of operation of this heat pump. (Despite the schematics shows 6 heat pump modules, there will be 8 as will be explained later).

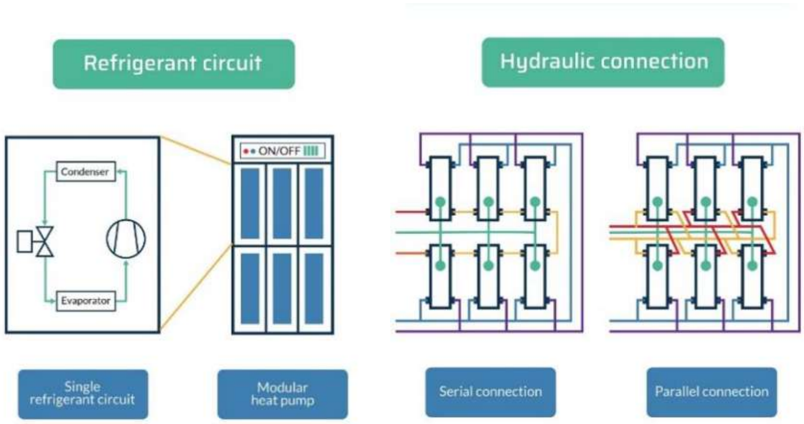


Figure 3: Modular heat pump with short-term PCM storage [5]

1.2. PROBLEM STATEMENT

As explained in the previous section, this work is justified by the ambitious decarbonization and energy efficiency goals of the EU, since globally, the operation of the building sector accounts for a large share of final energy consumption, 30% by 2021, rising to 34% if cement, steel, and aluminum production are considered [6]. Based on EU data alone, this share increases to 42% (2020 data) of the total energy consumed by all sectors. Of this percentage, two thirds are accounted for residential buildings, representing a share of about 28% of total energy [7]. This data can be observed on Figure 4.

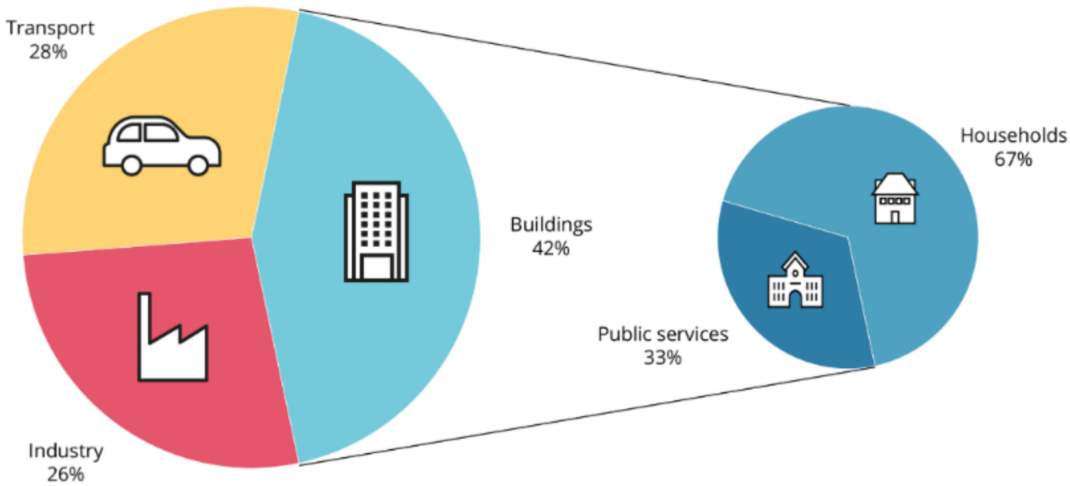


Figure 4: Final energy consumption by end-use sector, EU, 2020 [7]

Detailing the consumption data, 78% of total energy use in residential buildings is used in heating and domestic hot water (DHW) production, while cooling production accounts for less than 1%, of the total, as shows Figure 5, although due to the increase in global average temperature, this percentage is expected to grow in the coming years [7]. It can therefore be concluded that the production of heating, cooling, and domestic hot water in residential buildings accounts for about 22% of total energy consumption in the European Union [7].

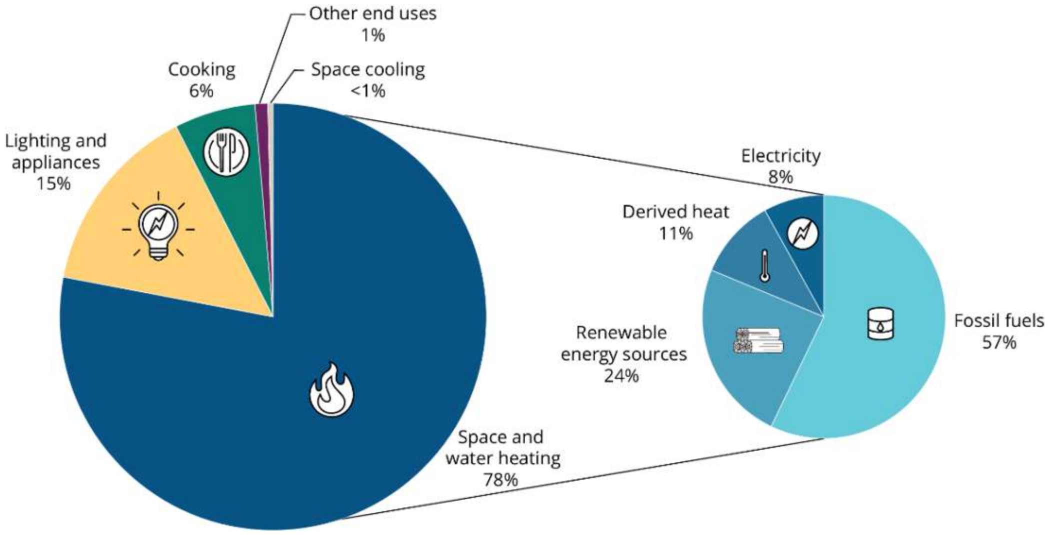


Figure 5: Final energy uses across EU households, with space and water heating disaggregated by fuel type, 2020 [7]

Of this total, it can be observed that more than half of the energy (57%) is produced by burning fossil fuels: natural gas (39%), oil (15%) and coal (4%), of which a large part is installed in old buildings with low efficiency boilers. Meanwhile, only 24% of energy production comes from renewable sources (mostly biomass), and only 13% of this percentage comes from heat pumps, (which represents about 3% of total energy production in residential buildings) [7].

Therefore, it is expected that the building sector is one of the largest emitters of greenhouse gases (GHG) in the world. This sector was responsible for 35% of the EU's energy-related greenhouse gas emissions in 2020 [7], and in 2022, only residential buildings were responsible for 21% of total emissions of the EU [8].

As a result, the building sector needs to change faster to meet the 2030 targets and the carbon neutrality scenario in 2050. These targets include: a 40% reduction in greenhouse gas emissions (compared to 1990 levels), a 32% increase in renewable energy in electricity production, and a 32.5% increase in energy efficiency [9]. In addition, as for the reduction of electricity consumption, it is intended to trim the final energy consumption in at least 40% and in a 42.5% in the primary energy consumption, compared with the level of 2007 for the year 2030 [10].

In parallel with this, the European Union has approved recently for the member countries, the ban of gas boilers in new buildings from 2028 onwards and the phase out of the use of fossil fuel-based heating systems from all buildings by 2035 and if not feasible as demonstrated to the commission, by 2040 at the latest [11].

To achieve all this, heat pumps have a very important role to play in the production of heating, cooling and DHW in buildings, as they arise as an essential technology for reducing energy consumption and GHGs emissions, improving the energy efficiency of buildings, and contributing to the decarbonization of the energy sector. They are a sustainable alternative, more energy efficient than conventional systems (gas boilers or electrical boilers) and are easy to integrate with renewable energy production systems, especially with photovoltaic panels [12]

Moreover, it is proven that this alternative could cover more than 90% of the world's space and water heating with lower CO2 emissions than condensing gas boiler technology (the most efficient technology from fossil fuels) [13], and that, with current refrigerants (pending the development of cleaner and more efficient alternatives, like natural refrigerants as propane, carbon dioxide or isobutane), greenhouse gas emissions could be reduced by at least 20% compared to a gas boiler [13, 14].

In the United States, the share of heat pump sales for new buildings exceeds 40 % for single-family homes and approaches 50 % for new multi-family buildings [15] Meanwhile, in Europe, while still being a low percentage of the alternatives, the market is expanding rapidly, with an average annual growth of 12% since 2015. France, Italy, and Spain account for half of all EU sales, and countries such as Sweden, Estonia, Finland, and Norway account for the highest usage rate, with more than 25 heat pumps sold per 1,000 households per year [15]. Despite this strong growth in recent years, the heat pump market must continue its expansion worldwide, with the aim of reaching the 253-million-unit target by 2050 (compared to 20 million units in 2016) [13].

One of the most interesting heat pump solutions is the modular reversible heat pump. Reversible because the same heat pump can produce both heating and air conditioning depending on demand, and modular because several heat pump modules can be connected in series or in parallel and controlled as a single unit. This will be explained in more detail in Chapters 2 and 3.

Thermal energy storage (TES) through sensible heat has traditionally been and continues to be used to increase system efficiency, with strategies such as reducing peak heat loads and shifting heating and cooling demands over time [15]. So, another key technology to achieve these goals is latent heat energy storage using phase change materials (PCM), which can absorb/release energy during their phase transition to provide sufficient heating/cooling energy. Therefore, PCMs present themselves as an interesting solution to achieve this energy efficiency, as they have a higher energy density compared to sensible thermal storage and have the ability to release and store a large amount of energy within a small temperature range [13]. As before, these concepts will be developed in Chapters 2 and 3.

1.3. METODOLOGY

In this work, a system with 4 heat pump blocks will be studied. Each one of these blocks has two modules of heat pumps, making 8 heat pumps in total, which can be connected in series or in parallel automatically depending on the desired supply temperature, the demanded flow rate and the acceptable pressure drop in the hydronic circuit. It will be also studied the integration of a 3-media heat exchanger Water-PCM-Water (WPW-HEX) as latent heat storage for domestic hot water production.

The main objective of the work is to study and optimize the series and parallel configurations separately, demonstrating the feasibility of the system understanding their strengths and weaknesses in order to to know in the future in which cases it will have to operate in one way or another, as the future of this project is the development of an optimal control strategy, which allows the system to switch from series to parallel operation mode automatically, achieving minimum electricity consumption and considering the different residential demands (heating, cooling, and DHW).

To achieve this, dynamic thermo-hydraulic simulations have been carried out using the Modelica and Dymola software, where the models of the heat pump, the WPW-HEX exchanger, its hydraulic connections, and its control strategy has been created. The simulations have been carried out over a period of one year in three different climate zones (Helsinki, Strasbourg, and Athens) in order to determine the performance and efficiency of the system under different conditions. The whole procedure and strategies used to obtain the results, as well as the analysis of those, will be discussed in the following chapters of this project. As well as the comparison in terms of CO2 emissions of this heat pump system with a conventional system consisting of a gas boiler, water tank and air conditioner (AC) unit.

Chapter 2 explains the principles of operation of heat pump and latent heat storage technologies using phase change materials, in order to give an overview of why these technologies are an advantage for the production of heating cooling and DHW in buildings compared with the traditional systems.

Chapter 3 shows a detailed description of the system and its components, from the heat pumps, the WPW-HEX, the building under study and its boundary conditions to the different operating modes and configurations, and then in Chapter 4 a comprehensive analysis of the results obtained will be made taking into account the indoor temperature and the DHW delivery temperature, as well as the performance of the system under the different operating modes, configurations and locations, both in terms of heat produced, electrical input and CO2 emissions.

Chapter 2

Principles and fundamentals

This chapter describes the basic principles and theorical concepts that need to be known to understand the background of the project.

2.1. HEAT PUMP

A heat pump, (HP), bases its operation on the second law of thermodynamics. Heat pumps absorb thermal energy on a low-temperature side (T_1), cooling it, and transfers it to a high-temperature side (T_2), heating it, by applying an external work (W_{in}). The main scheme of operation can be seen in Figure 6, where, the heat rejected to the heat sink, Q_{hot}, is equal to the heat extracted from the heat source, Q_{cold} plus the work required to run the cycle, $W_{in.}$ [16].

$$Q_{hot} = Q_{cold} + W_{in} \quad (1)$$

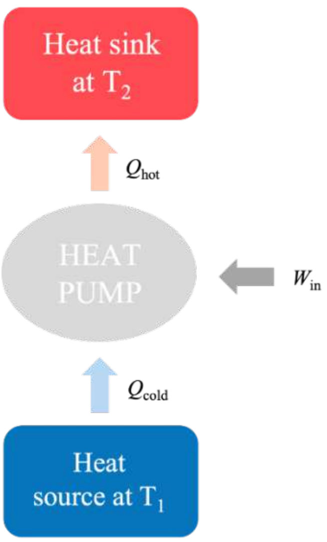


Figure 6: Heat Pump, basic principle of operation [16]

Heat transfer is achieved by circulating a refrigerant in a closed circuit, compressing it in the compressor to heat it and expanding it through an expansion valve to cool it. In combination, the refrigerant is passed through two different heat exchangers where it changes its state. In the low-temperature heat exchanger (called evaporator) it evaporates by taking heat from the surroundings, and in the high-temperature heat exchanger (condenser) it condenses by transferring heat to the environment [12].

This operation is based on the capability of heat to flow from a hotter body to a colder one. The refrigerant passing through the evaporator is cooler than its surroundings, so it absorbs heat from this source, cooling it. In the condenser, the refrigerant is hotter and expels the heat to a colder source, heating it.

HPs are based on that the environment of one heat exchanger is much larger and abundant than the other. This larger environment, which serves as an energy source, can be air, water, ground, solar energy, or even industrial waste heat. The other heat exchanger is located in the environment to be heated or cooled and is therefore smaller. For example, in DHW systems, heat energy can be extracted from the air (the source) and delivered to the sump (the hot water tank) [12].

Hence, the heat pump follows a closed cycle of four stages: compression, condensation, expansion, and evaporation, which can be seen in the scheme of Figure 7.

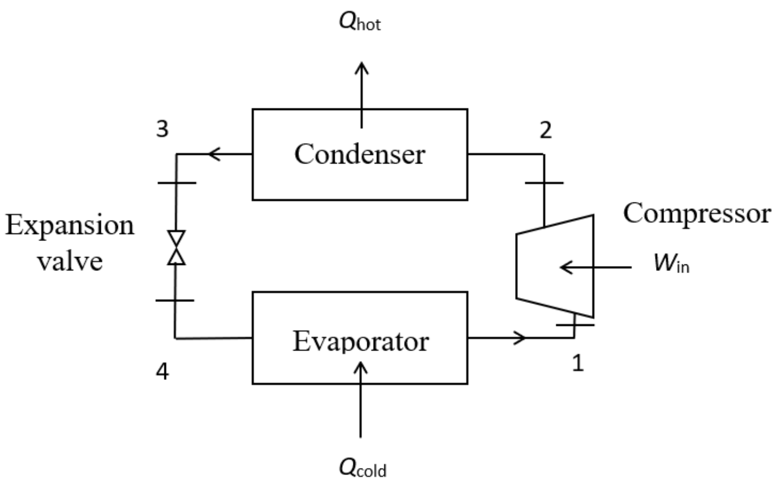


Figure 7: The schematic of a basic refrigeration cycle [16]

1- Compression: the refrigerant, which enters the compressor in a superheated or saturated vapour state, is compressed, thus increasing its pressure and therefore its temperature, reaching very high values.

2- Condensation: after leaving the compressor, the refrigerant, which is in a superheated vapour state, passes through the condenser where it transfers heat to the medium, which is at a lower temperature. The medium increases its temperature as the refrigerant condenses to a saturated liquid state. This process takes place at constant pressure.

3- Expansion: in the expansion stage, as the refrigerant passes through the expansion valve, the temperature and pressure of the refrigerant are reduced, to ease its subsequent evaporation. This is an isenthalpic process.

4- Evaporation: the cycle continues in the evaporator, which works in the opposite way to the condenser. Here the saturated liquid, being at a low temperature, absorbs heat from the medium, so it evaporates until it reaches the state of saturated vapour, closing the cycle at the same pressure and temperature at which it started [16, 12].

Figure 8 shows the typical heat pump p-h cycle with the 4 processes mentioned above. 1-2: compression, 2-3: condensation, 3-4 expansion and 4-1: evaporation.

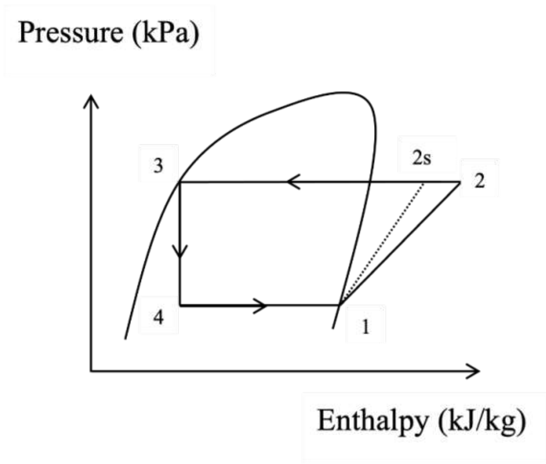


Figure 8: Real p-h diagram [16]

In the real process, the compression stage does not occur at constant entropy, due to energy destruction/entropy generation in the compression, so the temperature after the compression process (point 2) is higher than the ideal temperature of the isentropic process (point 2s) [16]. This increases the work done by the compressor during its stage and can be determined as the isentropic efficiency of the compressor.

2.1.1.Reversible heat pumps

A characteristic of some heat pumps is the ability of reversing the mode of operation to provide heating or cooling depending on the indoor thermal demand, thereby providing versatility and adaptability to the system [12].

One way to achieve this reversibility is with a 4-way valve, which can reverse the direction of the refrigerant flow. On this type of HP (also named split unit heat pumps) both heat exchangers can act as evaporator or condenser instinctively. These heat pumps also often include a liquid receiver to temporarily store the excess of refrigerant that occurs when changing the operating mode, as the heating and cooling modes use different amounts of refrigerant [17]. Figure 9 shows a typical schematic of a reversible heat pump.

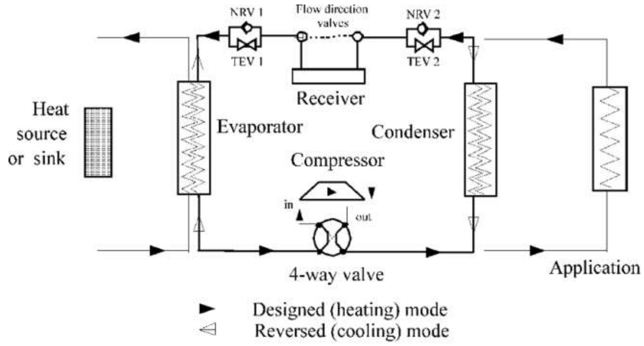


Figure 9: Schematic of the water-to-water reversible heat pump [17]

Another way to achieve this reversibility is to use a traditional heat pump outside the building, and without changing the operation of the HP use the heat generated in the condenser, the cold generated in the evaporator, or both at the same time (for cooling and DHW production) depending on the thermal demand of the building [12]. This type of HP is called a compact unit heat pump and is the HP model that has been used to develop this project.

2.1.2. Coefficient Of Performance (COP)

Having discussed the theoretical principle of heat pumps and their components, it is time to talk about their performance, and why they are so efficient, and consequently such a good alternative when it comes to heat and cooling production.

The efficiency of any thermal machine (such as a thermal engine) can be represented as the ratio of the work provided by the machine for the inputted heat, i.e., the amount of heat that is converted into work [18].

$$\eta_{\mathrm{th}} = \frac{W}{Q_{\mathrm{H}}} \qquad (2)$$

But heat pumps work in exactly the opposite way to thermal engines. Work is not an output, but an input, and thermal efficiency represents the degree to which the energy added by work is converted into net heat output. From a performance point of view, the best heat pump cycle is the one that is able to remove the largest amount of heat from the cold source and transfer it to the hot source, for the least mechanical work or electrical energy [18]. Therefore, the higher this ratio, which is called the Coefficient of Performance (COP), the more efficient the cycle will be.

This COP is usually higher than 1 (and a distinction must be made between heating and cooling COPs, as will be discussed below), basically because most of the heat is transferred rather than generated, which means that the heat energy production is usually several times higher than that needed to power the heat pump.

2.1.2.1. COP of cooling operation

The coefficient of performance of the cooling operation of the HP, also called energy efficiency ratio (EER) can be defined as the heat removed from the cold source Q_{cold} times the electrical work W_{in} done by the compressor. So, the efficiency of the heat pump increases the more Q_{cold} can be removed from the room (or the space to be cooled) for a given amount of work input.

$$\mathrm{COP}_{\mathrm{cool}} = \frac{Q_{\mathrm{cold}}}{W_{\mathrm{in}}} \qquad (3)$$

Following the first law of thermodynamics explained above, this equation can be rewritten as follows.

$$\mathrm{COP}_{\mathrm{cool}} = \frac{Q_{\mathrm{cold}}}{Q_{\mathrm{hot}} - Q_{\mathrm{cold}}} \qquad (4)$$

2.1.2.2. COP of heating operation

Whereas the COP of the heat pump in heating operation is defined as the amount of heat added to the hot source Q_{hot} divided by the electrical input of the compressor W_{in}.

$$\mathrm{COP_{heat}} = \frac{Q_{hot}}{W_{in}} \tag{5}$$

As before, this equation can be rewritten using the first law of thermodynamics to obtain,

$$\mathrm{COP_{heat}} = \frac{Q_{cold} + W_{in}}{W_{in}}$$

$$\mathbf{COP_{heat}} = \frac{Q_{cold}}{W_{in}} + \frac{W_{in}}{W_{in}} = \mathbf{COP_{cool} + 1} \tag{6}$$

This is further illustrated in the Figure 10:

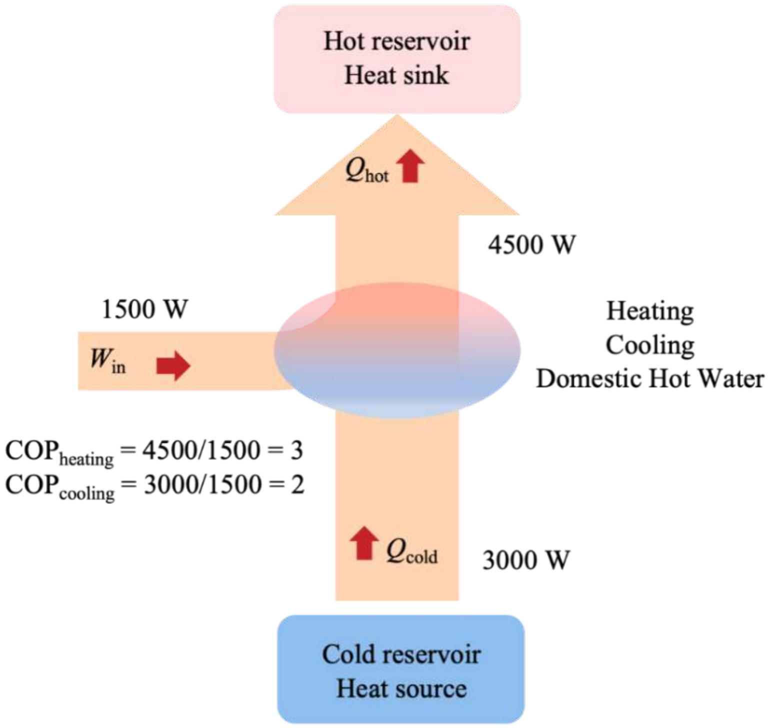


Figure 10: Basic principle of operation [18].

As can be seen, the COP in heating mode is always higher than the unit and higher than the COP in cooling mode, so heat pumps can be considered as technologies with an efficiency greater than 100% (although technically speaking this is impossible), compared to the most efficient boilers, which have an efficiency of around 96% at most [18].

Another way to characterize the efficiency of heat pumps is to use the COP or the EER over a given period of time, known as seasonal coefficient of performance (SCOP) or seasonal efficiency ratio (SEER). This explains why heat pumps are a great alternative to those conventional technologies and why the transition to heat pumps for heating, DHW and cooling production is taking place.

2.1.3. Classification of Heat Pumps

HPs can be classified according to many aspects, one of the most interesting being the heat sources, both hot and cold, i.e., where they take the heat from and where they transmit it to. These sources can be water, air, ground, solar energy, or even industrial waste heat. Other classifications according to the medium that transmits the heat, the type of compressors, or the different compression stages can also be made but will not be further considered. Instead, a brief description will be made of the most common heat pumps in residential buildings according to their energy source: air source heat pump, water source heat pump and geothermal heat pump.

- Air Source Heat Pumps (ASHPs)

In ASHPs, air is the fundamental heat source. They have been widely used for heating, cooling and DHW production due to their simple operation, high system efficiency and good environmental characteristics. The most typical heat pump system in the residential sector is the air-to-air system, where one heat exchanger extracts air from one ambient, and the other dissipates the heat to the air in another ambient. The other conventional system, typically used for DHW production is the air-water system, where the ambient air acts as the heat source in this system, and the water acts as a heat carrier. The main disadvantages of this technology are that the efficiency of the ASHPs decreases as the ambient temperature drops, because the evaporator cannot absorb as much heat energy from the environment when the temperature is low, and the formation of frost on the evaporator itself, as it can reach temperatures below 0°C, therefore, a new operation arises which is called defrosting, where the heat produced is used only to defrost the evaporator, so is not useful, making the COP lower[12].

- Water Source Heat Pumps (WSHPs)

Water can also be used as a good source and sink for heat, as it has a much higher density and specific heat capacity than air, so it can store considerably more energy per unit volume. The focus here will be on water-to-water heat pumps, as this is the case that will be studied and simulated in this work. Water has better thermal properties than air, making it an exceptional alternative, as the refrigerant can absorb more heat on the evaporator side of heat pumps, and release it on the condenser side, thus increasing the COP of the HP [12], in fact, several studies comparing the efficiency of WSHPs with ASHPs show significantly higher COPs for WSHPs.

Another advantage is the possibility of integrating heating, DHW production and cooling in the same hydronic circuit without additional heat exchangers. In the Figure 11 a scheme of a typical operation mode for water-to-water heat pumps is shown, where water is taken from a cold-water tank, and the heated water is sent to a hot water accumulator.

But this behavior can change, as the heated/cooled water can be used directly for space heating/cooling via radiators. And the hot water can also be used to heat a DHW tank using another heat exchanger, or to charge a PCM.

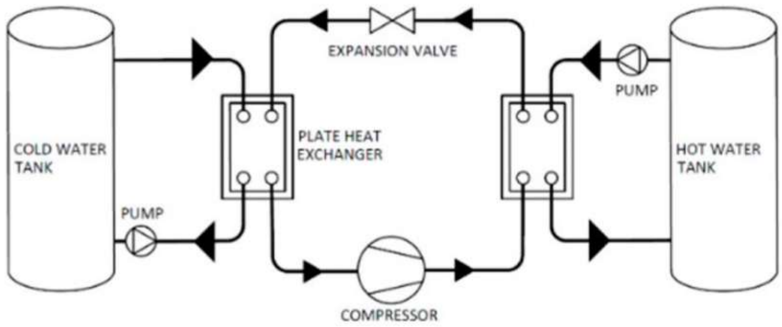


Figure 11: The schematic of the water-to-water heat pump [12]

The source of water may also vary, as in additional to being in cold water tanks, this can be underground, extracted from wells, or surface, extracted from ponds, lakes, or rivers. They can also be classified into two systems: open-loop and closed-loop (Figure 12), depending on if the water is returned to the source or not, as can be seen in the following figure, which shows a water-air heat pump, as air is used to transfer heat for heating or cooling [12]. However, hydrogeological standards must be respected (i.e., groundwater temperature must not be variated.)

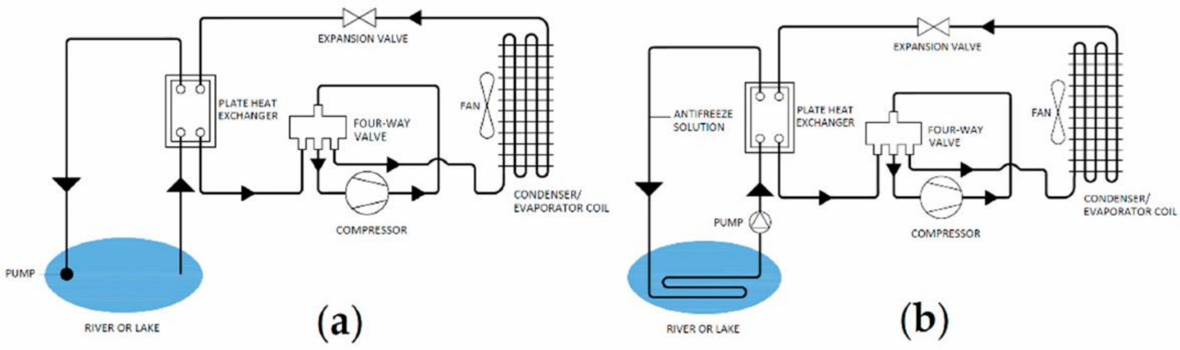


Figure 12: The schematic of (a) the open-loop and (b) the closed-loop in heating mode [12]

- Ground Source Heat Pumps (GSHPs)

The ground is widely used as a heat source and heat sink in heat pumps for space heating and cooling due to its higher temperature stability compared to air. Ground source heat pumps are one of the most efficient renewable energy sources in the world [12], as they are environmentally friendly, durable, suitable for storage and available around all day long. They can be of different types, such as geothermal heat pump, or groundwater heat pump, explained above [12].

2.2. PHASE CHANGE MATERIAL

Having already discussed heat pumps, their principle of operation, and why they are an excellent choice for heating, DHW and cooling, it is time to explain the second key technology for improving the efficiency of these systems. Phase change materials, hereafter PCM, are latent heat storage (LHS) materials. These materials absorb/transmit energy during their phase transition to provide sufficient heating/cooling energy. To understand how PCM work, it is first necessary to distinguish between the two main types of heat that substances have as their property, sensible heat, and latent heat.

Sensible heat, as is well known, can be defined as the thermal energy required to raise the temperature of a substance without causing any phase transition. Its unit in the international system is J/(Kg.K) [19].

Latent heat, on the other hand, is the amount of thermal energy required to cause a phase change on a material without altering its temperature. This phase change occurs at a fixed temperature, which may be the boiling point in the case of liquid to vapour transition, or the melting point in the case of solid to liquid transition and vice versa. The reason why the temperature of a substance undergoing a phase change remains constant is that the thermal energy is entirely used to overcome the molecular forces and cause the phase change. Its unit in the international system is J/Kg [19]. This is illustrated in the Figure 13, with the example of a material changing from a solid to a liquid.

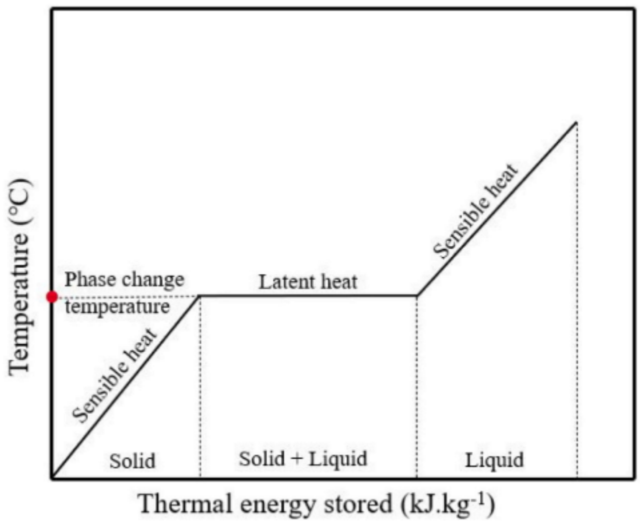


Figure 13: Ideal phase transition diagram of a solid to liquid LHS material [20]

PCM are used to take advantage of the latent heat property of storing large amounts of thermal energy in their melting or solidification (or evaporation and condensation) process, allowing temperature regulation in a specific application. When the PCM absorbs heat from its surroundings, it experiences a phase transition from solid to liquid (or liquid to vapour), which allows it to store thermal energy in the form of latent heat. When it cools, the PCM releases this stored energy in the form of latent heat, solidifying or condensing and releasing thermal energy to the surroundings [21, 22].

The classification of PCM materials can be based on several aspects, firstly, the phases between which this change can occur. The distinction can be made between solid-liquid, liquid-gas, or even solid-solid PCMs (where, although there is no change of state, there is a change in the crystalline structure), the first one being the most common. They can also be classified according to the type of material as organic, inorganic, and eutectic.

- Organic: they are composed of organic compounds such as fatty acids, hydrocarbons, alcohols, and esters, and they tend to be less prone to phase separation and are less corrosive. A very common organic PCM are paraffin waxes, with melting temperature ranges from 6ºC to 108ºC, although most commonly between 46ºC and 68ºC. Paraffin is popular in energy storage systems and in the thermal management of electronics [21].

- Inorganic: these materials are composed of salts, metals, and alloys, and have a higher energy storage capacity and better thermal conductivity, although their price tends to be higher. These include metals such as aluminum (Al), copper (Cu) and indium tin alloy (InSn), which have a fusion range from 150°C to 800°C, and are used in advanced power generation, for example in concentrated solar power (CSP) plants. Also, salts such as sodium chloride (NaCl) or calcium chloride (CaCl2) stand out, with melting temperatures higher than those of water, which can reach 100ºC. They are useful in large thermal storage applications, such as solar heating. And they are also common in consumer products such as pre-filled ice packs [21].

- Eutectic: these materials result from combining two or more PCMs in order to increase the energy storage capacity compared to other materials and to obtain a higher chemical stability. In addition, some of these, such as the eutectic mixture of calcium chloride and sodium chloride, have a very interesting property, which is the presence of different melting points, being able to regulate the temperature at different levels [21].

2.2.1. Phase change materials on heat pump systems

As explained above, thermal energy storage (TES) systems have traditionally been used in combination with heat pumps in order to increase the efficiency of the system, being able to collect, store and save thermal energy for short or long periods of time. These TES systems can store off-peak renewable energy and supplying thermal energy when needed, to help decarbonize the heating sector.

This thermal energy storage has traditionally been done using sensible heat storage materials (SHTES), storing energy as a function of the heat capacity and the temperature difference between the initial and final states [20]. Water has conventionally been used as a heat storage substance (due to its high heat capacity), in the form of water tanks. Those water tanks can be heated either by an electric heater or, as in the case of heat pumps, by a heat exchanger at the outlet of the condenser. Despite being cheap, abundant, and easy to implement, other solutions have been explored in recent years due to the lower energy density and higher energy loss of these systems compared to others [20].

These other systems can be, among others, latent heat storage, i.e., PCM, whose main advantage over SHTES is a higher storage and energy density, making them able to store a greater amount of heat in a smaller volume [13]. Other advantages of these materials over other materials are their availability over a wide temperature range, from very low to very high temperatures, providing more flexible operation and durability at a reasonable cost [13, 20].

This results in higher system efficiency, the reduction of room temperature fluctuations, and resuming space heating faster, with a better demand-side management, and bring the possibility of reducing the size of fuel tanks and domestic hot water (DHW) storage devices in order to avoid oversizing HP [15].

Although the cost of this technology is still high compared to SHTES, the number of industries producing promising PCMs has increased significantly in the last decade, with the expectation of shifting towards low-carbon technologies, so and these developments and studies are expected to lead to a reduction in the price of energy storage systems using PCMs [20].

Although it has mainly emphasized the use of PCM as LHS, as this is the main use that will be studied in this project, other possible uses have been studied, all with the aim of improving the efficiency of the heat pump system. These include the use of PCMs together with solar thermal collectors where they act as high temperature storage, introducing efficient defrosting methods in aerothermal HP, increasing the evaporator pressure in cold side storage devices, and thus increasing the COP, among others [13].

Chapter 3

System overview

In this chapter further details of the system components will be presented, including an exhaustive explanation of these components, their specific characteristics, the selection of parameters and the boundary conditions used for the simulation. Thus, diagrams, flowcharts and the numerical models will be used, although this last one will not go into much detail, as the general function of the system will be elaborated without having to go into specific aspects of the simulation tool used. Moreover, the different modes of operation and the Key Performance Indicators (KPIs) will be introduced.

3.1. DESCRIPTION OF THE HEAT PUMP SYSTEM

As highlighted in the previous chapters, this work considers 4 blocks of heat pumps, each with two modules. This results in a total of 8 heat pumps, with the particularity of being able to thermo-hydraulically connect them in series or in parallel. Several aspects therefore must be considered and investigated. First, the series/parallel control strategy is observed for the connection of different heat pump blocks, (not between modules in the same block) while it has been proven that HPs in the same block provide the same output whether they are connected in series or in parallel. The second aspect to consider is that all blocks are connected in series, or all are connected in parallel, so there is no possibility of having two blocks working in series and simultaneously in parallel with the remaining two blocks. Finally, the series/parallel strategy is carried out in the connections of the high-temperature circuit (the one on the condensers). The low temperature circuit (the one connecting the evaporators) is always connected in parallel. In addition, it is also important to emphasize that the hydraulic circuit is a closed loop, i.e., the water returning from the building, or from the latent heat storage is the same that enters the heat pumps, with the same temperature, pressure, and flow rate. This difference between the series and parallel operation can be seen in Figure 14 with an example of a system with 6 heat pump blocks.

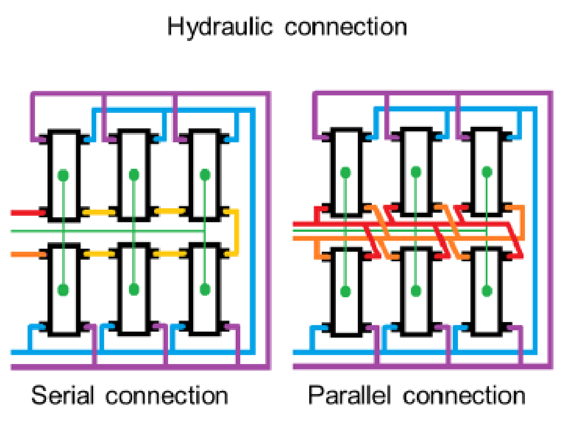


Figure 14: Possible hydraulic connection of the HP [5]

It can be observed, that as explained, the evaporator side is always connected in parallel no matter the operating mode. The water coming from the 5GDHC (purple line) enters each evaporator in parallel, and the cold water generated (blue line) is injected again in the 5GDHC. Meanwhile, in series operation, the water enters each condenser sequentially and increases its temperature (yellow to red line). For the parallel operation, the water enters each condenser separately and achieves the same temperature levels at each one.

As already known, each HP block contains two modules, each one with a nominal heating power of around 1.1kW, making a total of 2.2kW per block. As for the details of the refrigeration cycle, it should be noted that it works with propane (R290), with a maximum pressure allowed of 31 bars (in order to avoid arriving to the critical pressure) as refrigerant and with a subcooling in the condenser of 3K and a superheating in the evaporator of 7K. In addition, it is parameterized to have a pinch (minimum difference between the temperature of the refrigerant and the water) of 3K in the condenser and 20K in the evaporator, in order to simulate the behavior of the real heat pump. For the dynamic thermo-hydraulic modelling of these components, the TIL library [23] has been used, which is widely used in the refrigeration cycles industry. This allows a detailed representation of the physics and parameterization of each component of the heat pump. In Figure 15 the model of the heat pump developed in Dymola can be observed.

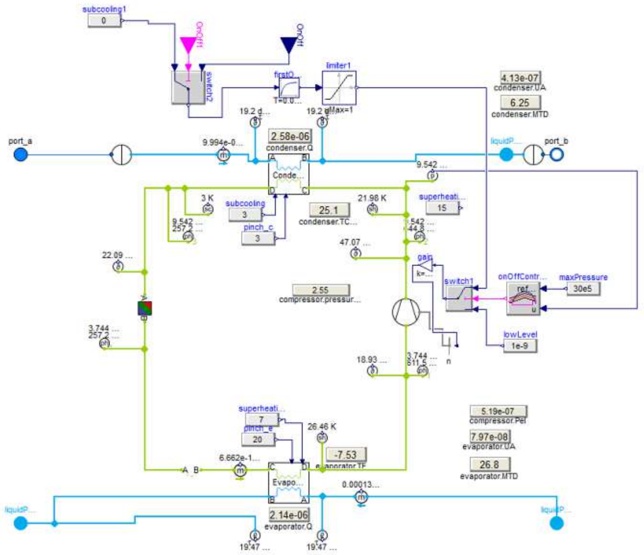


Figure 15: Numerical simulation of the HYPERGRYD heat pump in Modelica/Dymola

The first HP block is used to cover the entire demand (heating, cooling and DHW), the second HP block is also used to cover the entire demand in case the first one output is not sufficient, while blocks three and four are only used to cover the thermal demand (heating and DHW) in case the first two are not sufficient. Each HP block has two controllers that coordinate the operation of the corresponding heat pump. One of these controllers switches on or off the block depending on whether there is demand in the building. Meanwhile the second controller determines how many HP modules of each block should be activated (one, both or none), depending on the temperature values of the hydronic circuit compared to those necessary to ensure a good functioning of the system, regardless of whether there is demand in the building or not. This means that there may be a thermal demand in the building, but it is maybe not necessary to activate a specific HP, because it can be already covered with the ones that are already switched on.

For this reason, each controller is specifically tailored for each heat pump block, with certain parameters, that become more demanding as the number of HP blocks increases. These parameters include: the measured temperature at the entrance of the HP block ϑ_{mea}, the desired temperature ϑ_{set} (which depends on the working mode of the HP) and the difference between those two values. For further comprehension, Figure 16 and Figure 17 show an example in the form of a flowchart for the controllers of the second HP block, as they are the most complete one, (and therefore more representative).

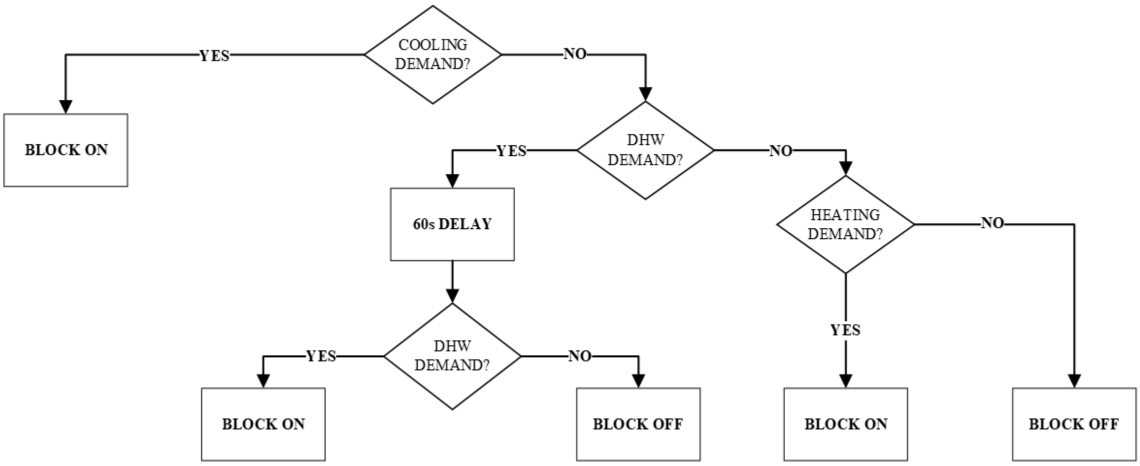


Figure 16: Flowchart of the 1st controller of the HPs

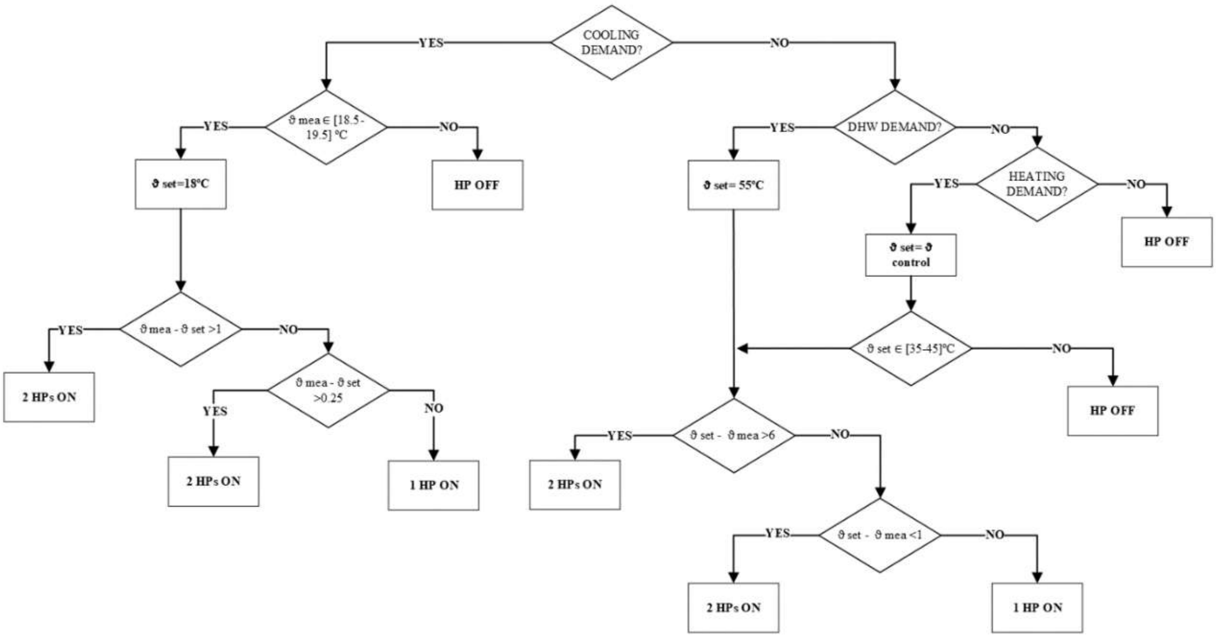


Figure 17: Flowchart of the 2nd controller of the HPs

As can be clearly seen, the first controller is the one that detects a specific demand in the building and commands the corresponding HP block to switch on accordingly (with a delay to better match the actual response, as this is not immediate). And the second one is the one that compares the measured values with the desired values to know if it is necessary to switch on that HP block or not and how many heat pumps of that block should be in operation. Therefore, to switch on a certain HP block, both controllers must give a positive signal simultaneously.

3.2. DESCRIPTION OF THE WPW-HEX SYSTEM

The heat storage used in this project is an evolution of the RPW-HEX (Refrigerant-PCM-Water Heat Exchanger) developed in the H2020 HYBUILD project [24] and the CHALLENGE project [25]. Such a storage concept uses water heated from the heat pumps system to charge the heat storage instead of the refrigerant, so will therefore be referred to as WPW-HEX as water is the working medium of both sides of this storage. Moreover, this storage is principally an aluminum heat exchanger that is filled with a PCM. To heat water on the demand side, the storage works as an instantaneous water heater capable of heating it directly to the desired DHW temperature.

The PCM used for the heat storage is Rubitherm RT55, which is a paraffin, and as its name suggests, it has a solid to liquid phase change temperature of 55ºC and is a very effective medium for storing heat and cold. even when limited volumes and small operating temperature differences are applied. The Table 1 shows the list of properties of this material.

Table 1: RT55 properties [26]

DATA	TYPICAL VALUES	UNIT
Melting Area	51-57 (main peak 55)	ºC
Congealing Area	56-57 (main peak 55)	ºC
Heat storage capacity ± 7.5%. (Combination of latent and sensible heat in a temperature range of 48ºC up to 63ºC)	170 48	kJ/kg Wh/Kg
Specific heat capacity	2	kJ/kg K
Density at solid (15ºC)	0.88	kg/l
Density at liquid (80ºC)	0.77	kg/l
Heat conductivity (both phases)	0.20	W/m K
Volume expansion	14	%
Max. Operation temperature	90	ºC

To achieve the desired water temperature, two WPW-HEX connected in parallel, both on the hot and the cold water side, are necessary. These two heat storage units operate as two aluminum plate heat exchangers, with a nominal storage capacity of 1.2kWh, resulting in a nominal of 2.4kWh. With this data, the dimensions of the WPW-HEX and, therefore, the number of plates can be set, giving a height and width of 0.5m and 28 plates each exchanger. As before, the Figure 18 shows the Dymola model of the WPW-HEX storage system as well as a single heat exchanger.

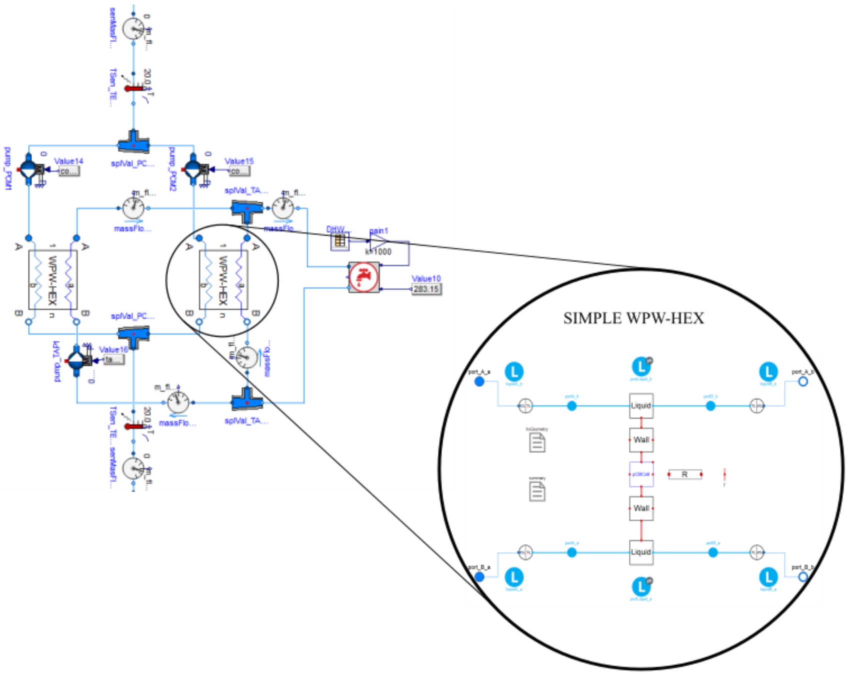


Figure 18: Numerical simulation of the HYPERGRYD WPW-HEX in Modelica/Dymola

As can be seen, the two WPW-HEXs are connected in parallel on both sides, and each of them functions as a single heat exchanger, with the PCM material enclosed between aluminum plates. To consider the heat losses to the environment, each WPW-HEX is connected to the environment through a thermal resistor representing the insulation.

The WPW-HEX is discretized into a given number of cells, in this case 5, and the energy stored in total can be calculated using the following formula:

$$H_{\text{storaged}} = \sum_{i=1}^{N\text{cells}} (m_{\text{alu,i}} \cdot c_{\text{p,alu}} \cdot (\vartheta_{\text{alu}} - \vartheta_0) + m_{\text{PCM,i}} \cdot \int_{\vartheta_0}^{\vartheta_i} \tilde{c}_{\text{p,PCM}} (\vartheta)\, d\vartheta) \qquad (7)$$

Where ϑ_0 and ϑ_i are the reference and the simulated temperatures in the cell, respectively. The apparent specific heat capacity $\tilde{c}_{\text{p,PCM}}$ incorporates the latent heat to the sensible heat, and the temperature-dependent apparent specific heat capacity $\tilde{c}_{\text{p,PCM}} (\vartheta)$ to calculate the total stored energy, was determined from manufacturers heat capacity data using spline interpolation.

To calculate the state of charge, the liquid fraction of the PCM (χ) is used, i.e., how much of the PCM volume is in the liquid state. This variable is used to measure the state of charge of the storage, since the more PCM in liquid state, the more energy can be transmitted to the DHW circuit. The liquid fraction in each cell is measured and the value is obtained in the simulation, to calculate the total state of charge (SoC) of the WPW-HEX system as:

$$\chi_{\text{tot}} = SoC = \frac{\sum_{i=1}^{N\text{cells}} \chi_{\text{i}}}{N_{\text{cells}}} \qquad (8)$$

As there are two WPW-HEX in parallel, both with the same characteristics, and as the amount of water passing through both heat exchangers is the same, the temperatures distribution within each of them and the state of charge in each of the two heat exchangers will always be the same. So, from now on in this work, only one HEX will be referred to, as both of them act in exactly the same way.

As for the HPs blocks, this heat exchanger is operated by a controller, that determines when to charge the storage. The main feature of this control is that it uses a time and temperature dependent strategy. This means that it is charged for certain periods of time per day if it is necessary (further details will be provided later) and is also charged if the top or bottom temperature (ϑ_{top} or ϑ_{bottom}) of the PCM falls below a certain level when there is a demand of DHW. This provides greater flexibility to the system and the ability to always ensure a certain state of charge to support peak DHW demand. This controller can be represented as a flowchart in the Figure 19.

As can be seen, it has two branches, one depending on whether it is in a set charging period, so it is checked that it is necessary to charge it during that period, while if it is not time to charge it, but there is a DHW demand in the building and it is foreseen that with the current SoC of the WPW-HEX it will not be possible to cover it, it is charged as well.

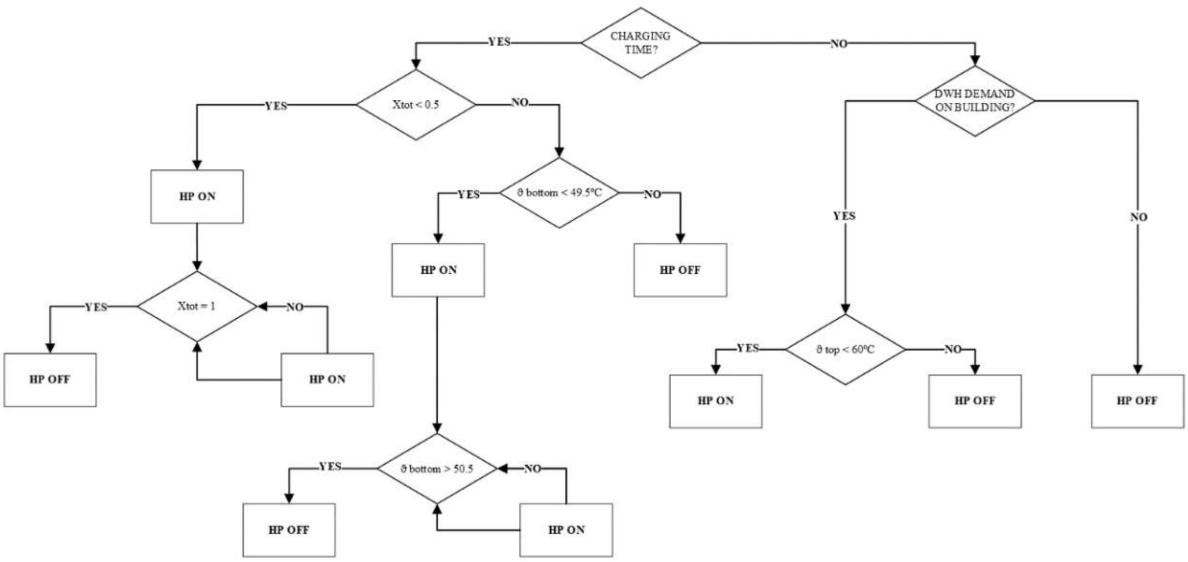


Figure 19: Flowchart of the charging control strategy of the WPW-HEX

The charging periods mentioned above are the following ones: two periods of 20 minutes and one of 30 minutes during the daylight (11:40-12:00, 15:10-15:30 and 18:45-19:15), and two periods of 30 minutes during the night (00:30-01:00 and 03:30-04:00). This yields a total of two hours and twenty minutes of charging per day, irrespective of the DHW demand in the building. These periods have been selected following a thorough analysis aiming to keep the WPW-HEX as much charged and ready as possible without affecting the building temperature.

3.3. DESCRIPTION OF THE BUILDING

The building model has been developed using Modelica's BUILDINGS library [27], so it can be parameterized for any number of buildings and surfaces that may be involved in heat transfer. This model emulates an intermediate apartment within a multi-storey building and has a floor area of 8 x 10 m^2 and a height of 3 m. As it is an intermediate apartment, both the floor and the ceiling are shared with the apartments below and above, respectively. The apartment interacts with the exterior through the side walls causing changes in the indoor temperature according to the outdoor temperature. In addition, it has ventilation (i.e. air circulation with the outside), whose values according to the norm, for a healthy ventilation rate are approximately 0.35-0.5, which means that every hour between one third and one half of the total volume of the building should be renewed. The reference value was taken as 0.37, and the ventilation flow rate was calculated as follows:

$$\dot{m}_{vent} = V_{apartment} \cdot ventilation_{rate} = \frac{8m \cdot 10m \cdot 3m \cdot 0.37}{3600s} = 0.02467\frac{m^3}{s} \quad (9)$$

The external walls are made up of two layers, a layer of insulation, that forms the outer layer, and another layer of concrete, located on the inside. The same materials are used for the construction of the floor and the ceiling. As it is an intermediate floor, both the floor and the ceiling have 3 layers (concrete, insulation, and concrete). The floor is formed by the concrete layer of the floor below, the insulation layer and its own concrete layer. While the ceiling is formed by the concrete layer of the upper floor, the insulation layer, and its own concrete layer. Both are viewed from the exterior to the interior. Table 2 shows the main characteristics of these materials and Figure 20 a schematic of the apartment in a front view.

Table 2: Layer materials characteristics

VARIABLE	VALUE	DESCRIPTION
$k_{insulation}$	0.03 W/(m.K)	Thermal conductivity of insulation layer
$c_{p,insulation}$	1200 J/(kg.K)	Specific heat capacity of insulation layer
$\rho_{insulation}$	40 kg/m^3	Density of insulation layer
$k_{concrete}$	1.4 W (m.K)	Thermal conductivity of concrete layer
$c_{p,concrete}$	840 J (kJ.K)	Specific heat capacity of concrete layer
$\rho_{insulation}$	2240 kg/m^3	Density of concrete layer
	External Wall	
$X_{insulation}$	0.1 m	Thickness of insulation layer
$X_{concrete}$	0.2 m	Thickness of concrete layer
	Floor/Ceiling *	
$X_{concrete1}$	0.2 m	Thickness of first concrete layer
$X_{insulation}$	0.15 m	Thickness of insulation layer
$X_{concrete2}$	0.05 m	Thickness of second concrete layer

*This layer disposition is for the floor. For the ceiling it would be the reversal values (i.e., the first concrete layer would be of 0.05m thick and the second 0.2m).

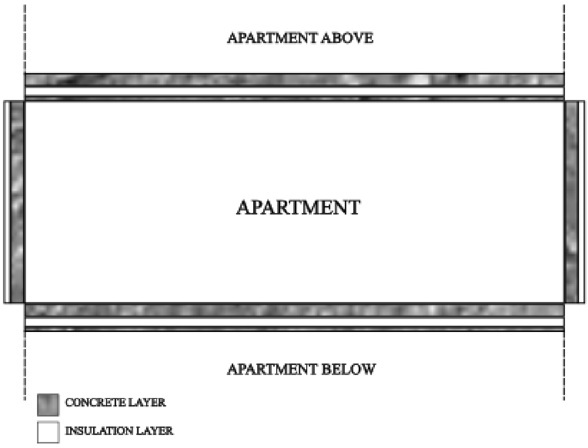


Figure 20: Front view of the studied apartment

Another advantage of this model is the possibility of including windows in the exterior walls, with defined dimensions and thermal properties. The window is a triple-pan type (clear glass, gas, and clear glass), in addition to the width of the frame. This window is characterized according to its dimensions and the U-value of the frame. In this case a 2 x 2 m^2 window has been chosen for each of the walls of the room, whose properties are shown in Table 3

Table 3: Window materials characteristics

VARIABLE	VALUE	DESCRIPTION
H	2 m	Height of the window
W	2 m	Width of the window
f_{fra}	10%	Frame fraction of the window area
U_{fra}	2 W/(m^2.K)	U-value of the frame
	Clear glass	
X_{glass1}	3 mm	Thickness of 1st clear glass layer
X_{glass2}	3 mm	Thickness of 2nd clear glass layer
K_{glass}	1 W/(m.K)	Thermal conductivity of clear glass layer
τ_{solar}	0.6	Solar transmittance
ρ_{solar}	0.075	Solar reflectance
	Gas	
X_{gas}	12.7 mm	Thickness of gas layer
K_{gas}	0.002 W/(m.K)	Thermal conductivity of gas layer
$C_{p,gas}$	1002.7 J/(Kg.K)	Specific heat capacity of gas layer
M_{gas}	28.97 g/mol	Molar mass of gas layer

Furthermore, the building model is capable to consider the occupancy that the building will have, since the occupants will participate in the heat transfer of the building. Thus, the model contains an occupancy profile for each day of the year at hourly intervals. For heat transfer, the model converts the occupancy per person into a heat gain of 35 W/m^2, 70 W/m^2 and 30 W/m^2 (where the square meters are referred to the area of the person) for the radiant, convective, and latent heat, respectively.

Figure 21 shows an example of the occupancy profile for a 12-hour time interval. The first column reflects each period, and the second column reflects the number of people present in the building. Each adult is counted as 1 and each child as 0.5, meaning that if there are two adults and one child in the building, this value will be 3.5. In this work, a 2-person apartment is studied, so the occupancy profile in this case will be constant and equal to 2throughout the year, except for a period of 8 days, where there is no occupancy.

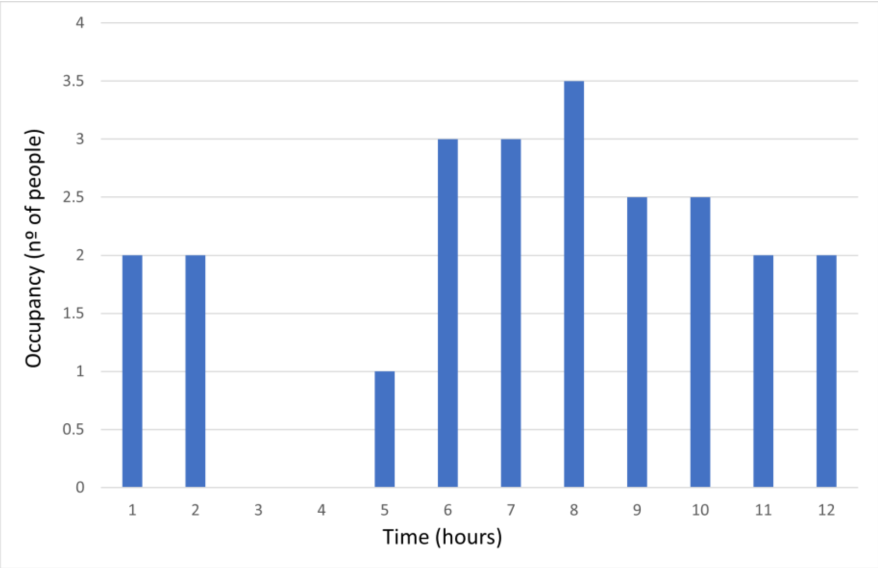


Figure 21: Occupancy profile example

3.4. BOUNDARY CONDITIONS

In this section all the boundary conditions of the system will be reported and discussed, from the outdoor weather, the required water mass flows, and the target temperatures in the building, among others.

3.4.1.Outside weather

In order to properly carry out the simulations, it is necessary to include the meteorological boundary conditions of the investigated location. This is due to the fact that the outside temperature plays a role in defining the thermal needs inside the building. For this purpose, the meteorological data for the three studied cities (Helsinki/FIN, Strasbourg/FR, and Athens/GR) have been imported into the top-level model from the EnergyPlus website [28]. These weather files contain weather data for a typical meteorological year (TMY) in each of the cities, so although there may be variations with reality, they show a good picture of the case study.

3.4.2.Hydronic mass flow

For this subsection, it is necessary to differentiate between the three modes of operation, heating, cooling, and charging the WPW-HEX, since each action requires a different mass flow rate.

3.4.2.1. Heating operation

To calculate the mass flow rate to be passed through the HPs in the heating mode, the typical heat transfer equation is used:

$$\dot{Q} = \dot{m}_{\text{heating}} \cdot c_p \cdot \Delta T \tag{10}$$

Thus, the desired flow rate must be able to generate a heat of 25 W/m^2 which is set by norms for energy-efficient building or renovated ones [29]. The temperature difference is set between the temperature of the water returning the building, and the setpoint supply temperature following a heating curve. This setpoint supply temperature considers the outside temperature and the needs of the building, so that it can be seen reflected in Figure 22

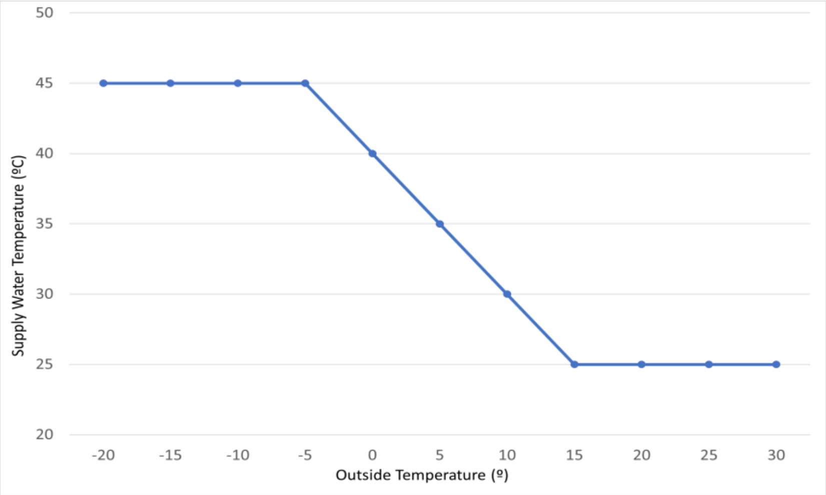


Figure 22: Heating curve that shows the setpoint supply temperature of the system as function of the ambient temperature

In this way, the following equation is obtained to obtain the mass flow of water:

$$\dot{m}_{\text{heating}} = \frac{25\,(\frac{W}{m^2}) \cdot A}{4.186\,(\frac{kJ}{kg.K}) \cdot (T_{\text{set,supp}} - T_{\text{set,ret}})} \tag{11}$$

This mass flow obtained may not be entirely accurate, so it must be corrected by considering the actual supply and return temperatures and the set point of those supply $T_{\text{set,supp}}$ and return $T_{\text{set,ret}}$ temperatures, 45ºC and 20ºC (An analysis with a 65ºC and 20ºC system will be carried out in ANNEX 3 to see the differences with this system). respectively, so that the final mass flow through the HP blocks during the heating stage is as follows:

$$\dot{m}_{\text{heating,real}} = \frac{\Delta T_{\text{real}}}{\Delta T_{\text{set}}} \cdot \dot{m}_{\text{heating}} \tag{12}$$

3.4.2.2. Cooling operation

For the cooling mode, the flow rate is easier to calculate, since a controller is used in each HP to determine a mass flow rate that makes the temperature difference between the outlet and inlet of each HP block to be 6K. Having in mind that on the evaporator side the HPs are connected in parallel, it might be that each heat pump has a different flow rate depending on the needs, so is calculated as follows:

$$\dot{m}_{cooling} = \frac{\dot{Q}_{ev}}{4.186\ (\frac{kJ}{(kg.K)}) \cdot (-6\ K)} \quad (13)$$

3.4.2.3. WPW-HEX charging operation

For the WPW-HEX charging operation the calculation is much easier since a mass flow rate of 0.042 kg/s will always pass through the HPs. This value is determined following a thorough analysis considering different flow rates, and it has been concluded that this is the optimum value.

3.4.3. Building Temperature Setpoints

The heat pumps system must be able to maintain the temperature of the building within a given range. Therefore, is necessary to give the system a target apartment temperature to be maintained. In this case, it is necessary to differentiate between heating and cooling modes, since depending on the thermal needs, one temperature or the other will be set. Thus, when heating is required, the target temperature during the day ($T_{sp,day}$) is set at 21ºC (from 07:00 to 19:00), and if the building is unoccupied or at night (from 00:00 to 07:00 and from 19:00 to 00:00), the set point ($T_{sp,night}$) is set at 18ºC. For cooling, the set point temperature ($T_{sp,cooling}$) is 25ºC.

To make the system operation smooth and prevent the HP system from switching on and off too often, the system is given a bandwidth within which the indoor temperature is comfort and proper. This bandwidth is 3K, so for example in daytime heating mode, the HPs would start if the indoor temperature drops below 19.5ºC, and would stop when an indoor temperature of 22.5ºC is reached. This is illustrated in the following equation. In addition, Table 4shows the set point temperatures together with their typical values

$$T_{sp} - \frac{\Delta T_{sp}}{2} < T < T_{sp} + \frac{\Delta T_{sp}}{2} \quad (14)$$

Table 4: Setpoint temperatures of the apartment

VARIABLE	VALUE	DESCRIPTION
$T_{sp,day}$	21 ºC	Day time set point for the indoor temperature
$T_{sp,night}$	18 ºC	Night time set point for the indoor temperature
$T_{sp,cooling}$	25 ºC	Cooling set point for the indoor temperature
ΔT_{sp}	3 ºC	Bandwidth for the temperature hysteresis

3.4.4. DHW Setpoints

Occupancy is also accompanied by domestic hot water consumption. As explained throughout the work, the WPW-HEX is the responsible for providing sufficient output to heat the water to the desired temperature. Here, different temperature values can be used, both for the tap water supply and for the desired DHW temperature. In this case, the tap water temperature will be set to 10ºC, and the DHW delivery temperature will be 53ºC for a given DHW application (e.g. shower, washing machine). The tap water temperature may vary depending on the location. In Europe it is usually between 10 and 15ºC depending on the country, but in this project the analysis will be done with 10ºC. It should also be noted that these values of 53ºC for the DHW delivery temperature and 10ºC for the tap water temperature are quite drastic but have been chosen to analyze how the system behaves under such unfavorable conditions. Additionally, a small analysis will be presented in ANNEX 2 on the city of Strasbourg for a period of one month, varying from 10 ºC to 12 ºC to15 ºC to see how this temperature affects the performance of the system.

To simulate the water consumption of the building, a consumption profile has been created using the DHWcalc Tool [30]. If there is a demand for DHW, the tap water is split and passed through the two WPW-HEX, increasing their temperature to the desired temperature, thus discharging the modules. In order to quantify the amount of water that should pass through the heat exchangers, a controller is used to regulate the mass flow so that the final water temperature is set to 53ºC. Finally, to adjust the flow rate and temperature to those desired, the heated water can be mixed with a fraction of tap water at 10ºC, providing water at the desired temperature to the building.

3.5. OPERATION MODES

The different modes in which the system can operate are as shown below:

1. Heating only
2. Charging WPW-HEX only
3. Cooling only
4. Cooling + charging WPW-HEX

The system is not capable of supplying the heating demand and charging the WPW-HEX at the same time, so if it occurs at the same time, one or the other will be satisfied. In this case, the WPW-HEX charging has priority over heating, since it is an immediate demand, so it must be satisfied before. Heating, as the indoor temperature can vary between certain levels, is considered to have a lower priority. On the other hand, it is able to provide cooling and WPW-HEX charging simultaneously, as the heat generated in the condenser and evaporator can be used at the same time to cover these two demands.

As briefly explained in section 1.3, this system is able to operate both in series and in parallel, depending on the needs of the building, although in this work, they have been studied separately, simulating a whole year for each location and each operation mode, in order to obtain and compare the results, as and to have a main idea of which is the optimal strategy to follow when developing the automatic system.

The main difference between these two configurations is the way in which the water is heated to the setpoint temperature.

While for the series mode the total mass of water to be heated passes sequentially through each of the heat pumps, progressively heating up in each of them and reaching the setpoint temperature at the end of the operation, in the parallel mode, that same water mass is divided and passes individually through each HP, reaching the setpoint temperature in each of them, and mixing at the end. This means, that in series, as the mass of water on each heat pump is greater, the temperature lift in each heat pump will be smaller, while in parallel, with a smaller water mass, the temperature lift in each heat pump will be greater. This can be easily illustrated by following the heat transfer equation.

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T \quad (15)$$

This results, as will be seen later, in that at the end the series configuration is able to reach higher temperatures (sometimes above the setpoint), which is favorable when it comes to meeting the thermal demand of the building. But it has the disadvantage that first, as the water is at a higher temperature, it has more heat losses with the environment, and second, as to reach the desired temperature a higher quantity of water has to pass through each of the HP blocks, the pressure losses in the heat pumps increases, as they depend exponentially on the mass following the next equation:

$$\Delta p = \xi \cdot \frac{l}{d} \cdot \frac{m^2}{2 \cdot \varsigma \cdot A^2} \quad (16)$$

As can be seen, pressure losses are directly proportional to the square of the mass, so the higher the mass, the higher the pressure losses. This cause that a higher electrical input has to be introduced into each heat pump to achieve the same objective, thus reducing the performance and increasing the electrical costs, as will be seen in the following analysis.

For the analysis of the operation modes, each possible operation will be explained separately, comparing between series and parallel, although, in order not to be repetitive, the general aspects to be considered will be explained below. First, it should be noted, as explained above, that the evaporator side is always connected in parallel, so in all configurations and modes of operation the hydronic connection on the evaporator side will be the same. Second, it is important to note that the return water from the apartment will be colder than the return water from the WPW-HEX, because the heat exchange with the apartment is higher than with the PCM (as the apartment is at a lower temperature), so the return line from the apartment (at about 20ºC) is shown in purple, and the return line from the WPW-HEX (at about 45ºC) is shown in yellow. Finally, it should be mentioned that 3 heat pumps have been used as examples for the heating and WPW-HEX charging operations, while only 2 have been used for cooling and cooling and WPW-HEX charging. This is because only the first two heat pumps can perform the cooling operation.

3.5.1. Heating only

This mode of operation is intended to cover the heat thermal demand from the building. The two configurations (series and parallel) for this mode of operation can be seen in Figure 23. As explained, it can be noticed that on the evaporators side both of them operate in the same way.

The water is obtained from the 5GDHC and passes through the evaporator of each of the activated HP blocks through a parallel configuration. This cooled water is returned to the 5GDHC via another pipe from the same network.

The difference can be seen on the condenser side. In series mode the water passes through the first HP block, heating up to a certain point, and then passes through the second and third blocks to reach the desired temperature (and if necessary, through the fourth). From there, it goes directly to the apartment, where heat transfer takes place via heat terminals (e.g. radiators or radiant floor). As it is a closed loop, the water leaving the apartment after the heat exchange at about 20ºC is the water that enters the first HP bock, and so on. In parallel mode, this return water is divided equally and passes through each of the different HP blocks (in this case the first three) individually, heating up to the setpoint temperature. Depending on the thermal demand of the building and the setpoint temperature, this return water will be divided into more or less parts as it passes through the HP blocks (the higher the setpoint temperature, the more heat pumps will be activated with a smaller water mass flow in each of them in order to reach such a high temperature).

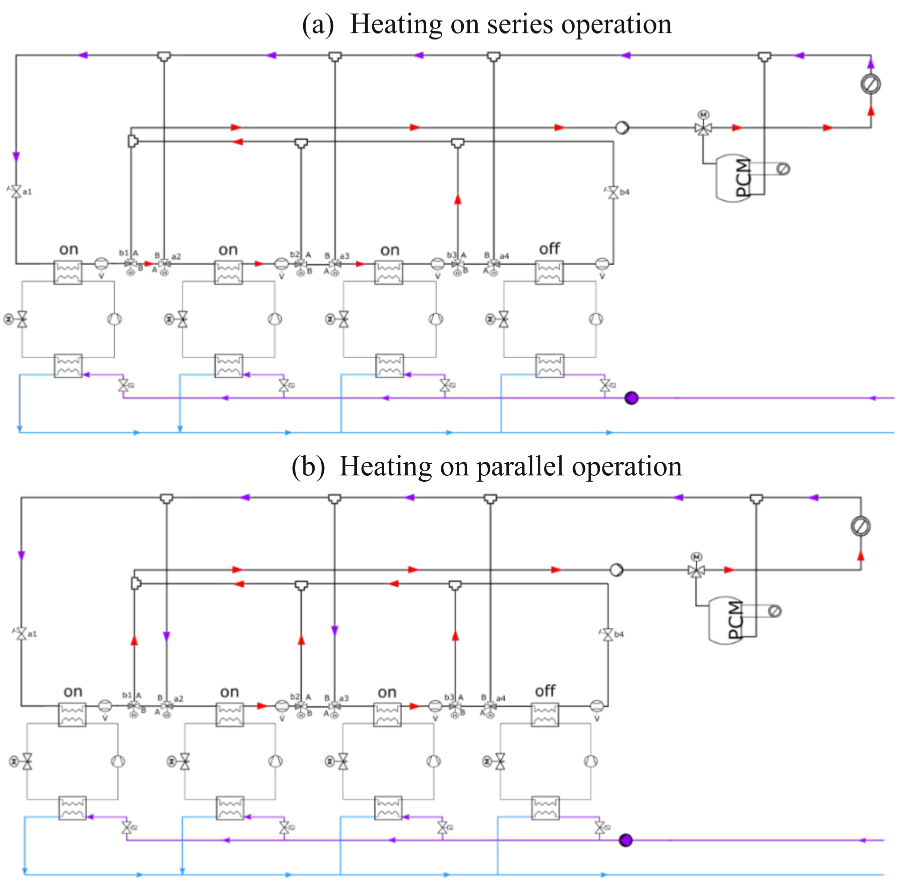


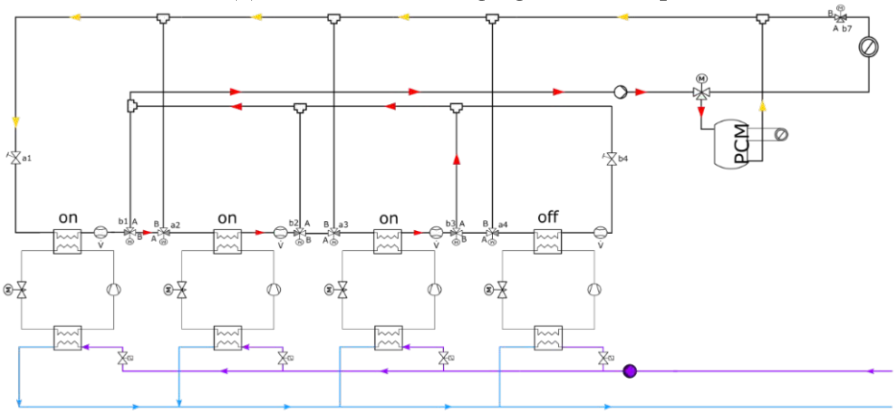
Figure 23: Heating operation schematics on series and parallel configurations

3.5.2. Charging WPW-HEX only

This mode of operation works in almost the same way as the previous one, with the difference that the heated water is sent to the WPW-HEX instead of to the apartment. In Figure 24 a single storage is illustrated, but as explained above there are two in parallel, so the hot water is divided, and mixed again once it has charged them.

As before, the evaporator side is connected in parallel, and the condenser side can be connected in both ways. In series, the water returning from the WPW-HEX at a higher temperature as on heating mode (about 45ºC, as the PCM is at a temperature of about 50ºC-60ºC, so the heat exchange is lower), enters sequentially through each of the HP blocks. While for the parallel mode, this mass of water is divided between the different HP blocks.

(a) WPW-HEX charging on series operation



(b) WPW-HEX charging on parallel operation

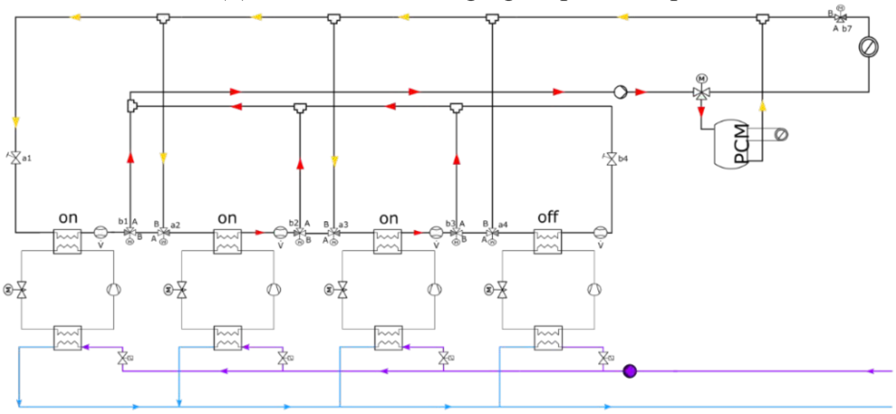


Figure 24: WPW-HEX charging operation schematics on series and parallel configurations

3.5.3. Cooling only

In this case it is intended to cover the cooling demand of the apartment. The evaporator side works the same as before in both cases, with the difference that now the cooled water instead of being delivered to the 5GDHC is used to supply the cooling demand of the flat.

As can be seen in Figure 25, a new pipeline appears, and the difference returns to the condenser side. As there is no thermal demand in the building, the condenser side no longer works as a closed loop. The cold water is drawn from the 5GDHC and passes through the first HP block (and if necessary the second), in series or parallel in the same way as seen in the previous two modes, with the difference that this hot water is sent back to the 5GDHC so that it can be used in another application.

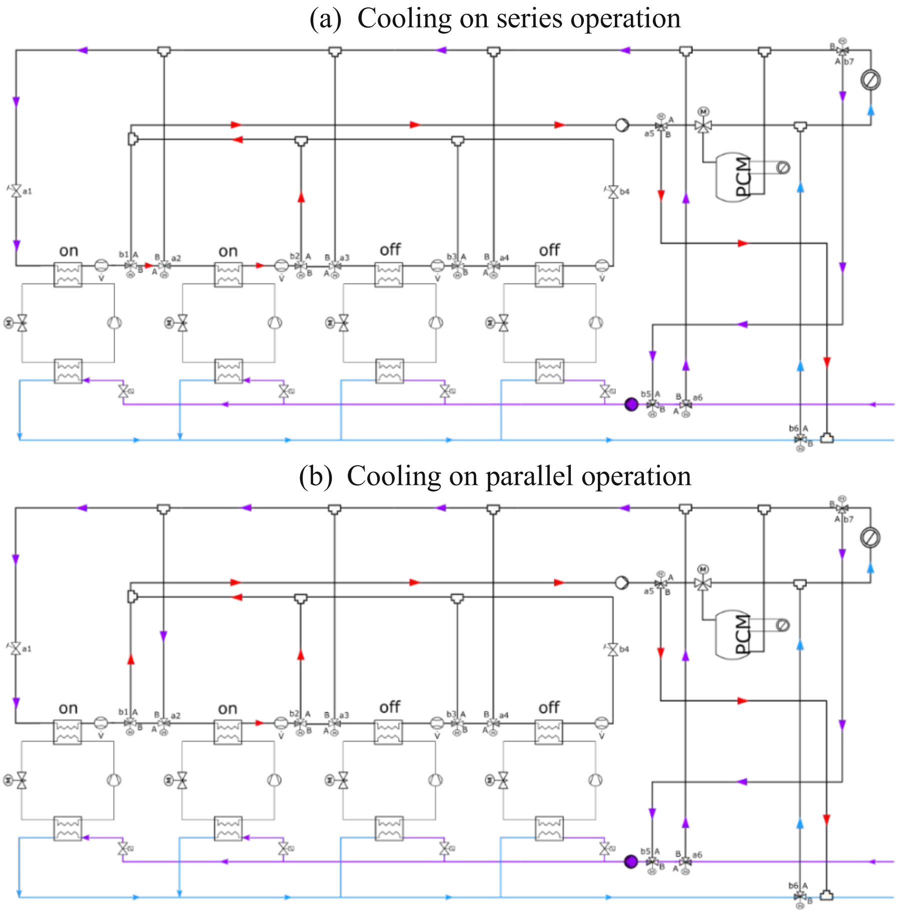


Figure 25: Cooling operation schematics on series and parallel configurations

3.5.4. Cooling + charging WPW-HEX

Herein, the evaporators side works in the same way as in the previous one, to satisfy the cooling demand of the apartment. On the other hand, on the condenser side, the heat produced is used to charge the WPW-HEX.

Thus, the difference between the two cooling operations is related to the WPW-HEX controller explained above. In case of cooling demand only, the heat generated in the condensers is injected into the 5GDHC, but if the controller determines that the WPW-HEX has dropped below the desired levels, that heat is used to charge the WPW-HEX as shown in Figure 26. Again, the hydraulic connection at the condensers can be in series, passing sequentially through the first two HP blocks, or in parallel, dividing the return water from the WPW-HEX in each of these two blocks.

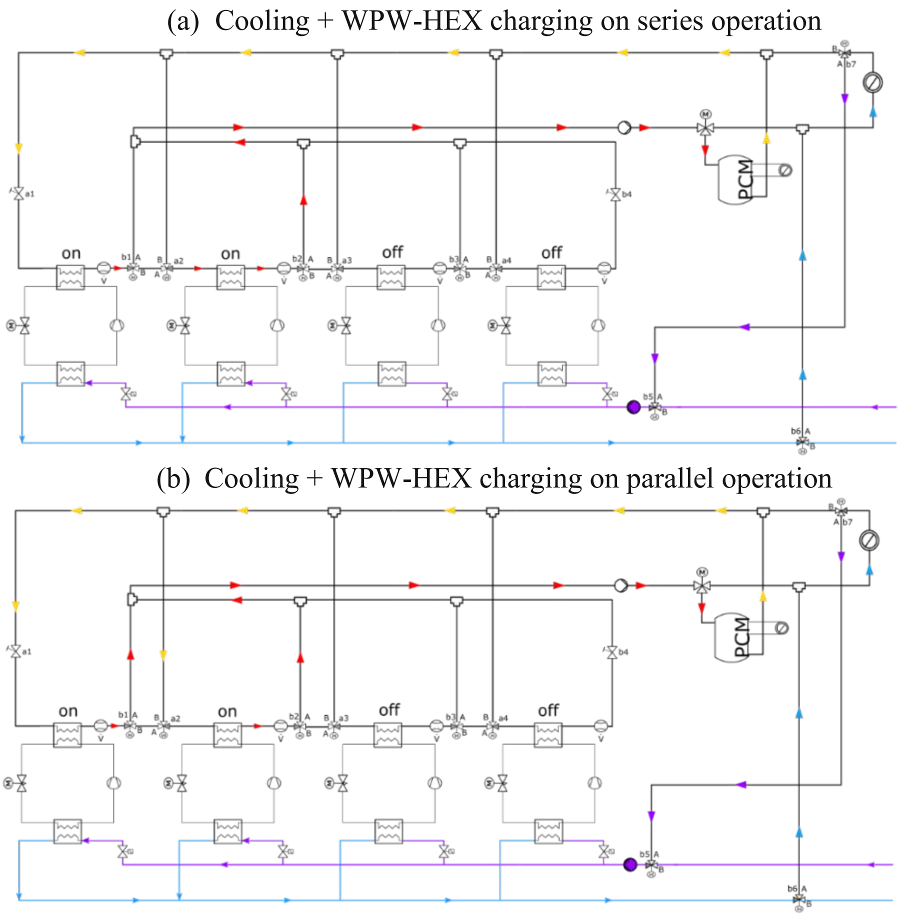


Figure 26: Cooling + WPW-HEX charging operation schematics on series and parallel configurations

3.6. KEY PERFORMANCE INDICATORS

For a correct analysis of the performance of both systems, a series of indicators must be introduced that quantify the performance of one system and the other and serve to compare them in order to choose the necessary control strategy in the future. These key performance indicators (KPIs) include physical variables, such as the temperatures to be monitored, the WPW-HEX state of charge (SoC), the efficiency (SCOP) of both systems, and the total mass of CO2 produced during the operation of the system. In this section a brief presentation of each of them will be made, and later, a more exhaustive description and analysis will be carried out.

The final temperatures of both the apartment and DHW delivery are the most important parameters to be monitored since the correct operation of the developed system depends on them. For the control of these temperatures, in addition to the physical magnitude measured both indoors and in the DHW delivery pipeline, other parameters on which these values directly depend will be analyzed. These parameters include the total heat transferred/absorbed from the apartment, as it has to be such as to keep the apartment within the desired temperature range, and the specific demand by square meter, which is also directly related to the water delivery temperature. The last parameter to be controlled will be the SoC of the WPW-HEX, (and consequently the temperature distribution inside the PCM), as the DHW delivery temperature depends directly on this value.

$$\dot{Q}_{\mathrm{ap}} = \dot{m}_{\mathrm{water}} \cdot c_{p,\mathrm{water}} \cdot (T_{\mathrm{sup}} - T_{\mathrm{ret}}) \qquad (17)$$

$$\dot{Q}_{\mathrm{specific}} = \frac{\dot{Q}_{\mathrm{ap}}}{A} \qquad (18)$$

$$SoC = \frac{\sum_{i=1}^{N\mathrm{cells}} \chi_{\mathrm{i}}}{N_{\mathrm{cells}}} \qquad (19)$$

In addition to these values, the efficiency of the system must also be controlled to ensure that it is a feasible system compared to other conventional alternatives. For this, the parameters used to measure the performance of the heat pumps (SCOP and SEER) will be used, both for each specific operation mode and for the overall efficiency of the system during the whole year.

$$SCOP = \frac{Q_{\mathrm{con\ (year)}}}{P_{\mathrm{el\ (year)}}} \qquad (20)$$

$$\mathrm{SCOP}_{\mathrm{heat}} = \frac{Q_{\mathrm{con\ (hea)}}}{P_{\mathrm{el\ (hea)}}},\ \mathrm{SCOP}_{\mathrm{DHW}} = \frac{Q_{\mathrm{con\ (DHW)}}}{P_{\mathrm{el\ (DHW)}}},\ \mathrm{SEER} = \frac{Q_{\mathrm{ev\ (cool)}}}{P_{\mathrm{el\ (cool)}}} \qquad (21)$$

Finally, as a comparison to conventional heat production systems, and in order to demonstrate the savings in GHG emissions that such a system can generate, the amount of CO2 produced during a year of operation will also be measured.

$$M_{\mathrm{CO_2}} = f_{\mathrm{CO_2}} \cdot E \qquad (22)$$

Chapter 4

Results and Discussion

In this chapter the results of the system will be analyzed. For this purpose. The KPIs previously introduced will be compared in each of the three locations to find out the performance and the saving potential on energetic, economic, and environmental levels in each location. It should be noted that the analysis will be carried separately for series and parallel operation, when in fact the aim of the project is to obtain a system that is able to switch from one operating mode to another automatically depending on the needs. But this analysis is useful to determine how the system behaves in each of the modes separately, in order to try to optimize the operation in the future. Moreover, the work will examine a conventional heating, ventilation, and air conditioning (HVAC) system for the locations in order to provide in-depth analysis to comprehend the differences.

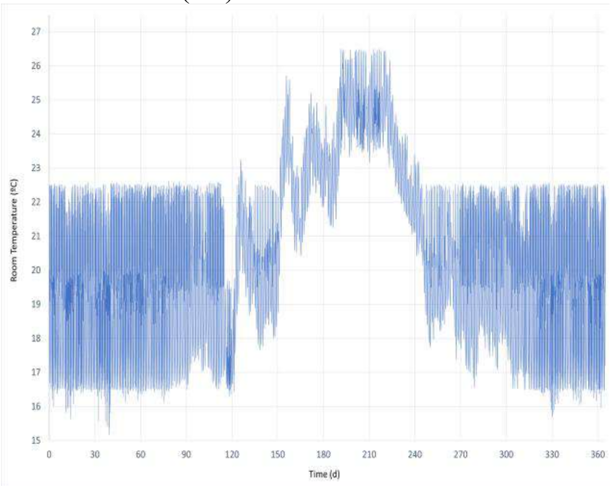
First an analysis of the indoor temperature distribution and the DHW KPIs will be presented separately for each of the configurations (for a better clarity and understanding). And the performance analysis will be carried out together, comparing the values obtained for both configurations in overall and in each of the operations.

4.1. INDOOR TEMPERATURE

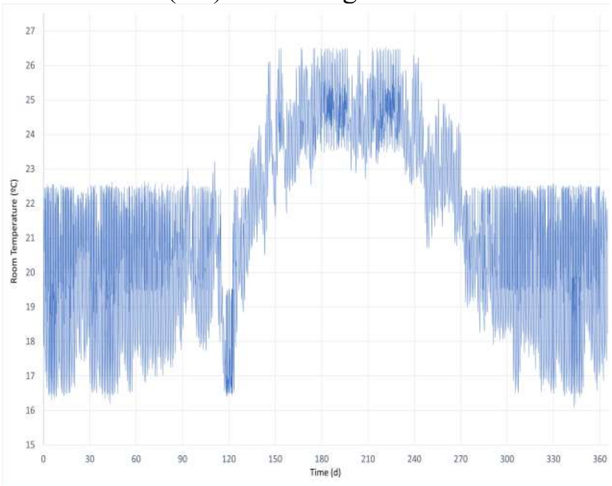
The first analysis is the temperature of the apartment, as it is one of the most critical parameters to control and on which the proper functioning of the developed system depends. As discussed in the previous chapter, the HPs operate to meet the heating load and respect the setpoint temperature (with a hysteresis of ±1.5K), so the indoor temperature must be within these levels in order to conclude the proper performance of the system.

Figure 27 shows the temperature distribution of the three locations in the following order: Helsinki, Strasbourg, and Athens, for both series and parallel. At a first glance, it can be observed that Helsinki has the lowest indoor temperatures, sometimes dropping below 16°C, and rarely rising observed 25°C. Strasbourg has milder temperatures, while Athens shows the longest summer period, and sometimes the indoor temperature reaches up to almost 28ºC (especially in parallel). It should also be noted that the drop in temperature seen in Helsinki and Strasbourg around day 120 is because the studied building is unoccupied during that period as explained before, therefore, the setpoint temperature during that period is always 18ºC. This temperature drop can also be observed in Athens, but as the outside temperature is higher, the apartment temperature is also higher and does not reach such lower levels. To further illustrate the behavior in the three locations, Figure 28 and Figure 29 show a detailed analysis of a typical week in winter (third week of February) and Figure 30 and Figure 31 a typical week in summer (second week of June) alongside the outside temperature both for series and parallel respectively. The blue line represents the simulated indoor temperature, while the orange one represents the respective setpoints for the investigated period. In addition, a more comprehensive comparison between different time periods, locations and configurations is presented in ANNEX 1.

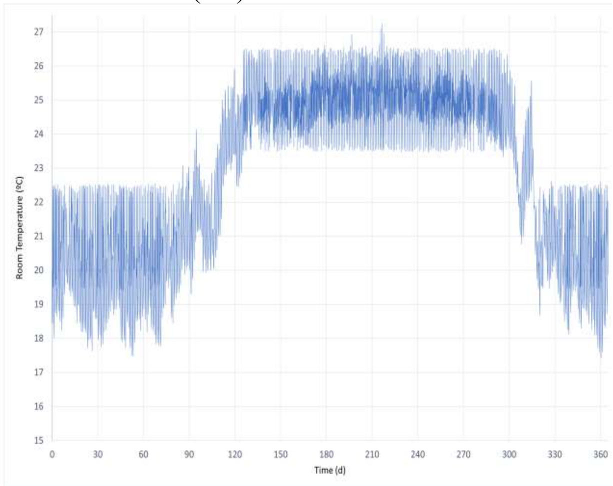
(a.1) Helsinki series



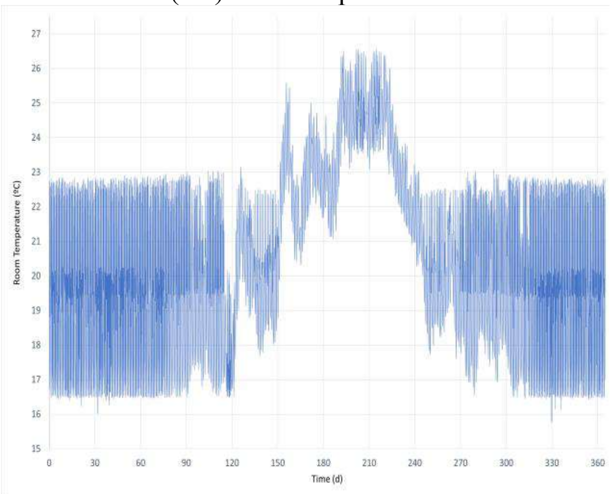
(b.1) Strasbourg series



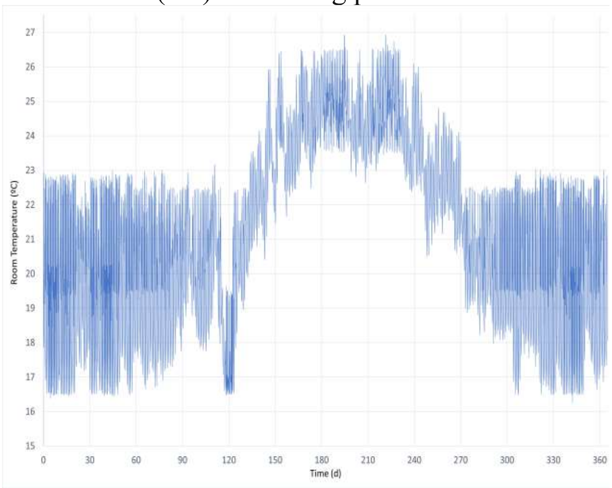
(c.1) Athens series



(a.2) Helsinki parallel



(b.2) Strasbourg parallel



(c.2) Athens parallel

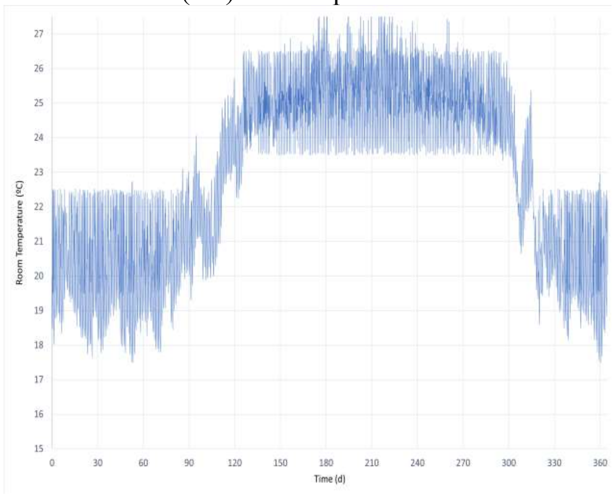
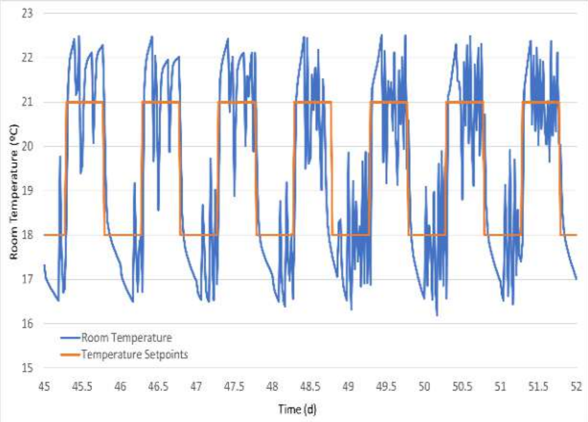
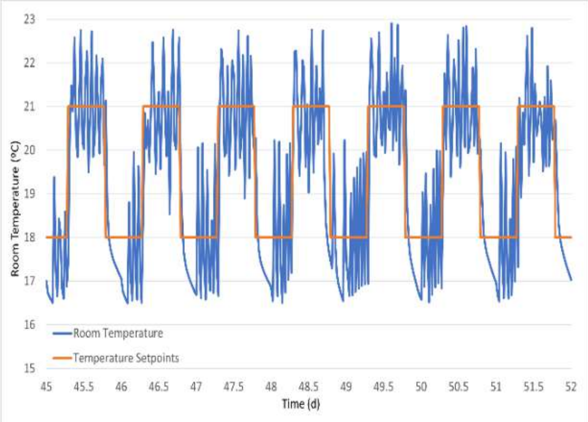


Figure 27: A year-round simulated indoor temperature for the building under three locations and configurations

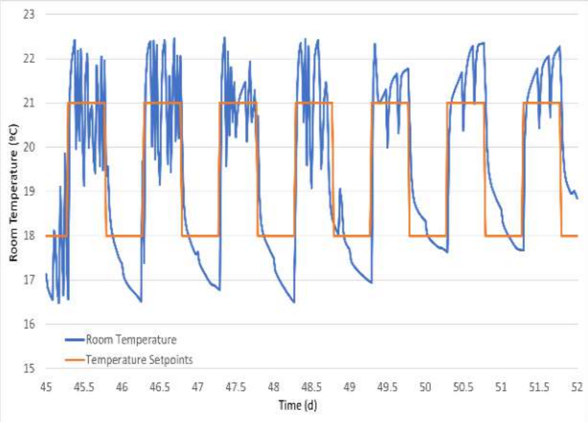
(a.1) Helsinki series



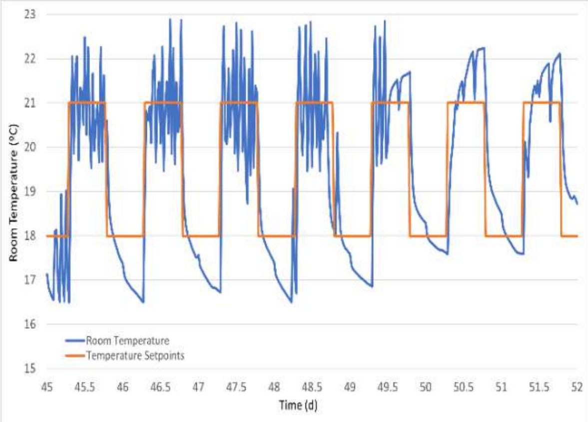
(a.2) Helsinki parallel



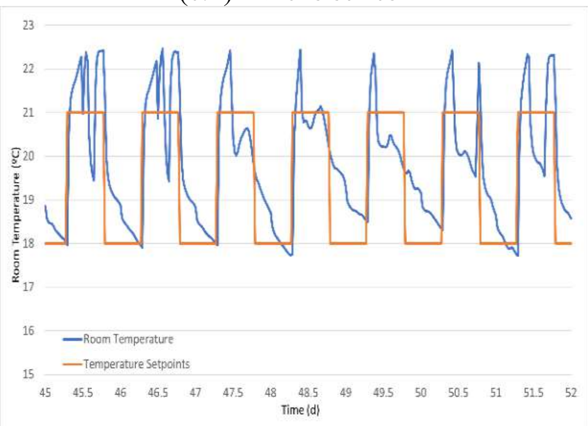
(b.1) Strasbourg series



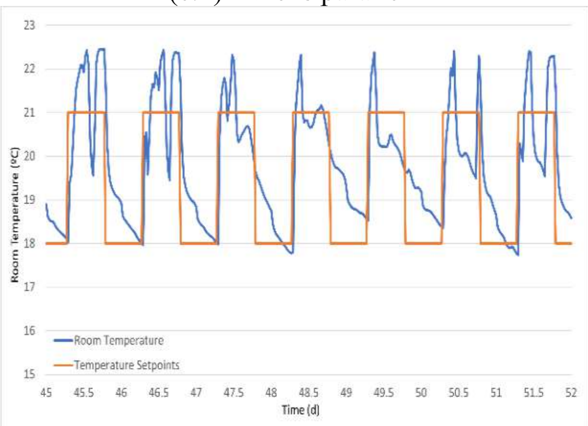
(b.2) Strasbourg parallel

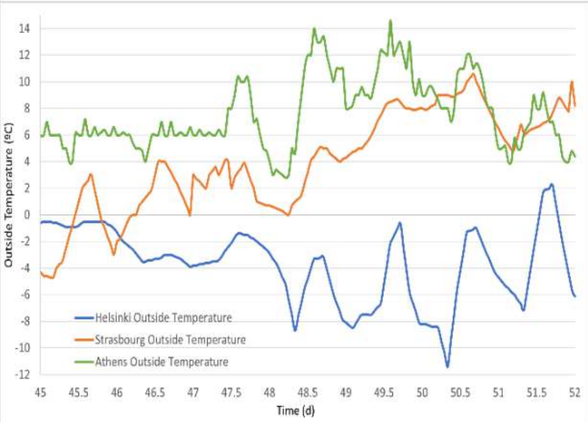


(c.1) Athens series



(c.2) Athens parallel





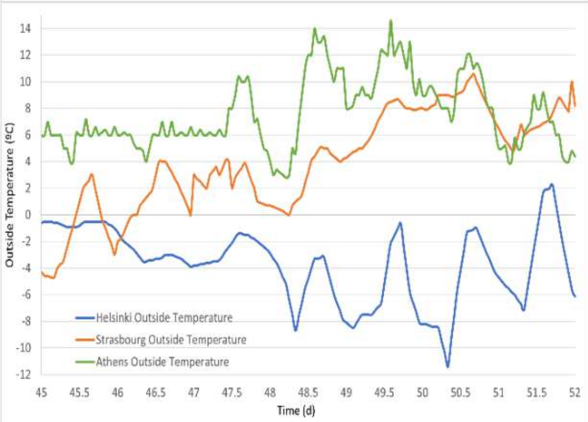


Figure 28: Simulated indoor temperature for series configuration during a typical winter week

Figure 29: Simulated indoor temperature for parallel configuration during a typical winter week

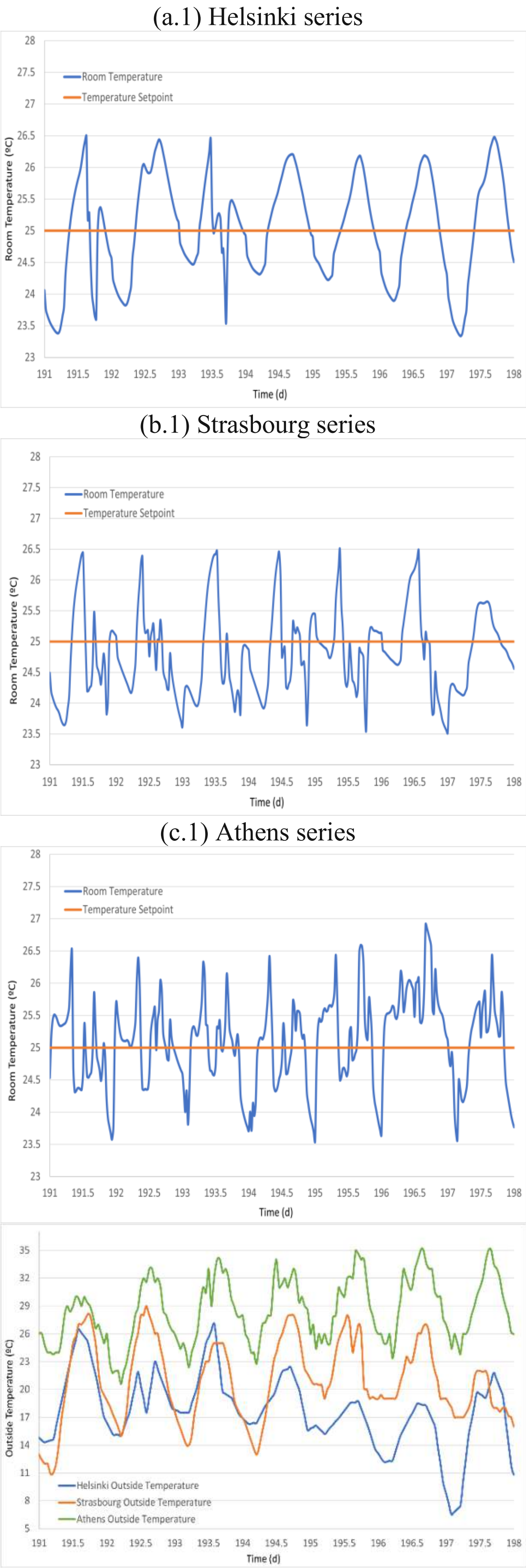


Figure 30: Simulated indoor temperature for series configuration during a typical summer week

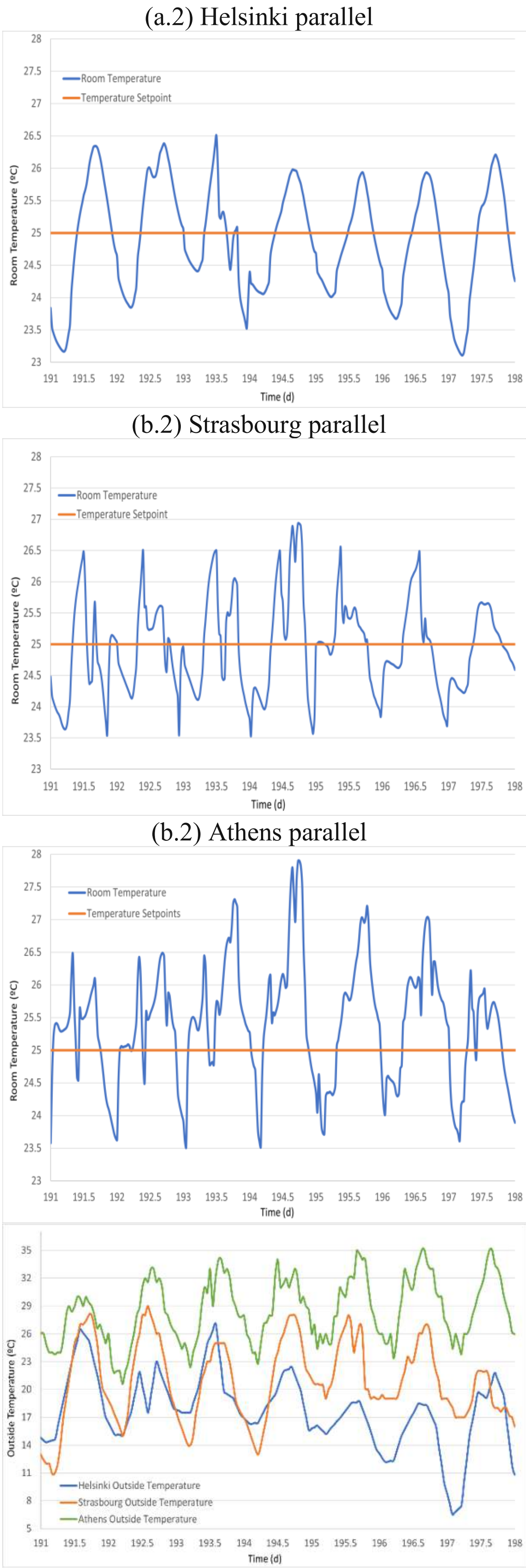


Figure 31: Simulated indoor temperature for parallel configuration during a typical summer week

The behavior in Helsinki and Strasbourg during winter is regarded similar to some extent, as they are cities with cold climates in winter (the minimum temperatures observed in winter in Helsinki and Strasbourg are -21.7ºC and -9.6ºC respectively). In Helsinki, there is a milder outdoor temperature during the first days and, thus, the HPs does not operate that often compared to that of Strasbourg. This behavior changes for the last studied days, as the outdoor temperatures in the two cities change too. The rapid temperature fluctuations are due to the large temperature difference between inside and outside, which means that the apartment cools down very quickly, and the HP system has to be switched on and off very frequently. At nighttime, due to the low temperatures in Helsinki, the HPs have to run continuously to avoid dropping below the desired temperature, whereas in Strasbourg it is hardly ever needed during this period. Unlike the other two locations, the behavior in Athens is completely different, since, having a warm climate, temperatures rarely drop below the target temperature (especially at night, where they almost never drop below 18°C), so the HPs system will run for much less time. Despite the clear difference between the three cities, it can be concluded that the general behavior is as desired, oscillating within the target indoor temperature. Yet, the indoor temperature falls below the desired levels for very specific periods of time, but as will be explained later on, this is not worrying in comparison with the overall performance, but it should be considered for the further development of such a system.

As can be seen, the difference between configurations is minimal, showing practically the same behavior, especially in Athens, where the heat pumps have to operate for a shorter time, while in Strasbourg and particularly in Helsinki, it can be seen that during very cold weather periods, there is a small difference on the oscillation of the temperature. This difference will be further discussed and analyzed on ANNEX 1, but as can be seen it does not make any difference as it oscillates between the exact same way between target temperatures.

In the summer analysis, a similar behavior can be observed in the three cities, with indoor temperatures oscillating around 25ºC, as the difference between the maximum outside temperatures observed during summer is not as high as in winter (28.7ºC, 31ºC and 37.1ºC for Helsinki, Strasbourg, and Athens respectively). The clear difference here is in the duration of the summer period, which, as shown in Figure 27, is considerably shorter in Helsinki and Strasbourg than in Athens, so they will require less cooling demand throughout the year. Athens, having the highest temperatures, is where the highest peaks are observed, and it has more temperature oscillations than both of them. This is because the high outdoor temperatures make the HPs to be switched on more often to achieve the setpoint temperature. The indoor temperatures in Helsinki and Strasbourg are similar during the first half of the week, but as can be seen, from the middle of the week and on, the drop in the Helsinki outside temperature results on a milder indoor distribution, as the temperature limits are never reached, and therefore the HPs are never switched on.

Here a difference can be observed between the maximum temperatures reached in each configuration, being higher with the parallel configuration and specially in Athens, as is the warmest climate. This difference is due to the controllers of the first heat pump block, as the controller that dictates how many heat pump modules to switch on is DHW-dependent and not cooling-dependent for the cooling and WPW-HEX charging operation, causing sometimes only one module to switch on when both modules should be running to meet the cooling needs. This affects the parallel configuration the most, since less water mass flow through the HP block will require less heat to reach the desired temperature, causing only one module to be switched on. This behavior will be explained as well on ANNEX 1. But despite this difference, it can be observed that the behavior is the same between configurations, and the temperatures are within the desired levels.

In order to put this into numbers, an analysis of the thermal demand in the building will be carried out as shown in Table 5. This analysis shows the amount of heat released or absorbed directly by the heat terminals in the apartment, the total heat released to the WPW-HEX during the charging operation, and the total heat released to the 5GDHC during the cooling operation.

Table 5: Building demands and heat injected into the 5GDHC for different locations and configurations

DEMAND ON BUILDING		HELSINKI		STRASBOURG		ATHENS	
		SERIES	PARALLEL	SERIES	PARALLEL	SERIES	PARALLEL
		BUILDING DEMANDS					
HEATING	Space heating (kWh)	7068.52	7579.72	4037.42	4135.97	790.67	826.19
	Specific space heating (kWh/m^2)	88.36	94.75	50.47	51.70	9.88	10.33
COOLING	Space cooling (kWh)	150.25	187.30	503.86	543.77	3198.79	3206.58
	Specific space cooling (kWh/m^2)	1.88	2.34	6.30	6.80	39.98	40.08
WPW-HEX CHARGING (kWh)		3730.71	3107.50	3764.75	3063.60	3799.79	3318.33
		HEAT INJECTED					
AMMOUNT OF HEAT INJECTED ON THE 5GDHC (kWh)		159.08	152.86	532.30	517.58	3450.53	3536.99

In both configurations, the results obtained follow the same pattern. Helsinki shows the highest space heating demand and therefore, specific space heating demand compared to other climates coming in accordance with the expectations due to the colder climate. Then Strasbourg with almost half of the Helsinki's heating demand, and lastly Athens with by far the lowest heating demand. As for the specific demand, which is the ratio of the total annual demand by the living area of the apartment, the values show the typical behavior in the three cases. The opposite behavior can be seen on space cooling demand, which is mainly needed in Athens, and hardly necessary in Helsinki.

The difference in the heating and cooling demand in the building between series and parallel can be easily explained, as it is due to the circulation flowrate through the HP blocks in each of these modes of operation. The circulation flowrate is a small amount of water that is circulated through the hydronic circuit when there is no demand to make the simulations easier, avoiding the heat pumps from switching off completely and the possible indeterminacies that may occur when having null flow rate at any time. This flowrate is set to 0.0001 kg/s on series mode, but on parallel the value cannot be that low because the temperature on the HPs would be really high and thus, the simulation could not be carried out. So, a circulation flowrate of 0.001 kg/s is set for each HP block, making a total of 0.004 kg/s (40 times higher than in series mode).

This causes 40 times more water mass to reach the building when there is not demand inside the apartment. As this water is at an average temperature of 22ºC it is able to generate thermal load in winter and cooling load in summer, as generally in winter the temperatures inside the apartment are lower than 21ºC, therefore it will heat it, and in summer the indoor temperatures are usually higher than 21ºC, hence it will cool it. This transmitted heat to the apartment is practically negligible on a day-to-day basis, but being cumulative is what causes the differences seen in Table 5.

However, it should be noted that this difference is only due to the needs of the simulation and in the real system, the thermal demand of the building would not be affected. Furthermore, as will be seen later, this does not affect the performance of the system, and as can be seen in Table 5, the thermal demand is fully satisfied in all three cities for the two configurations.

Related to the cooling demand, and as explained before is the amount of heat injected into the 5GDHC, which is the heat produced in the condenser during the operation of cooling only. As can be seen, the values are almost the same for both locations as they directly related to the cooling demand. The difference is in the comparison of this injected heat with the cooling demand inside the building. In the series configuration, these values are slightly higher than the demand values, as expected, as it is the heat produced on the condenser side during the cooling operation directly, excluding transfer losses. But in parallel, the demanded heat is higher than the injected heat (which would not be technically possible), again due to the amount of cooling load transmitted to the flat when it is not operating in cooling mode.

For DHW demand, the WPW-HEX charging demand is used as a representative value, since in order to satisfy the DHW demand, the WPW-HEX has to be sufficiently charged. As will be explained in the following section, all three cities have the same boundary conditions on the DHW side and the same demand profile in the building, making the heat demanded to charge the WPW-HEX and, thus, to satisfy the consumption practically the same. However, here a clear difference in demand can be seen between configurations, being higher in series mode than in parallel mode. This difference will be explained later in the analysis of DHW KPIs and in the performance analysis of operations. Focusing on each configuration separately, it can be observed that due to the identical boundary conditions of the three cities, the WPW-HEX demand values are practically the same for the series configuration, around 3700-3800 kWh. For the parallel mode, it can be observed that Helsinki and Strasbourg follow this pattern, while Athens has slightly more WPW-HEX charging demand. This is also due to this difference which will be explained later.

However, turning this WPW-HEX charging demand into a demand per day and person the values are between 4.15kWh/(day.occupant) and 5.2kWh/(day.occupant) (depending on the city and the configuration). So, as for the development of the DHW demand profile it has been used as an assumption of a demand of 4Wh/(day.occupant) it is possible to verify the correct functioning of the system when charging the WPW-HEX.

Finally, in order to verify the correct performance of the system, an analysis is carried out to quantify the percentage of time in which the indoor temperature is within the desired limits. To do this, it has been broken down into the following different setpoint temperatures (winter at night, winter during the day and summer) and into the different configurations. So, in Table 6 is shown the number of hours together with the percentage for each location and configuration where the indoor temperature is within or out of the bandwidth temperature. It should be noted that this percentage is based on the number of hours of each specific operation, not the overall number of hours during the year.

Table 6: Time of the temperature below the desired values on the different locations and configurations for heating and cooling

OPERATION	INDOOR TEMPERATURE (ºC)	HELSINKI				STRASBOURG				ATHENS			
		SERIES		PARALLEL		SERIES		PARALLEL		SERIES		PARALLEL	
		Time (hours)	%	Time (hours)	%	Time (hours)	%	Time (hours)	%	Time (hours)	%	Time (hours)	%
WINTER NIGHT	< 16.5 ºC	57	1.3	16	0.3	12	0.3	2	0	0	0.0	0	0
	16.5ºC < ϑ < 19.5ºC	2831	63.7	2825	63.7	2277	52.2	2284	51.1	911	23.6	878	24.4
	> 19.5 ºC	1558	35	1594	35.9	2075	47.6	2183	48.8	2947	76.4	2715	75.6
WINTER DAY	< 19.5 ºC	263	6.2	352	8.4	174	4.3	210	4.9	68	2.4	72	2.5
	19.5ºC < ϑ < 22.5 ºC	3006	71.4	2732	64.8	2555	63.2	2434	56.7	1779	62.3	1787	63.1
	< 22.5 ºC	942	22.4	1131	26.8	1314	32.5	1648	38.4	1008	35.3	973	34.4
SUMMER	< 23.5 ºC	0	0	0	0	1	0.1	1	0.3	0	0	0	0.0
	23.5 ºC < ϑ < 26.5 ºC	105	100	111	98.7	355	99.9	375	99.7	2025	98.9	2128	91
	> 26.5 ºC	0	0	2	1.3	0	0	0	0.0	24	1.1	210	9

* For the purpose of clarity, those values that are furthest away from the desired values have been highlighted.

As can be seen, there is a small percentile of time in each of the operations (where Helsinki stands out) in which the indoor temperature falls below the levels of the desired temperature. This is not due to a poor performance of the HPs, rather, it can be attributed to the system's characteristics of prioritizing the WPW-HEX charging over the heating operation. This is particularly observed during the day, as there are 3 charging periods and more demanding setpoint indoor temperatures than at night. In Helsinki, as the temperature difference with the outside is greater, the apartment cools down faster (arriving at an 8% of the year where the temperature is not satisfied).

The difference is also noticeable between both configurations. At night, the parallel mode presents better results, since there is generally less DHW demand in the building during that period of time, and since the WPW-HEX is more charged on average (as will be seen in 4.2.2), the system has a greater facility to cover the heating demand inside the apartment, so it can be observed that the time below the desired minimum temperature is less in parallel than in series (although it is not a big difference, since both values are very low in all cases).

During the day the behavior changes and the parallel configuration shows poorer results, especially in Helsinki, as already mentioned. During the day, as there is more DHW demand in the building and more WPW-HEX charging periods, despite having a higher SoC, the WPW-HEX will have to be charged more often than at night (so both configurations will have a similar behavior during the day). This, combined with the low outside temperatures, causes the indoor temperature to drop below the desired levels, and as explained above, the configuration of heat pumps in series allows higher temperature levels to be reached, so the setpoint temperature inside the apartment is reached earlier than in parallel. This is why the time below the desired minimum temperature during day is greater in parallel than in series.

In summer, only in Athens the temperature rarely rises above the desired temperature, which could be corrected by increasing the number of heat pumps in operation for cooling, or by modifying the control parameters of the existing ones (as will be explained in 4.3.3, the second HP block does never switch on for cooling due to its restrictive controller). In parallel, this rise in the Athens's indoor temperature is bigger as could be shown in Figure 27 causing it to be out of the desired temperature levels for a longer period of time. This is due to the aforementioned controller of the heat pumps in parallel. This, again, will be analyzed more exhaustively in the ANNEX 1

However, in all the cases (heating and cooling for both series and parallel), this could be solved by changing the charging times, modifying the control strategy to try satisfying both demands (heating and WPW-HEX charging) at the same time. Otherwise, another solution could be the use of the water after charging the WPW-HEX, if it is at a sufficiently high temperature, to be led to the heat terminals in the building to heat it up. Yet, this requires further analysis in order to check the potential heat rate and its match to the heating load. Yet, they are not extremely low temperatures, as they are always around 16ºC and not for a long period of time, so it is not a serious problem for the installation.

4.2. DHW KPIs

In the following subsections, the key parameters of DHW delivery (temperature distribution and SoC of the WPW-HEX, and the actual supply temperature) will be analyzed, as explained before, first for the series configuration and after for the parallel.

4.2.1.Series operation

In this case, it should be considered that in the three locations the results will be practically the same, since the boundary conditions of the DHW system are the same for all three (tap water temperature, set point delivery temperature, hot water temperature for charging the WPW-HEXs, charging times and DHW demand), so the differences between them will not be emphasized. Moreover, as explained in section 3.2, as there are two WPW-HEX in parallel, both work in the same way, obtaining the same values for the KPIs to control, thus, only one will be analyzed in order to make the analysis easier to read.

The first parameter to be analyzed is the temperature distribution inside the PCM. As explained above, the storage is discretized into 5 different cells, in order to achieve greater precision when performing the calculations, so each one has a different temperature profile, ranging from a higher temperature in cell 1 to the lowest temperature in cell 5. So, what is important here is not so much the temperature of each cell as such, but the average temperature of the PCM, which must be high enough so it can heat the DHW to 53°C after it has passed through the five cells.

Figure 32 shows the temperature distribution due to rapid charging-discharging cycles, and, therefore, it does not provide insights into the temperature evolution. Besides, an overexposed data can be also noticed. Therefore, it is decided to present the results of Helsinki as a representative case of the three locations since the difference is minimal due to the similarity in boundary conditions for the DHW system, and after, in Figure 33 a weekly comparison between the three cities is presented to demonstrate what has been explained, and to visualize the few differences between the three cities.

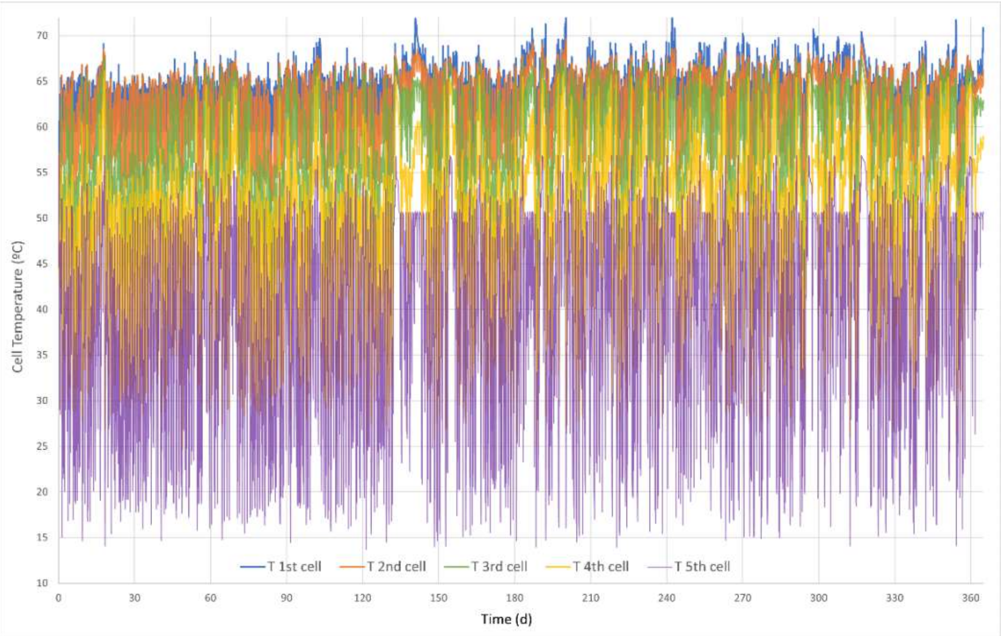
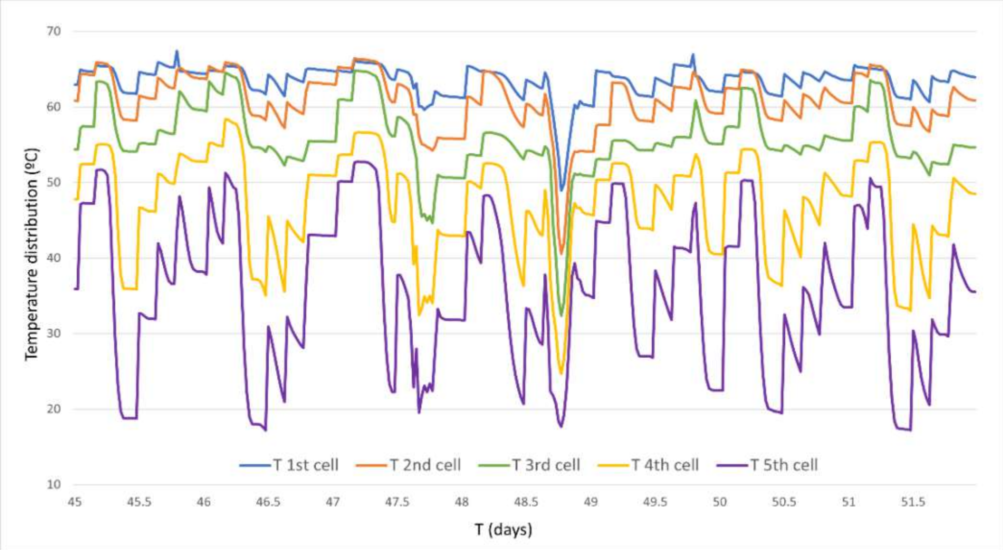
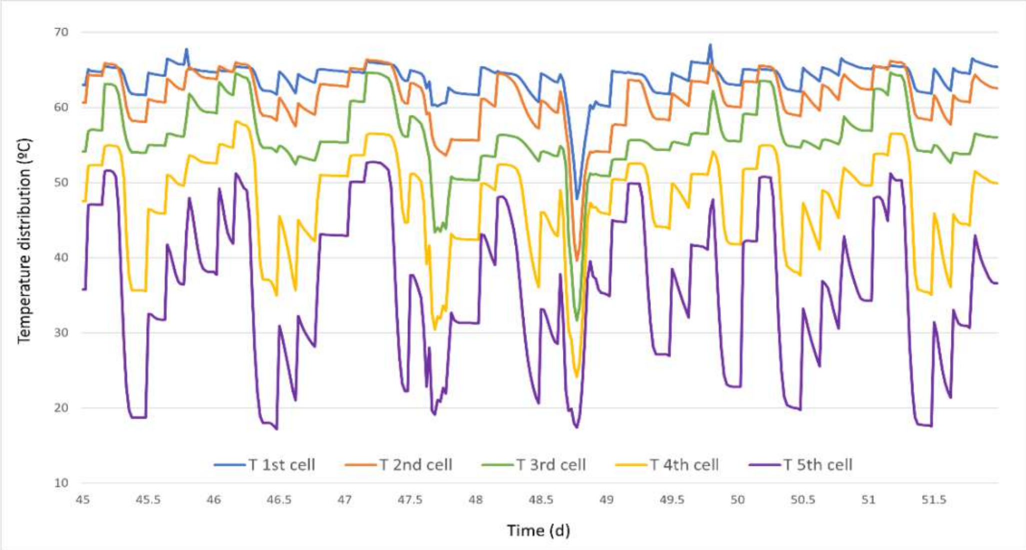


Figure 32: Temperature profile inside the PCM on Helsinki discretized by cells

(a) Helsinki



(b) Strasbourg



(c) Athens

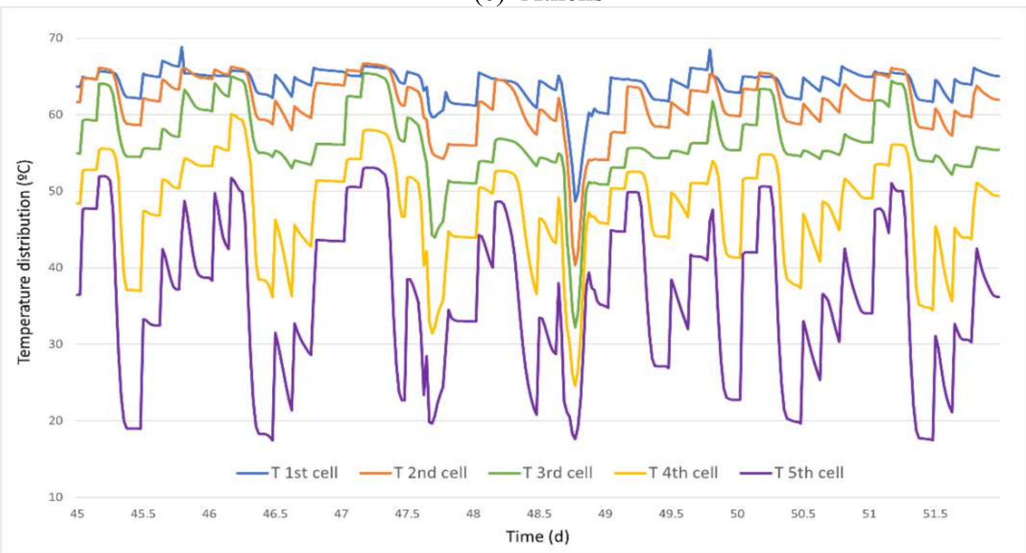


Figure 33: PCM cell temperature on the three locations for one week

As can be seen, cell 1 is the one with the highest temperatures with an average of 65ºC, while cell 5 rarely goes above 50ºC. This means, that the PCM does not have a high charging level. Even though, the average annual temperature of the PCM is 54.58ºC, which is considered sufficient to guarantee a supply temperature of 53ºC. The average annual temperatures on Strasbourg and Athens are 54.53ºC and 54.40ºC, meaning that the behavior is practically the same on the three cities.

The differences between the PCM temperatures in the three locations are minimal (varying only a few tenths in some points due to small differences in the supply temperature). The temperature on day 49th is noteworthy for analysis, as it drops below 50ºC even in cell 1. This behavior will be studied later on, and as will be seen in the following sections, it is a one-off case due to an extreme DHW demand on the building.

Related to the previous point is the SoC of the WPW-HEX, which as explained above is defined as the amount of PCM that is molten. As before, for the purpose of clarity, and in order not to be repetitive, only the graphic related to Helsinki will be shown on figure Figure 34. Later on, on Figure 35, the same week as before will be shown, in order to discuss the SoC of the three locations at the same point.

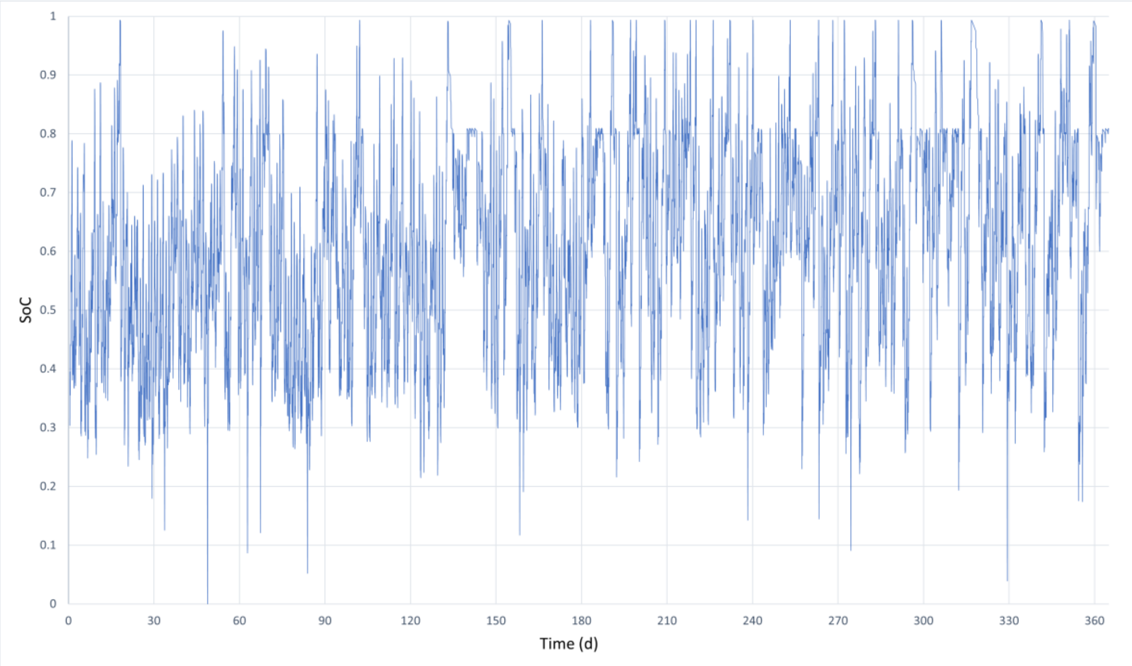


Figure 34: State of Charge of the WPW-HEX for Helsinki

As can be seen, the SoC usually oscillates between 0.2 and 0.9, with an annual average of around 0.6. Yet, there are some points where the WPW-HEX is completely or almost discharged, which are given after a consumption peak, where the WPW-HEX is completely discharged in order to meet the demand, and there is no charging period afterwards, so it remains with a low SoC for a while. This means that if there is a high demand in this period, it may not be able to supply it completely until it is charged to a certain level. In the following picture, the analysis over a week can be seen.

On Figure 35 it can be seen the demand during this period of time too, with an average of 0.015 kg/s, with a high peak of around 0.062 kg/s that makes the WPW-HEX discharged in order to heat up such a high flow rate. Around day 49, the SoC is 0 since all cell temperatures are below 55ºC (the melting point of the PCM). This will be discussed and analyzed on the next subsection.

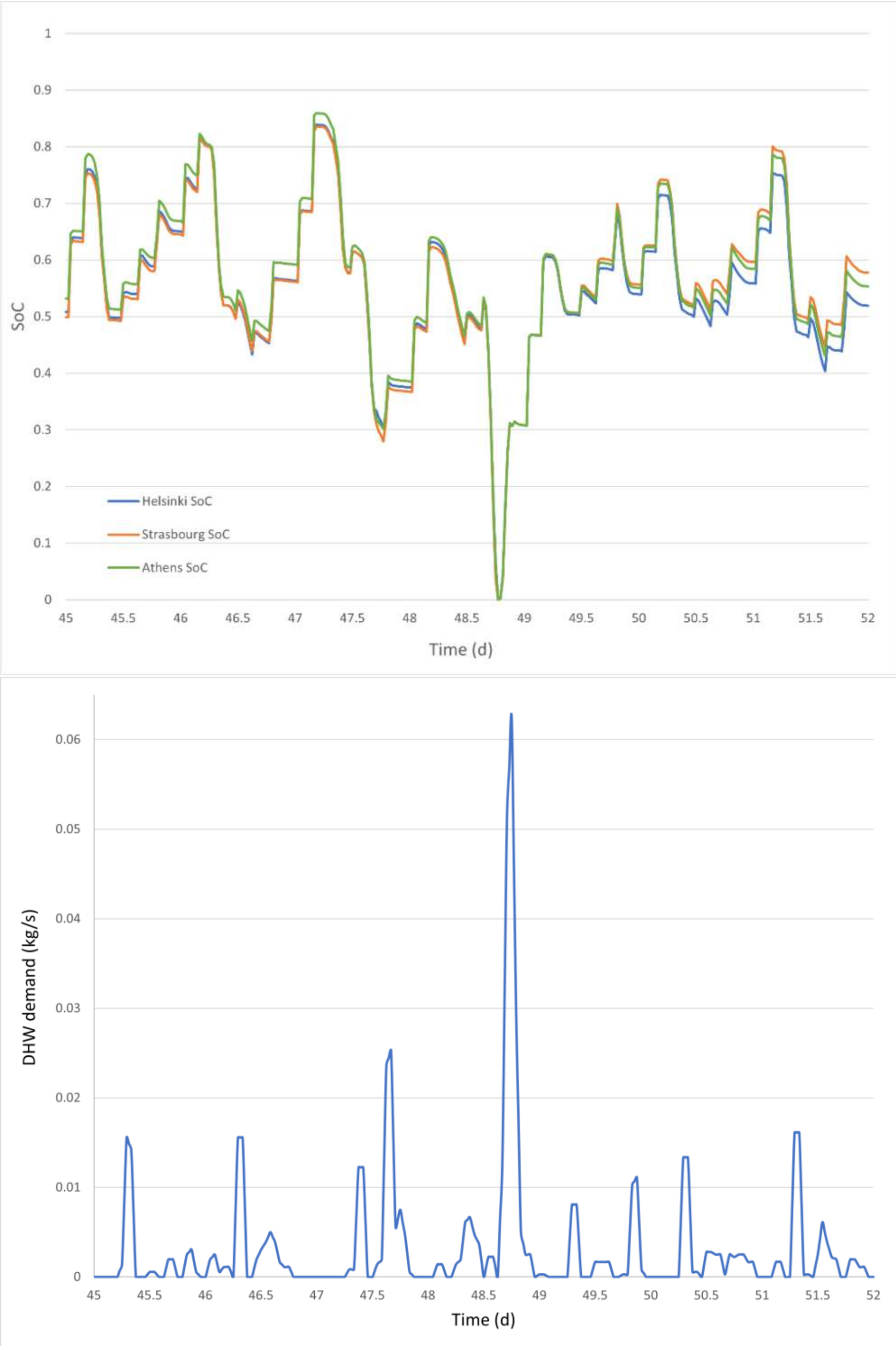


Figure 35: State of charge on the three locations for one week vs the DHW demand

As they are related, as with temperature, the differences between the different locations are minimal. The changes are due to the different heat losses with the environment (where Athens, having a smaller temperature difference, has less heat loss), which is why it tends to be the city with the highest SoC, or due to differences in supply temperatures, where in Helsinki or Strasbourg they can sometimes be higher, causing it to be more loaded for a period of time.

Figure 36 shows the temperature at which the DHW would reach the corresponding application if there were a demand at that precise moment. In order to know the actual temperature of water arriving to the DHW application at any given moment, this figure shall be compared with the building's consumption table. It is important to mention that the setpoint temperature for the DHW application is 53°C and this can be considered high for several DHW applications. Yet, it is chosen in order to reveal the capacity of the solution proposed in this HPs system.

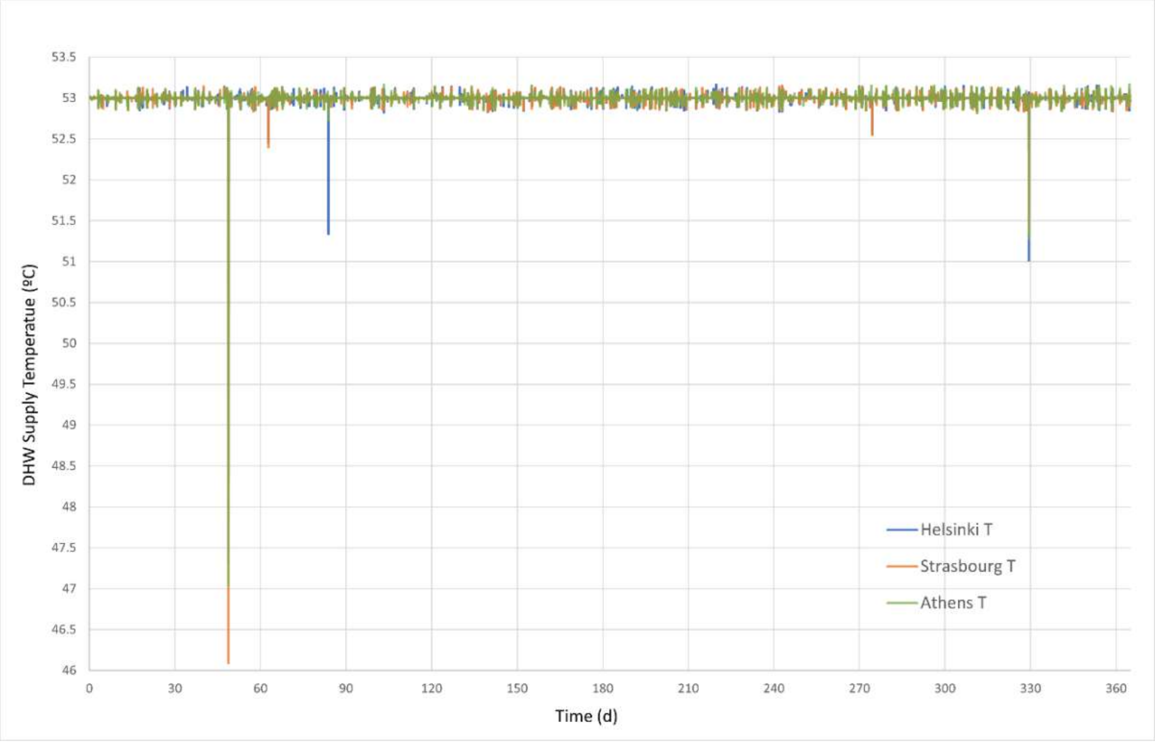


Figure 36: Delivery temperature of DHW for the three locations

As can be seen, the DHW temperature is always around 53ºC, except for four specific occasions that should be corrected, using an additional electrical heating element that will raise the temperature to the desired one (i.e. 53ºC). The most remarkable drop in the DHW temperature is the one that occurs around day 49, where the high DHW demand makes the discharge of the WPW-HEX, and thus, the temperatures inside the PCM are not sufficient to satisfy the 53ºC demand. However, it should be noted that the lowest temperature observed during a year is due to an extreme case, and even so, 46ºC would be considered sufficient in most DHW applications. This day can be seen in more detail in Figure 37.

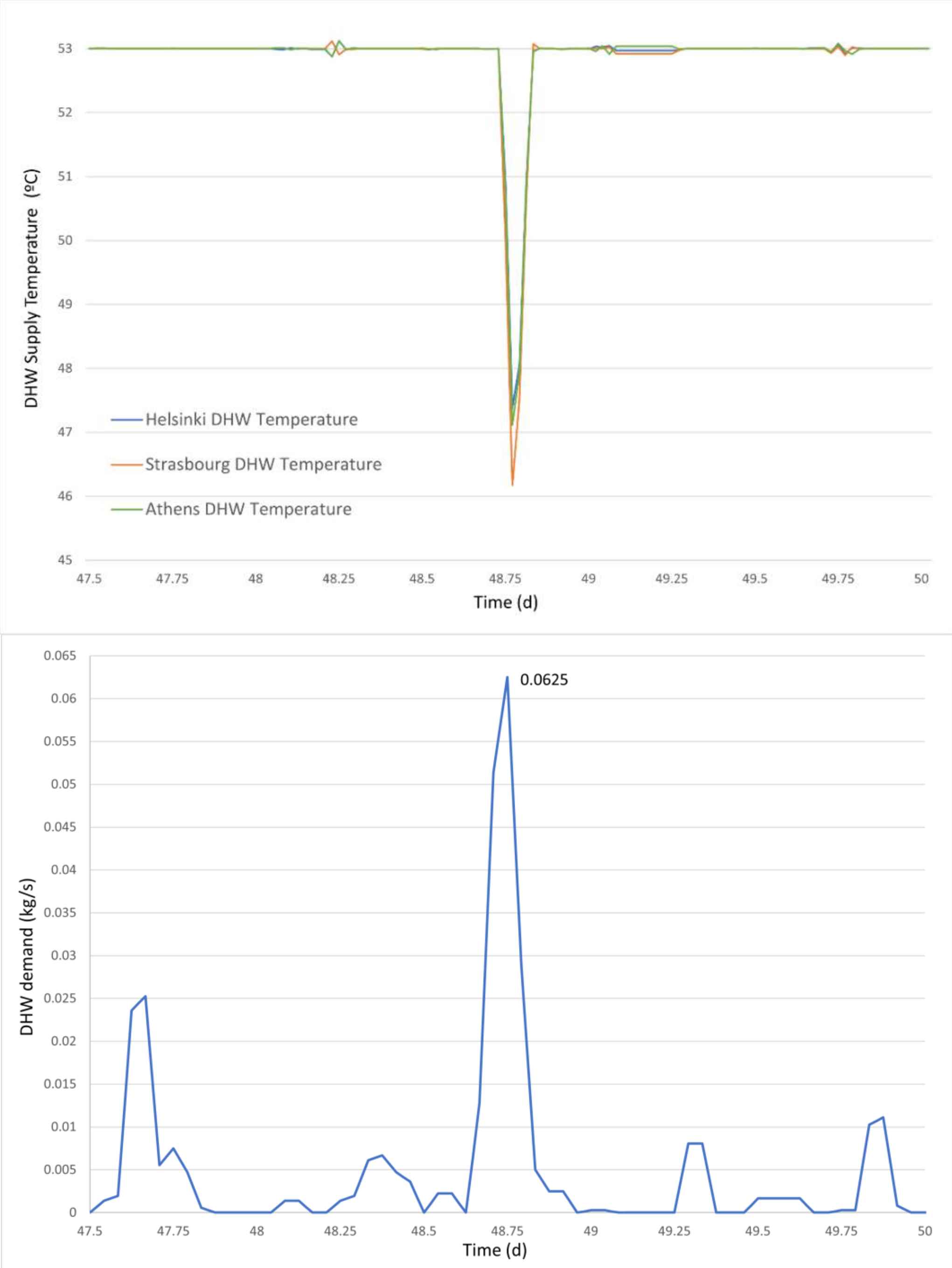


Figure 37: Supply DHW temperature on the 48th day for the three locations vs the DHW demand

A decrease in DHW delivery temperature can be observed for about 2 hours (the duration of the demand) as remarked above This demand corresponds to 0.0625 l/s, which is 225 l/h, a high amount, since, in Austria, for example, the maximum allowed is 190 l/h [31]. Yet, the system is able to deliver a temperature of 46ºC. This has been done together with the delivery temperature of 53ºC and the tap water temperature of 10ºC to analyze the system and check its performance under extreme conditions, therefore the performance of the system to meet the DHW demand can be validated.

4.2.2. Parallel operation

In theory, the results for the parallel configuration should be similar to those of the series configuration, since they share setpoint temperatures, controllers and boundary conditions. But due to some particularities of this configuration, there are slight changes in the behavior, so the analysis here will be done considering these differences.

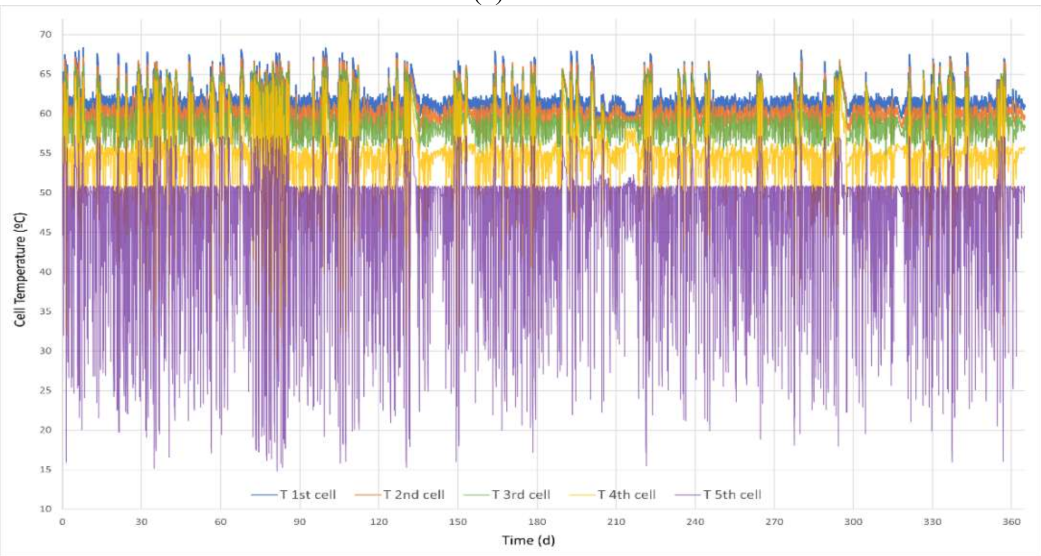
The first one is the difference in the water mass flow through the WPW-HEX during charging operation. As explained in 3.4.2.3, the mass flow rate to achieve the desired temperature is 0.042kg/s. The difference here is that in series, this is the total mass flow, while in parallel, this is the flow rate through each of the HP blocks (in order to achieve the desired charging level). Therefore, the final mass flow rate that arrives to the WPW-HEX is 4 times higher, in the order of 0.168kg/s. That is why during its charging, a greater amount of heat is transmitted to it, and as will be seen below, it presents higher temperatures and a higher SoC. This also causes the temperature distribution inside the PCM to be more homogeneous (in the series configuration, being always charged at close to limit levels, the heat pumps switch on and off very frequently, causing a lot of oscillation). In this configuration, as each charging period transmits a greater amount of heat, higher temperature levels are reached, making the next charging more prolonged in time, and therefore stabilizing the inside temperatures of the PCM.

The second difference is due to the controller of the second HP block (see section 3.1). As explained, this block of HPs is used to cover the heating, cooling and DHW demands, thus, is able to cover the cooling and charging WPW-HEX operation, which is the one that is affected. The controller seen on Figure 16 can detect either demand for cooling or DHW and send the signal to switch on the block, but the controller seen in Figure 17, having cooling as the first path to follow, if the requirements for the HPs block to be switched on are not met, it will remain off, regardless of whether there is DHW demand or not, because as explained, both controllers should give a positive value simultaneously in order to switch on the HP block.

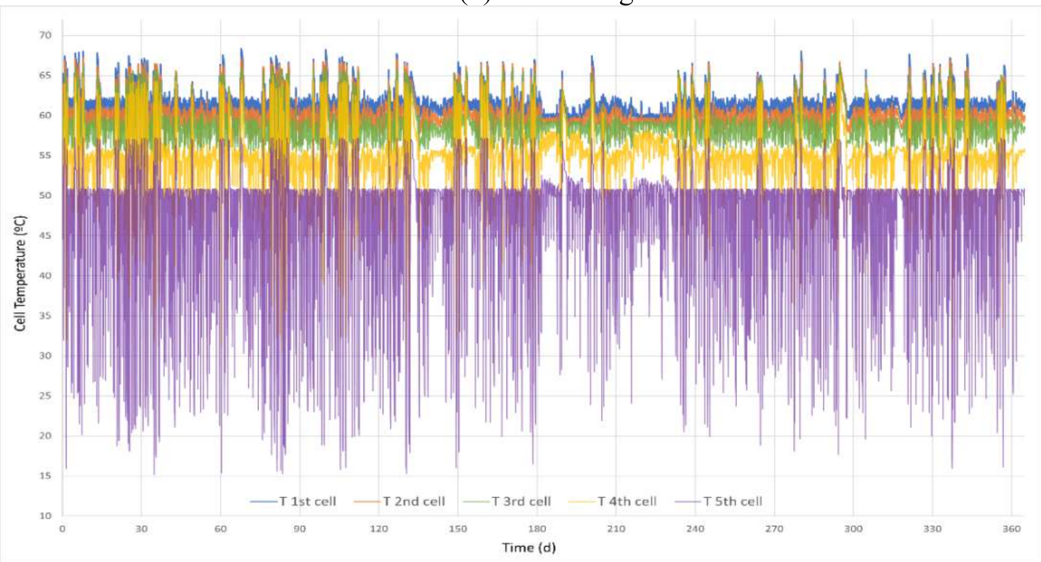
This does not affect the series mode, as the water passing through the next two HPs blocks heats up to the required temperature, but on parallel, with one less block running, the water mass flow through the remaining three blocks is 0.056 kg/s (instead of 0.042 kg/s), thus reaching a lower temperature lift, meaning that the water arrives to the first cell of the WPW-HEX at a lower temperature. This will be exemplified later, in the SoC analysis, and it will be seen that it affects mostly Athens since it is the city that works more in cooling operation.

Thus, due to the higher uniformity of temperatures inside the PCM, (which gives a better clarity when representing the data), and to the already mentioned differences in operation due to the controller, in Figure 38 the results of the annual temperature distribution for the three locations are presented. In addition, as seen above, and as can also be seen here, in winter the behavior is practically identical in these three cities, so in Figure 39 the comparison is presented in a summer week (which will also be used to exemplify what happens in Athens in comparison), to see the differences.

(a) Helsinki



(b) Strasbourg



(c) Athens

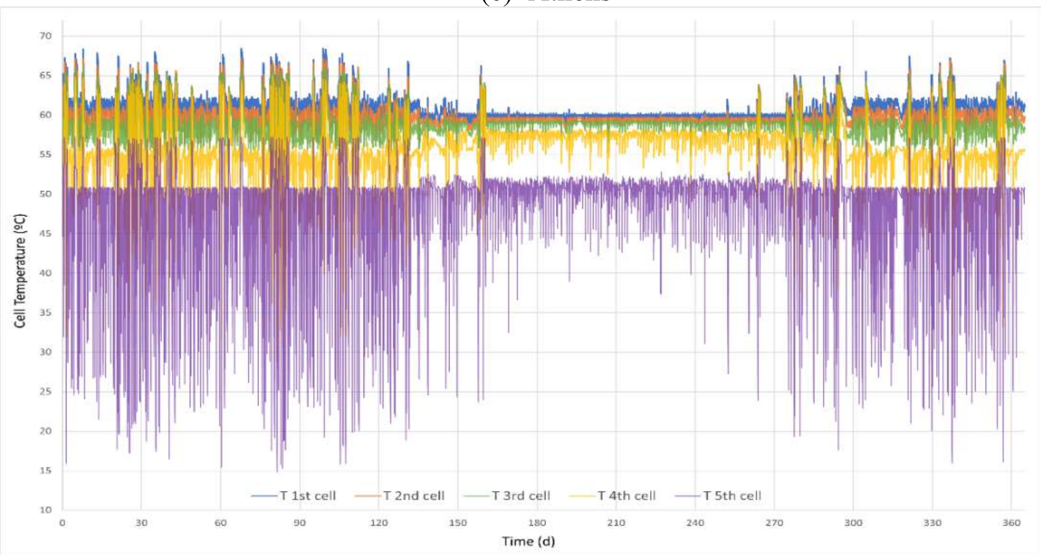
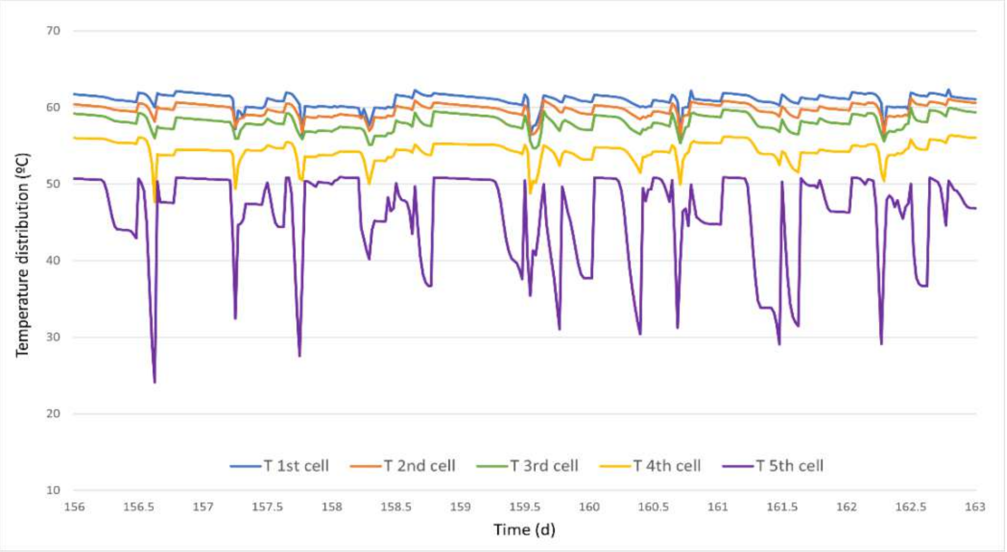
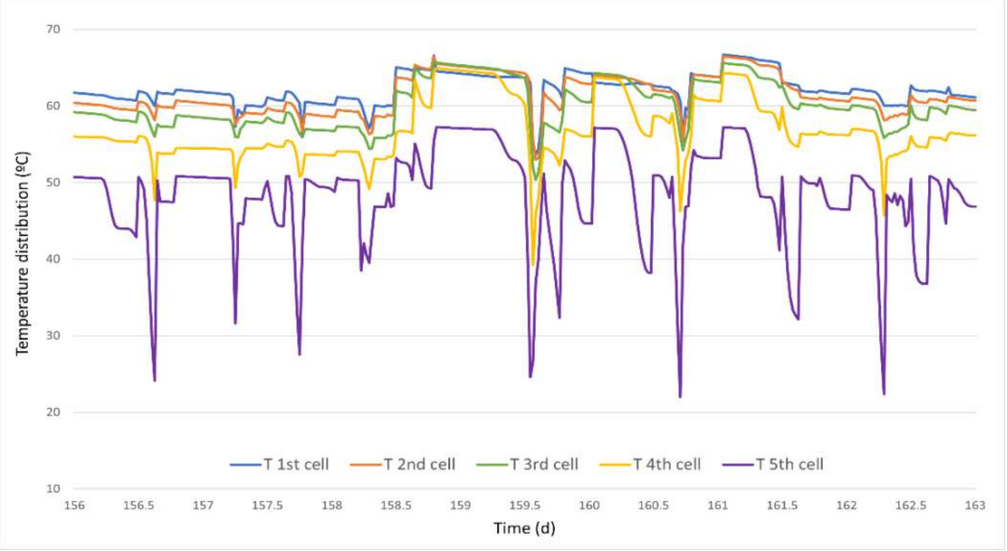


Figure 38: PCM cell temperature discretized for the three locations

(a) Helsinki



(b) Strasbourg



(c) Athens

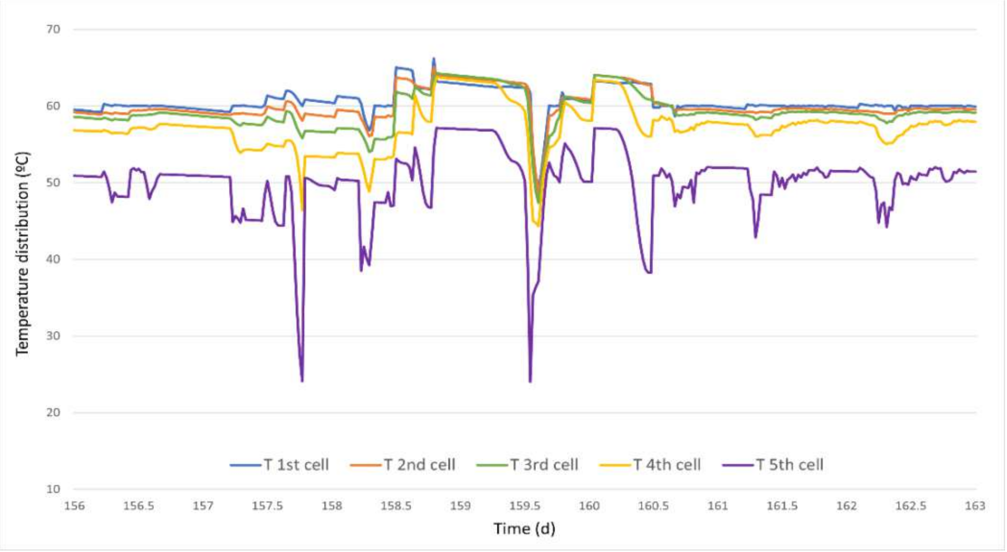


Figure 39: PCM cell temperature for a summer week in the three locations

As can be seen, and following the explanation above during winter, (or as long as there is no cooling demand in the building), there is more uniformity in the temperatures than in series, and in all the three cities the behavior is the same, with high peaks that reach up to 68ºC in the first cell and low peaks of 15ºC in the last one. And also, it can be observed an annual average temperature of around 57ºC on the three locations.

When it is possible to observe the difference in operation is during the summer period, which is particularly noticeable in Athens. Helsinki, being the city with the shortest cooling period, has almost the same temperature distribution throughout the year, with peaks of more than 65ºC. In Strasbourg, between days 180 and 210 (corresponding to the end of June and the beginning of July) a decrease in temperature peaks and a stabilization in temperatures can be seen. Whereas in Athens this is much clearer. From day 150 to 270 (May to September) a general drop of the highest temperature of the PCM and a stabilization of the temperatures at 60ºC can be observed.

This is due to the fact that during this period the heat pumps operate mainly to provide cooling to the apartment, and explained and as will be exemplified in section 4.3.3, the second HP block is never switched on for cooling, not being able to provide charge for the WPW-HEX neither during that period. This results in a lower water temperature reaching the WPW-HEX (around 60ºC compared to the 70ºC it should reach), causing the stabilization of temperatures within all the PCM around that temperature, and although the first cell never rises temperatures above the 60ºC, the other cells do. This can be seen in Figure 39, where there is a lower temperature difference between the first four cells in Athens than in Helsinki or Strasbourg, being all of them at around 60ºC, achieving then a higher average SoC.

However, this causes a paradoxical behavior, as the temperature of the first cell (which dictates whether the WPW-HEX should be charged or not) is lower than in other cities, it needs to be charged more often. So, despite of the higher SoC, a higher number of operating cycles will be necessary, which means more heat transmitted to the WPW-HEX and therefore a higher electrical input as will be seen in 4.3.1.

This inability to reach higher temperatures can also cause the temperature drop that can be observed in Figure 39 around day 159th inside the PCM in Athens. This also causes that the WPW- HEX discharges slightly more in Strasbourg and especially Athens than in Helsinki. To further illustrate this, Figure 40 shows the SoC distribution of the three cities over the whole year, and Figure 41 shows the SoC of each of the three locations over the week studied in this subsection.

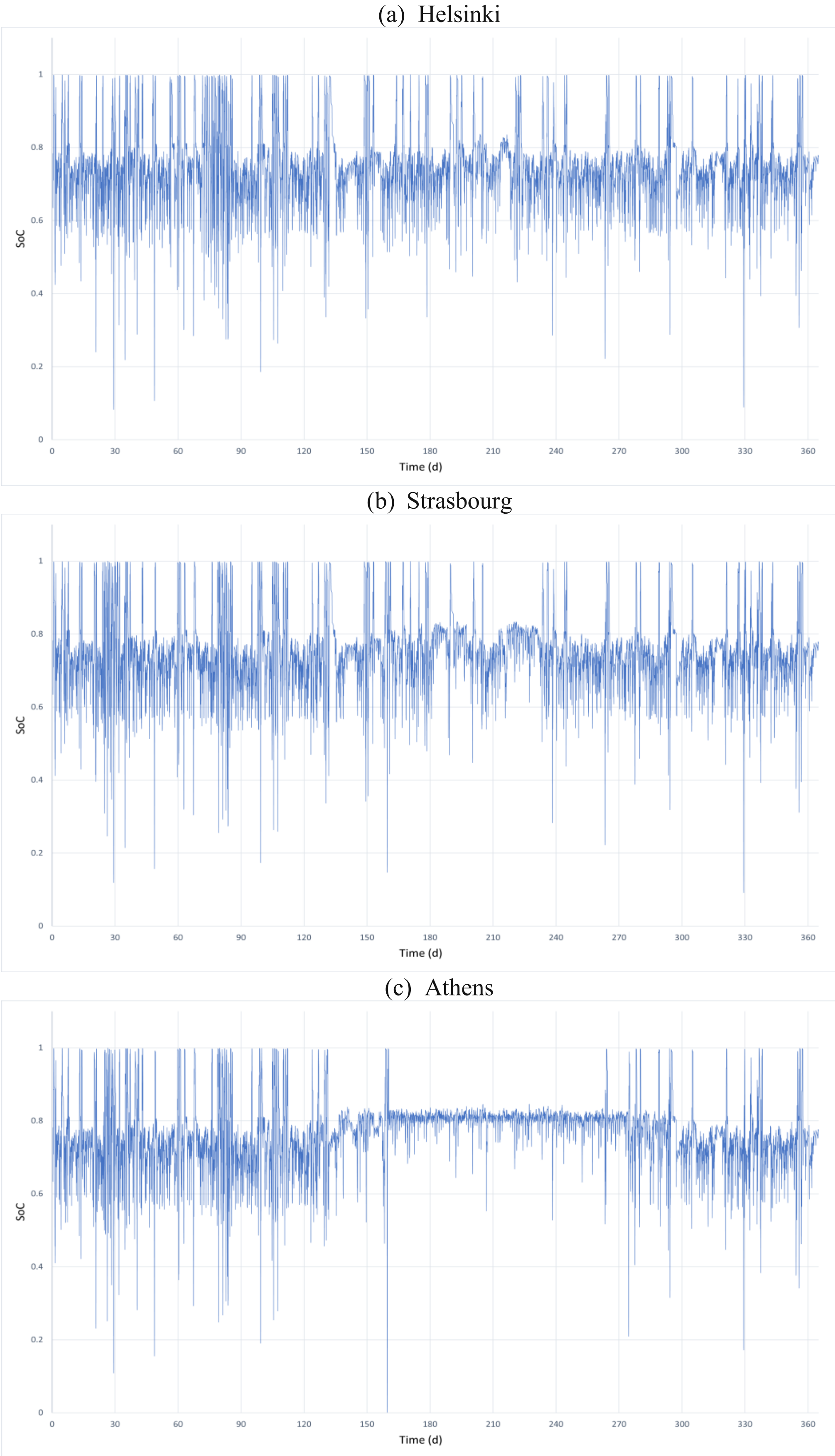


Figure 40: Annual SoC of the WPW-HEX for the three locations

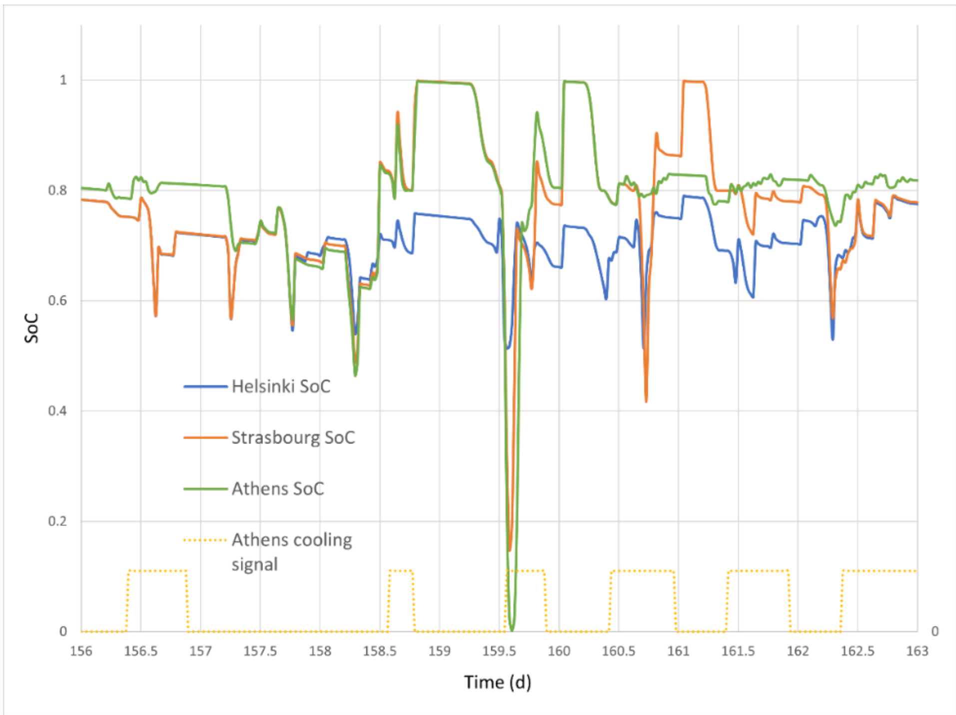


Figure 41: SoC of the three locations during a week in summer. Comparation with Athens cooling signal

The temperature drop of the PCM (and therefore of the SoC) in Athens is due to a cooling demand at that moment (represented as the dot line on Figure 41), making only 3 blocks of HPs switched on, and therefore not being able to charge the WPW-HEX as much as it should. In Strasbourg this demand also exists but has a shorter duration, so it does not discharge to such an extent.

As explained throughout this sub-section the SoC follows the same pattern for all three locations during the winter months, but for summer this behavior changes. In Strasbourg and especially Helsinki, SoC peaks up to 1 can be observed in Figure 40 during summer, due to the higher water temperature reaching the WPW-HEX. However, in Athens, the WPW-HEX remains constant at around 0.8 SoC as it is not able to charge further. Although it can be seen that as it has more charging cycles, it remains constant at that value, while in the other two locations low peaks of 06 SoC are observed.

Despite these differences, the average annual state of charge of the three locations is around 0.75 in each of them, compared to 0.6 in the series configuration. This difference is due to the higher mass flow of water through the WPW-HEX on parallel configuration, and means that, as it is more charged along the year, it will be better able to meet the setpoint water temperature during the DHW peak demand.

This can be seen exemplified in Figure 42, which shows the DHW delivery temperature. In contrast to the series configuration, in this way it is possible to cover the DHW demand throughout the year, since, as can be seen, the delivery temperature is always around 53ºC.

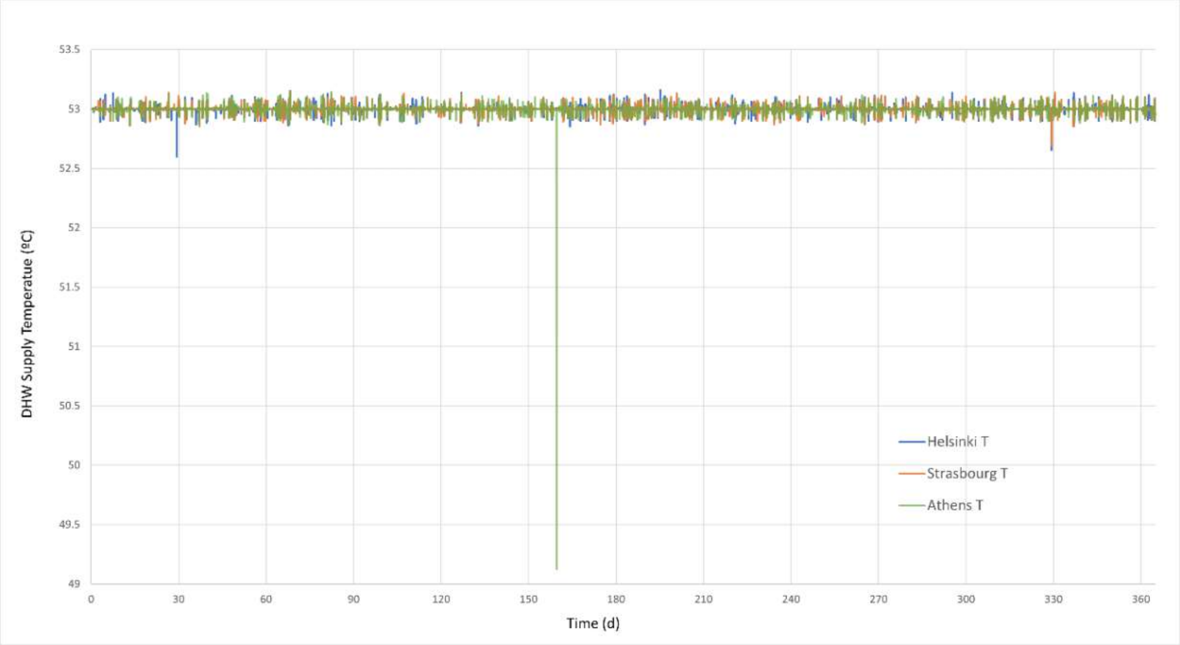


Figure 42: DHW supply temperature on the three locations during the year

Only the point mentioned in the previous graphics falls below the desired delivery temperature, but as explained, it only occurs in Athens for a very short period of time (10 minutes), and besides the minimum temperature reached would be more than 49ºC, which is a valid temperature for most applications requiring DHW, so no further emphasis will be placed on this event. However, it is clear that for future analysis and in order to improve the operation of the system, the heat pump controllers should be reviewed, in order to avoid these events and also to achieve a better overall performance.

4.3. OPERATIONAL KPIs

Next, an analysis of the performance will be carried out, using the parameters introduced on 3.6. In this section the behavior at the different locations will be compared with each of the configurations. As will be shown below, the overall behavior (comparing only what happens in the different locations) follows the same pattern as seen in the demand analysis. For this reason, the general differences in behavior in each of the cities will be discussed first, and then the differences due to the use of one configuration or another will be discussed in more detail.

4.3.1.Specific performance analysis

For this analysis the 3 main operations (heating, cooling, and WPW-HEX charging) have been isolated and studied separately, in order to obtain the total heat produced and the electrical power required in the heat pumps system for each of these operations. This will help to determine the specific SCOP for each of them as Table 7 represents.

Table 7: Performance for the different operations and configurations for each location

OPERATION		HELSINKI		STRASBOURG		ATHENS	
		SERIES	PARALLEL	SERIES	PARALLEL	SERIES	PARALLEL
HEATING	$Q_{condenser}$ (kWh/a)	7973.88	7781.11	4667.22	4490.55	912.97	875.28
	$P_{electric}$ (kWh/a)	2615.94	2514.33	1398.34	1334.88	237.99	223.55
	$SCOP_{heating}$	**3.05**	**3.09**	**3.34**	**3.36**	**3.84**	**3.92**
COOLING	$Q_{evaporator}$ (kWh/a)	159.98	147.79	535.86	498.81	3333.87	3249.44
	$P_{electric}$ (kWh/a)	67.58	71.46	224.20	232.23	1358.34	1418.95
	SEER	**2.37**	**2.07**	**2.39**	**2.15**	**2.45**	**2.29**
WPW-HEX CHARGING	$Q_{condenser}$ (kWh/a)	3854.29	3289.72	3818.43	3265.55	3921.38	3775.89
	$P_{electric}$ (kWh/a)	1716.52	1487.50	1697.01	1476.31	1728.21	1663.65
	SCOP DHW	**2.25**	**2.21**	**2.25**	**2.21**	**2.27**	**2.27**

The highest energy values for heating operation can be observed for Helsinki and for cooling operation in Athens, following the demand of the building seen in Table 5. The values of heating operation are slightly lower in parallel than in series because the temperature difference at the inlet and outlet of the heat pumps is lower: the supply temperature is slightly lower compared to the values of the series operation, (remember that in the series mode a higher temperature can be reached), which means that less heat is produced during this operation. This lower temperature difference, coupled with the lower pressure losses of the parallel configuration explained in 3.5 result in a lower electrical input required to achieve the same objective. Therefore, as there is an energy saving, the saving will also be economical. The lowest SCOP for the heating operation is about 3 for Helsinki and starts to increase in Strasbourg and Athens, marking the highest of 3.92 in Athens, being always higher in parallel mode than in series. This behavior will be explained later on the SCOP analysis.

The values during cooling operation are almost the same when compared by configuration, since in all cases the system is designed to produce a 6K decrease the evaporator side, so the difference between configurations is minimal. The SEER values are slightly lower than the SCOP, as explained in the theoretical framework, so they are also valid values [18]. The low SEER values in parallel mode can be explained by the fact that as the indoor temperature is generally higher (especially in Athens as seen in Figure 27), the return water temperature will be slightly higher as well, and as the heat pumps work to give the same 6K thermal lift, they will require more energy to achieve this.

It is noteworthy to mention that the values of thermal energy rejected (i.e. heating in the condenser side for heating and WPW-charging operations, and cold in the evaporator side for cooling operation), are slightly higher than the final thermal demands delivered to the building seen on Table 5. This is because these values correspond to the total heat generated in the heat pumps, without considering the heat losses, which can occur in the two circuits (from the heat pumps to the hydronic circuit in the condenser/evaporator, and the other from the hydronic circuit to the apartment in the heat terminals). This highlights that these circuits are not 100% effective and are subject to heat losses in the pipes during the circulation of the heated water.

The difference of the values during the charging the WPW-HEX operation can be understood by what is explained in 4.2.1 and 4.2.2. In series, having the same boundary conditions, the WPW-HEX charging operates in the same way in three locations, obtaining very similar results as expected. In parallel, these values are significantly lower, since, as seen above, the average SoC is higher, which means that it will have a charging need throughout the year. The difference in values between Helsinki and Strasbourg (which have the same behavior) and Athens, (which requires more energy throughout the year) can also be explained with the above discussion. Athens, operating most of the time with only 3 HP blocks for charging the WPW-HEX, has in general a lower first cell temperature, making it necessary to charge it more frequently. In this way its behavior resembles that of the series configuration, obtaining similar values.

The low performance in the WPW-HEX charging operation can be also explained. This is mainly due to two reasons: first, the target setpoint temperature after the heat pumps to charge the WPW-HEX is higher than the required to cover the thermal demand of the building. Thus, a higher electrical power will be needed. In addition, since the PCM is already at a much higher temperature than the apartment (about an average of 50ºC compared with about 20ºC on the apartment), the temperature difference at the inlet and outlet of the WPW-HEX will be low, meaning that little heat will be transferred to the PCM (not because the system is performing poorly, but because it is required to do so).

This can be reflected especially in the case of Strasbourg in series configuration (as heating and charging operations have similar values).

Here the WPW-HEX charging operation requires higher electrical input (1691 kWh/a vs 1398 kWh/a) which is reflected in a lower heat transfer (3818 kWh/a vs 4546 kWh/a), resulting in a lower SCOP. Even so, this value is around 2, which is a bit more than the double of the most efficient conventional systems [32], such as condensing boilers, so in principle it would still be a system.

4.3.2. SCOP analysis

In this section the total heat and total electrical input of each of the heat pumps is reported in Table 8 as well as the annual SCOP at each of the locations. As expected, in series configuration HP 1 produces the most heat, as it is switched on whenever there is demand in the building. followed by HP 2, which also frequently covers the remaining demand. In parallel, the first heat pump block also produces the most heat, as it is also the one that is switched on the longest, but it can be seen that the other HP blocks produce more heat in Helsinki and partly also in Strasbourg, while in Athens they serve only as backup. This will be discussed in more detail in the next subsection.

Table 8: SCOP for the annual operation on the different configurations and locations

HEAT PUMP BLOCK		HELSINKI		STRASBOURG		ATHENS	
		SERIES	PARALLEL	SERIES	PARALLEL	SERIES	PARALLEL
HP 1	$Q_{condenser}$ (kWh/a)	7024.93	3806.94	6127.94	3958.33	6328.48	5672.50
	$P_{electric}$ (kWh/a)	2276.47	1262.47	1971.37	1232.66	1985.93	1575.28
HP 2	$Q_{condenser}$ (kWh/a)	4076.08	2549.55	2128.71	1420.36	904.48	634.58
	$P_{electric}$ (kWh/a)	1681.10	922.25	909.07	550.19	417.76	289.36
HP 3	$Q_{condenser}$ (kWh/a)	722.42	2614.75	596.70	1525.86	721.50	1097.11
	$P_{electric}$ (kWh/a)	361.22	944.81	299.00	593.61	355.72	480.06
HP 4	$Q_{condenser}$ (kWh/a)	149.35	2614.75	131.53	1525.86	187.05	1097.11
	$P_{electric}$ (kWh/a)	82.45	944.81	68.58	596.61	95.22	480.06
TOTAL	$Q_{condenser}$ (kWh/a)	11972.79	11585.99	8984.87	8430.41	8141.50	8501.30
	$P_{electric}$ (kWh/a)	4401.25	4074.33	3248.02	2973.08	2854.63	2824.75
SCOP		**2.72**	**2.83**	**2.77**	**2.84**	**2.86**	**3.01**

Here, in addition to the differences in the heat produced in each of the HP, which will be analyzed later in terms of operating time, it is worth noting that along the lines of the previous subsection, in the series configuration more heat is produced in the condenser side (and therefore more electrical input is required) than in the series configuration. This is due to the same reason as before. Since the series configuration is capable of reaching higher temperatures, a greater amount of heat will be needed in the capacitors to reach it. Whereas the maximum temperature reached with the parallel configuration is lower than in series, therefore, a lower amount of heat will be transmitted. The only city that differs from this behavior is Athens, and this is due to the circulation mass flow already mentioned, as it has by far the shortest operating time for heating, and therefore the longest time the circulation mass flow runs through the heat pumps. And since this circulation mass flow is much greater in parallel than in series, more heat will be transmitted to it, causing this difference. But despite this difference, it can be observed that the compressor input is still lower, following the lines of the other two locations, so the overall behavior results in more heat and electrical energy being produced with series operation. (So the behavior on the condenser side in Athens can be understood as an isolated case and for simulation purposes).

It can also be observed that the SCOP follows the pattern mentioned in the previous subsection. Athens is the highest, followed by Strasbourg and finally Helsinki. This difference is because of the cold ambient temperature in Helsinki (and also Strasbourg), that makes the thermal demand in the building higher due to higher thermal losses. Therefore, the heated water exchanges more heat with the building and returns at a lower temperature (the return temperature of the building will be the same temperature that enters the first heat pump block), thus, being at a lower temperature, the temperature lift to reach the target supply temperature will be higher, which translates into a higher electrical input. This is coupled with the fact that, as explained in 3.4.2 the target temperature also depends on the outdoor temperature (the lower the outdoor temperature, the higher the setpoint temperature), which further increases the temperature difference in cities like Helsinki.

The difference between the annual SCOP in the three locations is not as great as it might seem at first (in the previous subsection, the highest difference in heating operation was 0.87 and the final one is only 0.29). This is due to the fact, that although hot cities like Athens perform much better in heating operation than cold cities, they work much more frequently in cooling operation, which as seen before, has a lower efficiency (SEER) than heating operation. So, the final SCOP difference is not that big, but it is still along the lines of what has been said above.

Differentiating between configurations, parallel shows a higher SCOP in all locations, and as mentioned before, due to a lower heating/cooling production in all operations and less pressure losses on the heat pumps, less electricity input is required throughout the year, thus obtaining energy and cost savings, and since in 2022 the average energy price on Austria was around 0.23€/kWh [33], obtaining for Helsinki for example a saving of:

$$\begin{aligned} Cost\ savings &= 0.23 \cdot P_{\mathrm{el,ser}} - 0.23 \cdot P_{\mathrm{el,par}} = 0.23 \cdot (4401.25 - 4074.33) \\ &= 75.2€ \end{aligned} \quad (23)$$

Therefore, with the parallel configuration, an annual cost saving of around 75€ could be achieved. Although, as what the aim of the work is to create a system that can switch from series to parallel automatically, looking for the highest efficiency, cost savings and the best overall performance of the system when meeting the desired setpoints, the economic aspect is not the only one to be taken into account, and a first approach to this automatic system will be proposed later on, based on the results obtained.

4.3.3. Operation time analysis

In addition to the above analysis, it is interesting to quantify for how long each HP block is in operation. This has been carried out assuming that the heat pumps are switched on if they generate more than 1.1 kW of heat on the condenser side, as this is their nominal output (see 3.1

Table 9: Operation time analysis of the HPs for the different configurations and locations

HP BLOCK	HELSINKI		STRASBOURG		ATHENS	
	SERIES	PARALLEL	SERIES	PARALLEL	SERIES	PARALLEL
HP1 (Hours)	3029	1704	2718	1869	3125	2976
HP1 (%)	34.58	19.45	31.03	21.34	35.67	33.97
HP2 (Hours)	2077	1122	1083	654	444	308
HP2 (%)	23.71	12.80	12.36	7.46	5.07	3.51
HP3 (Hours)	380	1144	308	697	362	521
HP3 (%)	4.33	13.05	3.51	7.96	4.13	5.94
HP4 (Hours)	74	1144	66	697	94	521
HP4 (%)	0.84	13.05	0.75	7.96	1.07	5.94
TOTAL (Hours)	**5560**	**5112**	**4174**	**3917**	**4025**	**4324**
TOTAL (%)	**63.46**	**58.36**	**47.64**	**44.71**	**45.94**	**49.36**

Having a look at Table 9, as expected, looking at the heat released in the condenser side, for series configuration HP 1 is the one that runs the longest, HP2 turns on with lower frequency, while HPs 3 and 4, which support heating and WPW-HEX charging, have the shortest running time. In parallel, HP1 is the one that is on the longest throughout the year, while HP2 is on slightly less time than HP 3 and 4 (which have the same time since their controllers are identical), due to the impossibility of heat pump 2 to provide cooling and WPW-HEX charging, as mentioned in 4.2.2. This is accentuated and makes the biggest difference in Athens, since it is the city that would have to provide this demand the longest. Helsinki is the city where the highest percentage of the time the HPs are on, while Strasbourg and Athens have a similar running time, due to the large amount of cooling time in Athens At the end it can be seen that the differences between configurations for each location are minimal, and these differences can be explained in the same way as done for point 4.3.2, as they follow the same pattern. This can be seen in more detail in Table 10, Table 11 and Table 12, where each of the operations is isolated and listed for a better understanding.

Here, it should be noted that the number of total hours, and therefore the total percentage, does not refer to the number of hours in relation to the whole year, but to the number of hours in which the heat pumps are in operation, also taking into account that they can operate simultaneously.

Table 10: Operation time analysis of the HPs for heating operation for the different configurations and locations

HEATING OPERATION						
HP-BLOCK	**HELSINKI**		**STRASBOURG**		**ATHENS**	
	SERIES	**PARALLEL**	**SERIES**	**PARALLEL**	**SERIES**	**PARALLEL**
HP1 (Hours)	2042	1225	1510	1143	394	471
HP1 (%)	23.31	13.98	17.24	13.05	4.50	5.38
HP2 (Hours)	1520	763	547	285	22	5
HP2 (%)	17.35	8.71	6.24	3.25	0.25	0.06
HP3 (Hours)	184	762	85	284	18	4
HP3 (%)	2.09	8.70	0.97	3.24	0.21	0.05
HP4 (Hours)	52	762	31	284	11	4
HP4 (%)	0.59	8.70	0.35	3.24	0.12	0.05
TOTAL (Hours)	**3797**	**3512**	**2172**	**1996**	**445**	**484**
TOTAL (%)	**43.34**	**40.09**	**24.79**	**22.79**	**5.07**	**5.53**

Table 11: Operation time analysis of the HPs for cooling operation for the different configurations and locations

COOLING OPERATION						
HP-BLOCK	**HELSINKI**		**STRASBOURG**		**ATHENS**	
	SERIES	**PARALLEL**	**SERIES**	**PARALLEL**	**SERIES**	**PARALLEL**
HP1 (Hours)	105	106	355	352	2045	2211
HP1 (%)	1.20	1.21	4.05	4.02	23.34	25.23
HP2 (Hours)	0	0	0	0	0	0
HP2 (%)	0	0	0	0	0	0
TOTAL (Hours)	**105**	**106**	**355**	**352**	**2045**	**2211**
TOTAL (%)	**1.20**	**1.21**	**4.05**	**4.02**	**23.34**	**25.23**

Table 12: Operation time analysis of the HPs for WPW-HEX charging operation for the different configurations and locations

PCM CHARGING OPERATION						
HP-BLOCK	**HELSINKI**		**STRASBOURG**		**ATHENS**	
	SERIES	**PARALLEL**	**SERIES**	**PARALLEL**	**SERIES**	**PARALLEL**
HP1 (Hours)	882	373	854	374	686	294
HP1 (%)	10.07	4.26	9.74	4.27	7.83	3.36
HP2 (Hours)	558	359	536	369	422	303
HP2 (%)	6.36	4.09	6.12	4.21	4.82	3.45
HP3 (Hours)	196	382	223	413	344	517
HP3 (%)	2.24	4.36	2.54	4.71	3.92	5.90
HP4 (Hours)	23	382	35	413	84	517
HP4 (%)	0.26	4.36	0.40	4.71	0.95	5.90
TOTAL (Hours)	**1658**	**1495**	**1647**	**1569**	**1535**	**1630**
TOTAL (%)	**18.93**	**17.06**	**18.80**	**17.91**	**17.52**	**18.60**

As before, total time and percentages do not refer to total annual time. To know this percentage, in the series configuration, it would be necessary to look at the values of HP 1, as it is the one that is switched on whenever there is an existing demand, meaning that it shows the total operation time. Thus, it can be determined that the HPs are in operation in Helsinki for 34.58% of the year, in Strasbourg for 31.03% and in Athens for 35.67%. In the same way the same analysis can be done with the values of each operation. For example in Helsinki, the heating operation represents 23.31% of the year, cooling only 1.2% and WPW-HEX charging 10.07%. The same analysis can be done for the rest of the cities, obtaining a lower percentage for Strasbourg and almost null for Athens, and practically the same for WPW-HEX charging in all three locations.

In parallel, the analysis is more complicated to do, as the HP blocks tend to operate simultaneously, but to perform the analysis, the values of the first two HP blocks can be taken as a reference, as they are the ones that are almost always switched on. In this way, the analysis results in values very similar to the standard values, but slightly lower, as we have seen throughout the analysis.

The analysis is generally in line with expectations, with a higher percentage of operation in Helsinki for heating, in Athens for cooling and of WPW-HEX charging practically the same in all cases, following the expected guidelines. As explained throughout the analysis, the parallel configurations have shorter time in each of the operations in Helsinki and Strasbourg, while the opposite is the case in Athens. This longer operating time in Athens is due to the fact that it has been assumed that a heat pump block is operating when it is capable of generating 1.1 kW of heat. Therefore, once again, due to the higher circulation mass flow, this value is reached in the heat pumps more frequently and is counted as operation (as could be seen in Table 8, more heat was produced on the condenser side for parallel configuration). However, it is observed that the general behavior is as expected, and that the following equation is fulfilled to verify correct operation in all the cases:

$$WPW - HEX_{\text{op,time}} = Total_{\text{op,time}} - Heating_{\text{op,time}} - Cooling_{\text{op,time}} \tag{24}$$

In series configuration the heat is mainly produced using the first two HPs, with HPs 3 and 4 serving as back-up to achieve the desired temperature in specific cases. For the cooling operation, in Helsinki is practically negligible, meanwhile in Athens it represents the highest percentage of its time operation (a 23.34% of the 35.67% of the total, resulting in more than a half). It must be noted again, that for cooling, although the second HP is also responsible for this operation, it never switches on, due to the hysteresis set in its controller, which is perhaps too restrictive. For the WPW-HEX charging operation, as mentioned above, it is practically the same in all three cities, and accounts for about 10% of the time. Here in Athens HPs 3 and 4 are used more frequently than in Helsinki and Strasbourg (especially HP 4). This is because the water setpoint temperature for the indoor in Athens is lower than in the other two cities, so if a WPW-HEX charge is required at a time when there was demand in the apartment and consequently, the water temperature is not that high, it has to be heated when passing through the third or fourth pump in order to meet the charging WPW-HEX demands. As can be seen, blocks 3 and 4 are practically never put into operation, so in ANNEX 4 an analysis will be carried out in the city of Strasbourg (as it has a milder climate and therefore the results may be more representative) removing these two blocks of heat pumps to see how the system performs with only the first two and whether it would be sufficient to validate the correct functioning of the system.

For the parallel mode, in heating operation, it is worth noting that in Helsinki, although the first HP block operates the longest, the other three are in operation for a significant percentage of the time, as a higher heating requirement is needed. In Strasbourg, the percentage of use of these heat pumps is lower, and in Athens it is negligible, as only one block is needed to achieve the setpoint temperature (as can be seen in series too). For cooling, the opposite behavior can be seen, in the same way as for the series configuration, only the first HP block is used, and with a higher percentage in Athens than in the rest. In addition, as the average indoor temperature is higher in parallel mode, more cooling is required than in series mode. For the WPW-HEX charging operation, all heat pump blocks should operate for the same time (and in fact have very similar operating times), but it can be observed that HP 2 is clearly the one that operates the shortest time (seeing this difference especially in Athens). This is due to the already explained behavior because of the controller of this second heat pump block. This means that since it does not switch on for cooling operation (which can also be seen in serial operation), it is not able to perform the WPW-HEX charging function either.

4.4. ENVIRONMENTAL ANALYSIS

This section will compare the CO_2 emitted throughout the year by the heat pump (operating both in series and in parallel), with the CO_2 that would be emitted by a conventional system operating under the same conditions. This system, which is shown schematically in Figure 43 consists of a gas boiler with a nominal heating capacity of 4.5kW and an efficiency of 90%, used to cover the building's thermal demand and DHW consumption, and a conventional air conditioning unit, with a nominal cooling capacity of 2kW and a SEER of 2.6 to supply the building's cooling demand. In addition, latent heat storage has been replaced by a conventional water storage tank with a volume of 120 liters.

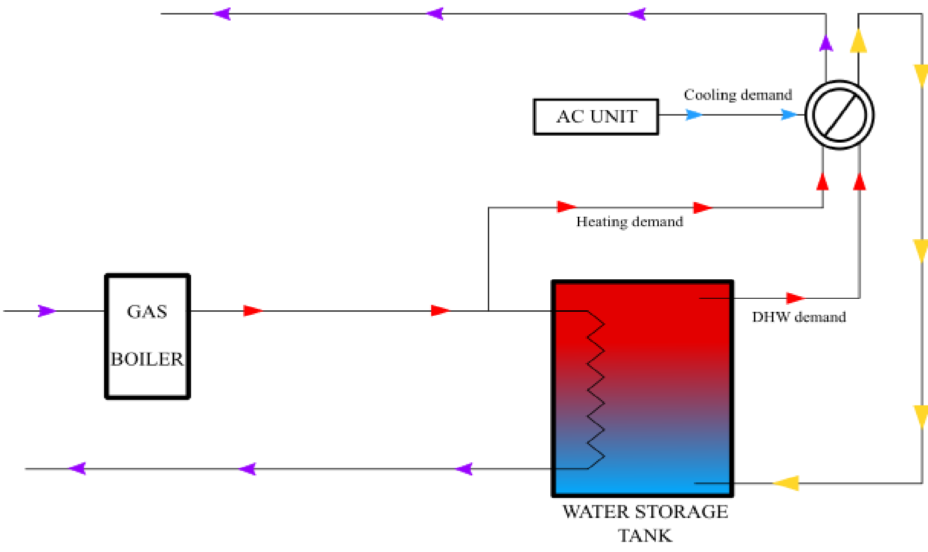


Figure 43: Conventional system schematic

For the calculation of CO_2 production, the following equation will be used, which relates the energy used to generate the entire demand to a factor that depends on the type of technology used, as explained below:

$$M_{CO_2}\left(\frac{g}{a}\right) = f_{CO_2}\left(\frac{g_{CO_2}}{kWh}\right) \cdot E\left(\frac{kWh}{a}\right) \tag{25}$$

That said, a distinction has to be made between the CO_2 emission calculation of the heat pump and the conventional system. The heat pump does not generate any CO_2 emissions during its operation, but the generation of electricity necessary for its operation does. Therefore, the emission factor will be measured in gCO_2/kWh_{el}, i.e., amount of CO_2 produced per kilowatt-hour of electrical input. It is also worth noting that depending on where this electricity comes from, the emission factor will vary (in countries where the power is mainly produced from sustainable energy sources this factor will be lower, and in countries where it comes mainly from fossil fuels it will be higher). Therefore, two distinctions will be made, one using the Austrian electrical mix, where energy is generated mainly from hydropower, so it has lower carbon intensity, and thus, a factor of $202 gCO_2/kWh_{el}$ [34]. Whereas, in other European countries, such as Poland, fossil fuels play a critical role in the electricity mix, so an emission factor for Europe, according to the EU-27 of $265 gCO_2/kWh_{el}$ is considered [35].

The annual electrical input values for each of the configurations and each of the locations have already been seen in 4.3.2, so the amount of CO_2 emitted for the heat pump system will be using the Austrian and European mix respectively:

$$M_{CO_2}(HP) = \{202{,}265\} \cdot P_{\mathrm{el,HP}} \tag{26}$$

In the case of the conventional system, it is different, as the gas-fired boiler does generate CO_2, since the energy input of this system is natural gas with an emission factor of 268 gCO_2/kWh_{gas} [34]. This only covers the heating and DHW demands, so in addition, the cooling production has to be considered. In this case, as it is an electric air conditioning unit, it works in the same way as HP. To calculate the total mass of CO_2 generated it has been assumed that the efficiency of the gas boiler is 90%, so the values of heat produced have to be multiplied by 1.1 in order to obtain the total amount of natural gas burnt, while the efficiency (SEER) of the electric air conditioning unit is 2.6, meaning the values of cooling produced have to be divided by 2.6 in order to obtain the electrical input. In Table 13 those values (obtained by simulating this system over the course of a year.) can be seen, and by comparing them with the demand and operation tables of the heat pumps it can be seen that they follow the same pattern and that this system is able to cover the entire demand of the building as well.

Table 13: Heating, cooling and electrical input values for the conventional system

	Q_{boiler} (kWh/a)	Q_{fuel} (kWh/a)	$Q_{cooling}$ (kWh/a)	$P_{el,cooling}$ (kWh/a)
HELSINKI	10787.69	11986.32	252.73	97.2
STRASBOURG	8086.95	8985.5	645.1	248.12
ATHENS	5570.13	6189.03	3507.96	1349.21

The mass emitted for the conventional system is thus calculated using the following equation for the Austrian and European mix respectively:

$$M_{CO_2}(conventional\ system) = 268 \cdot Q_{\text{fuel}} + \{202{,}275\} \cdot P_{\text{el,AC unit}} \qquad (27)$$

Finally, in Table 14 it can be observed the CO_2 values in tons emitted annually by each of the systems, using the Austrian and European mix.

Table 14: CO2 emissions during the annual operation

SYSTEM SIMULATED	MASS OF CO2 EMMITED DURING OPERATION (t/a)	
	AUSTRIAN MIX	EUROPEAN MIX
	HELSINKI	
HP SERIES	0.89	1.17
HP PARALLEL	0.82	1.08
GAS BOILER + AC UNIT	3.23	3.24
	STRASBOURG	
HP SERIES	0.66	0.86
HP PARALLEL	0.60	0.79
GAS BOILER + AC UNIT	2.46	2.47
	ATHENS	
HP SERIES	0.58	0.76
HP PARALLEL	0.57	0.75
GAS BOILER + AC UNIT	1.93	2.02

Here it can be seen that the biggest difference is around 2.4 tons of CO_2 produced per year, which occurs in the case of Helsinki, with the parallel configuration, as this requires the least electrical input, and with the gas boiler, since it is the one that requires the most heat, and therefore, in which the most natural gas will have to be burnt. Meanwhile, the smallest difference occurs in Athens with the series configuration and the conventional, which is where the boiler works for the least time (since the AC unit almost always does), but even so, the difference is 1.25 tons of CO_2 per year.

So, it can be seen that the use of a heat pump system for the production of heating, cooling and DHW means a reduction from 1.2 ton of CO_2 ton to 2.4 tons of CO_2 emitted per year per each apartment, thus helping to meet the decarbonization targets set by the European Union. To this saving in GHG emissions, cost savings must also be added due to the price of CO_2 emission rights, which in 2022 were around €100/tonCO_2 [37], representing an economic saving of between €100 and €240 per year. It should also be noted that this reduction in CO_2 emissions, with its consequent cost savings, is for each family under the investigated boundary conditions of this work, so that on a larger scale (considering the whole building, neighborhood or city), it would mean a huge reduction in GHG emissions per year.

Chapter 5

Conclusions, recommendations and future outlook

The buildings stock, and therefore the production of space heating, space cooling and DHW account for a large share of final energy consumption in the EU. Of this energy, more than half is produced by burning fossil fuels. As a result, the building sector is one of the largest emitters of GHGs in Europe. So, in order to achieve the ambitious goals of decarbonization and energy efficiency set by the EU, heat pumps, alongside with latent heat storage, arise as an excellent choice for the production of heating, cooling and DHW.

The present work consists of a system of 4 HP blocks with two heat pump modules each, which can be connected automatically in series or in parallel. It also considers a WPW-HEX using Rubitherm RT55 as heat storage. Such a system is used for the production of space heating in winter, space cooling in summer and to supply the DHW demand. The system has been simulated both in series and in parallel separately in an 80m^2 apartment for a period of one year using a nominal supply temperature of 45ºC (equivalent to radiant floor heating/cooling) in three different cities (Helsinki, Strasbourg and Athens) to verify its performance under different climatic conditions and understand the behavior of both configurations , for the subsequent development of the control strategy that will enable the system to switch automatically between the two configurations.

The simulation analysis has shown that for heating operation, during the day (and especially in cold climates), due to the demanding conditions of indoor comfort temperature, the series configuration performs better, as it is able to reach higher water temperatures, thus the setpoint temperatures are met for a longer time. While the parallel configuration, due to the higher mass flow reaching the WPW-HEX, is able to keep it with a higher SoC over time. This makes the system able to perform space heating operation more often. This advantage is especially seen during the night, where the indoor setpoint temperatures are reached more often because they are lower than during the day (so a higher water temperature is not needed to reach them). For cooling operation, as the evaporator side is always connected in parallel, and operates to achieve the same temperature decrease, there is no difference between configurations. But for cooling and WPW-HEX charging operation, the parallel configuration performs better as it is able to charge the WPW-HEX further while keeping the indoor temperature at the desired levels. Despite these differences in the results between configurations, it has been possible to verify the correct functioning of both configurations when meeting the desired indoor and DHW delivery temperatures. In terms of performance and electrical consumption, it has been observed that the parallel mode, mainly due to the lower pressure losses in the heat pumps, shows a higher efficiency and lower electrical input, which will result in both energy and cost savings.

Finally, both configurations have been compared to each other and to a conventional HVAC system consisting of a gas boiler and an electric AC unit (present in the majority of households), in terms of CO2 emissions.

Firstly, it was found that as the parallel configuration requires less electrical energy it emits slightly less CO_2 than the series configuration. And secondly, that both configurations represent a substantial reduction in the amount of CO_2 emitted per year with respect to the conventional system, from 1 ton to 2.4 tons of CO_2 per year per studied apartment, depending on the location.

5.1. OPERATION GUIDELINES

With these results analyzed and understood, guidelines and possible improvements for the system can be given. Therefore, the following recommendations will be given as a starting point for how the automatic system should work depending on the climate zone, the season, the time of the day or the operation to be carried out.

5.1.1. Seasonal operation

As mentioned above, depending on the season of the year, it will be advisable to operate the system in one way or another. For winter, a series configuration would be advisable for cold climates in order to maintain the indoor temperature at the desired levels, for moderate climates depending on the outdoor temperature it could be switched between series or parallel (opting for a parallel configuration when the outdoor temperatures are not extremely cold), while for hot climates, the parallel configuration performs better as it is able to meet the desired temperatures with a lower energy cost.

As for the operation in the summer season, the result in the indoor temperature would be the same for both configurations. But for the cooling and charging operation of the WPW-HEX, the series configuration would be recommended, because as seen in the analysis, it is able to reach higher SoC levels with a lower electrical input, so to avoid constant switching between configurations it would be advisable to always use the parallel configuration during summer season.

For mid-season operation, if space heating is required, the chosen configuration would depend on the temperature difference with the outside, while if cooling is required, a parallel configuration would be chosen.

5.1.2. Daily operation

One way to optimize the above behavior would be to vary within the same season between series and parallel depending on the moment of the day. As a first approach, during winter on cold and mild climates, the series configuration could be used during the day, both for heating and WPW-HEX charging. As it can reach higher temperatures, is able to keep the indoor temperature at the desired levels for a longer time (as seen in Table 6: Time of the temperature below the desired values on the different locations and configurations for heating and cooling) and is able to deal better with drastic temperature drops. While at night it could be switched to the parallel configuration, as it has presented better indoor temperature values, and would charge the WPW-HEX at higher levels during that time. In this way, the higher WPW-HEX SoC has two clear advantages during the day. First of all, it avoids the occasional problems where the series configuration was not able to meet the DHW temperature due to a lower SoC. And secondly, as the WPW-HEX is more charged, fewer charging cycles will be needed during the day, which combined with the higher water supply temperature of the series configuration, will be able to keep the indoor temperature at the desired levels for a longer period of time. During the summer, as mentioned above, it would be advisable to always use the parallel configuration.

5.1.3. Demand-driven operation

Another approach could be depending on the type of demand inside the building. Keeping a series configuration to supply the heating demand on cold and mild climates (during day and night), and switch to a parallel configuration to charge the WPW-HEX. This would keep the WPW-HEX charged for a longer period of time, always providing the desired DHW temperature, and requiring less electrical input to maintain the WPW-HEX SoC at the required values. And this also would made that the indoor temperatures would not drop as much by not having to prioritize charging over heating as often. Here again, for cooling operation and therefore, cooling and WPW-HEX charging operation a parallel configuration would be always recommended.

In this way, possible guidelines have been given to maintain the demanded temperatures for heating, cooling and DHW at the desired levels depending on the needs of the building and always looking for energy, cost and GHG emissions savings. For mid-season operation and for a better system performance, the control strategy should be developed considering also the outdoor temperature, trying to operate in parallel whenever the desired indoor temperature levels can be guaranteed, for a lower energy consumption and therefore a more efficient system, both energetically and environmentally.

5.2. FUTURE OUTLOOK

Apart from the operation guidelines, the following considerations and recommendations, which have been discovered throughout the analysis of the results, must also be noted in order to implement future improvements in the final system.

First as it has been explained in section 4.1 it would be interesting to update the system to be able to provide space heating demand and WPW-HEX charging, without the need to prioritize one over the other, or if this is not possible, to try to affect the indoor temperature as less as possible by modifying the charging times or using the water after charging the WPW-HEX to provide space heating if it is at a sufficiently high temperature, for example.

Other changes to be made, which have been discovered through the simulations, are regarding to the control strategies of the first and second HP blocks, especially for parallel configuration. As explained in 4.1, the controller of the first HP block considers only the needs of WPW-HEX charging when performing the cooling and WPW-HEX charging operation, so sometimes only one heat pump module is switched on (as it is sufficient for WPW-HEX charging) but for cooling both would be needed. This is also coupled with the control strategy of the second HP block, since, as explained in 4.2, it has been discovered that it is very restrictive and, despite having a cooling demand inside the building, it never switches on. This causes two main problems, the first one is that the first HP block has to cover all the cooling demand (which also means more electrical input), which in cold places may be sufficient, but in hot climates it needs the support of another heat pump block (and even more if the controller of that first HP block is not fully optimized either). The other problem, which has been seen especially in the parallel configuration, is that being off for cooling, it is also unable to provide WPW-HEX charge even though there is demand, thus affecting the temperature inside the PCM and therefore the DHW delivery temperature.

Therefore, the strategy of both controllers should be checked to find a way to cover the cooling and WPW-HEX demands in the most efficient way, for instance, by default switching on one module of each of the HP blocks when there is cooling or cooling and WPW-HEX charging demand in order to cover both demands, and in case more power is needed, switching on the second module of the first HP block.

Finally, although it has already been explained that it will not affect the real performance of the system, and that it is only due to the reasons of the simulation, a way to run the system in parallel without the need to have such a large circulation flowrate should be implemented, because when generating a combined system that is able to switch from series to parallel automatically, this mass flow could cause a slow transient response, and therefore, a poor performance of the system.

Furthermore, the simulations and the analysis has been done here for the three locations with the same conditions (except for the outside temperature), but when implementing the final system, the special characteristics (e.g. tap water temperature or number of HP blocks to be installed) of each of the cities would have to be taken into account in the simulations, in order to achieve a system that adapts and works correctly in any climate conditions. With all these guidelines and recommendations, it should be possible to start to develop the automatic system in order to know its impact and its improvement with respect to a traditional solution.

Therefore, it can be concluded that the system studied, in addition to fulfilling its technical objective, represents a great improvement in terms of GHG emissions reduction and is therefore positioned as a great alternative for the production of heating cooling and DHW.

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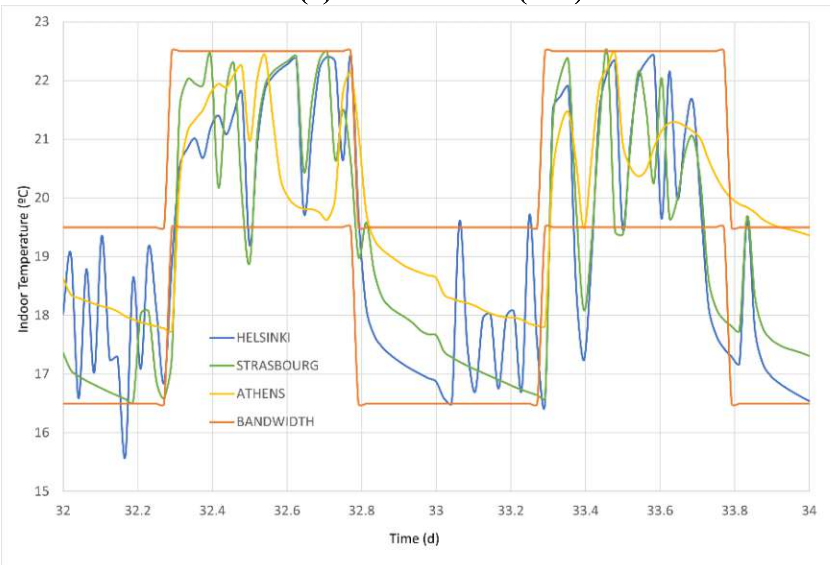
ANNEX 1

Detailed indoor temperatures

As can be seen throughout 4.1, the indoor temperature results are very similar between configurations, and in all cases meet expectations. However, for clarity and comprehension, a more detailed graphics will be introduced in this annex, comparing between cities and configurations in the period of two days over different seasons. Furthermore, for this analysis, instead of using as reference the set point temperatures of 18ºC, 21ºC and 25ºC respectively for night, day and cooling, the 3K bandwidth between which the temperatures can vary in each of the cases has been used to show clearly that the temperature almost always oscillates within the desired levels.

For this, Figure 44 shows the first two days of February per location for each of the configurations and Figure 45 these same days comparing between locations with the same configuration and with the outside temperature. This same analysis has been followed in Figure 46 and Figure 47 with the first two days of December (winter season still). For summer, the first two days August in Figure 48 and Figure 49 have been used and analyzed in the same way. Finally, to analyze the time between seasons, the first two days of October have been chosen, which can be observed in Figure 50 and Figure 51.

(a) Series winter (Feb)



(b) Parallel winter (Feb)

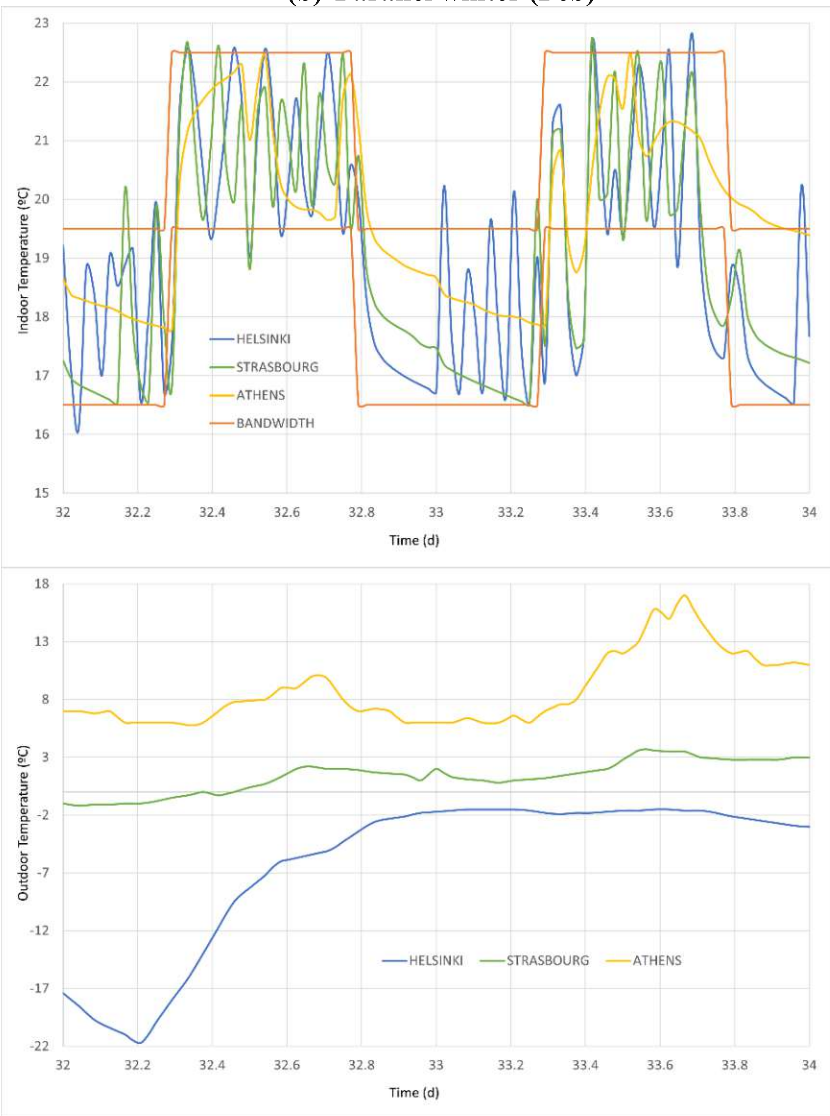
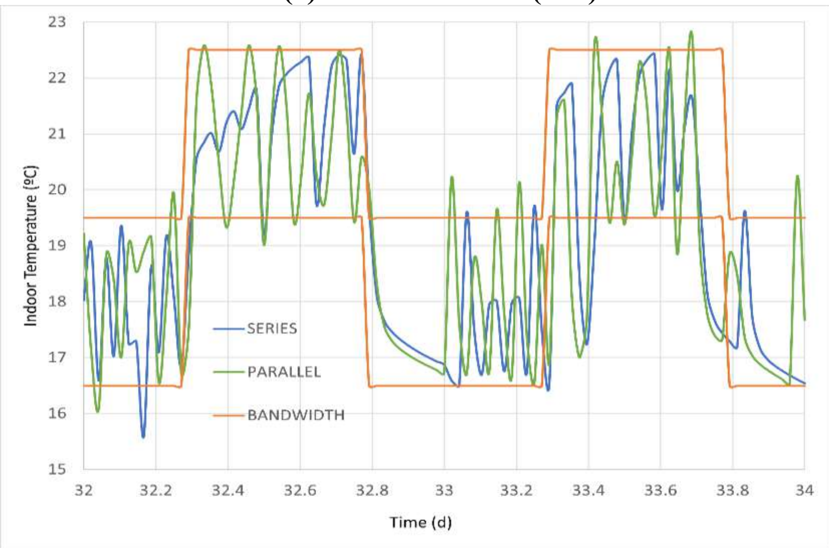
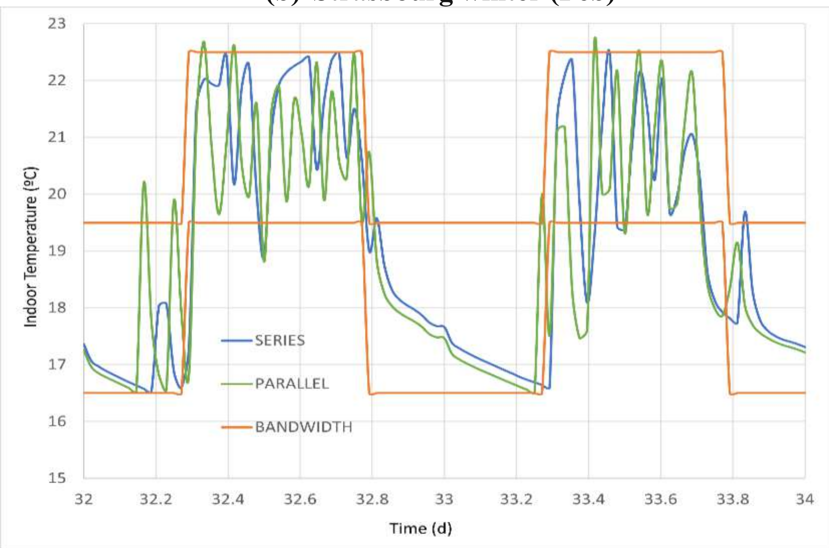


Figure 44: Indoor temperatures for two February days. Comparison between configurations.

(a) Helsinki winter (Feb)



(b) Strasbourg winter (Feb)



(c) Athens winter (Feb)

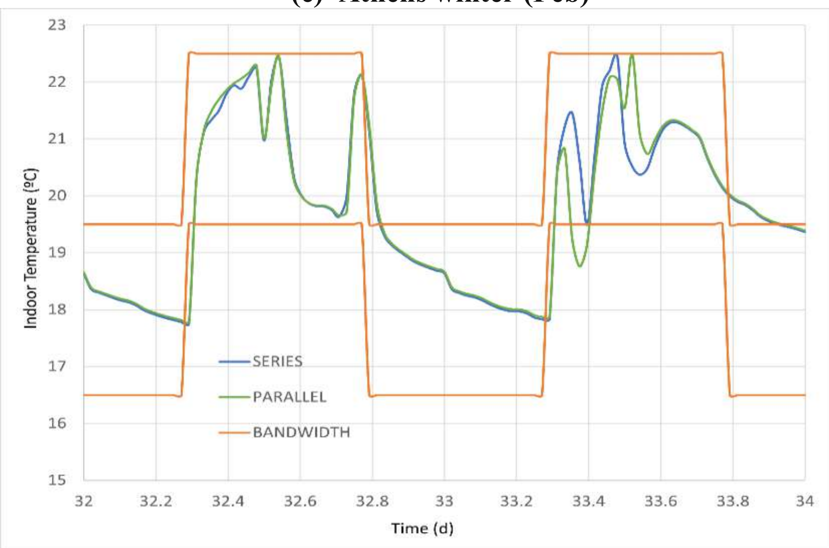
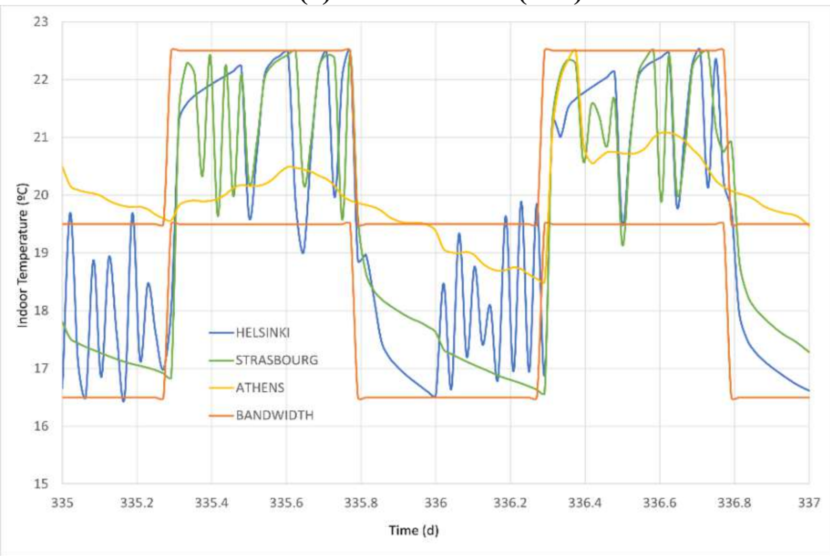
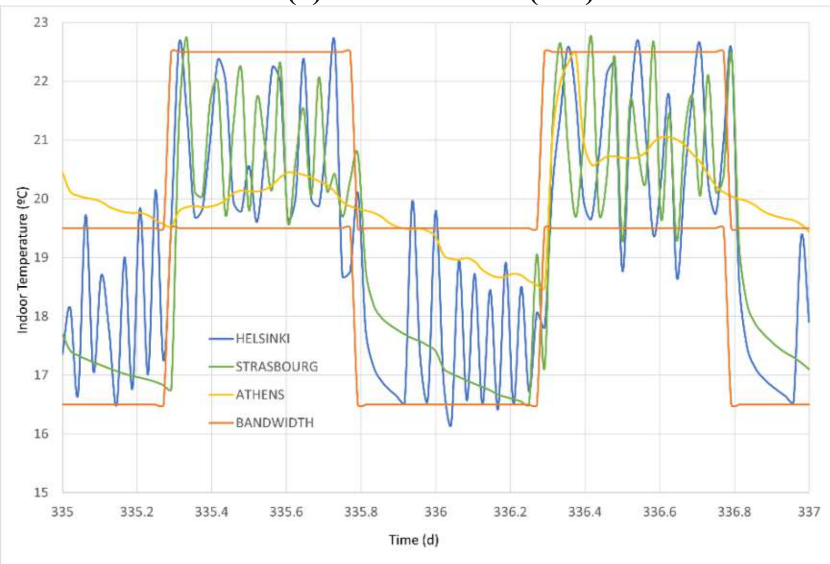


Figure 45: Indoor temperatures for two February days. Comparison between locations.

(a) Series winter (Dec)



(b) Parallel winter (Dec)



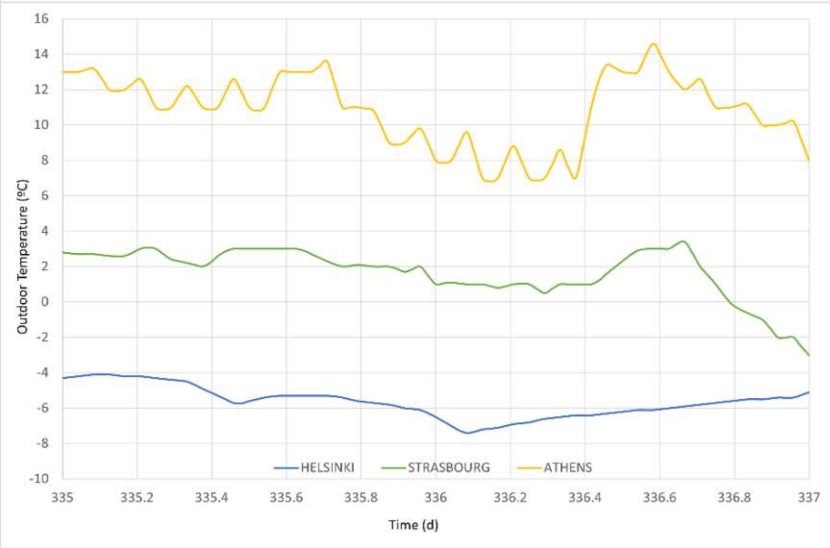
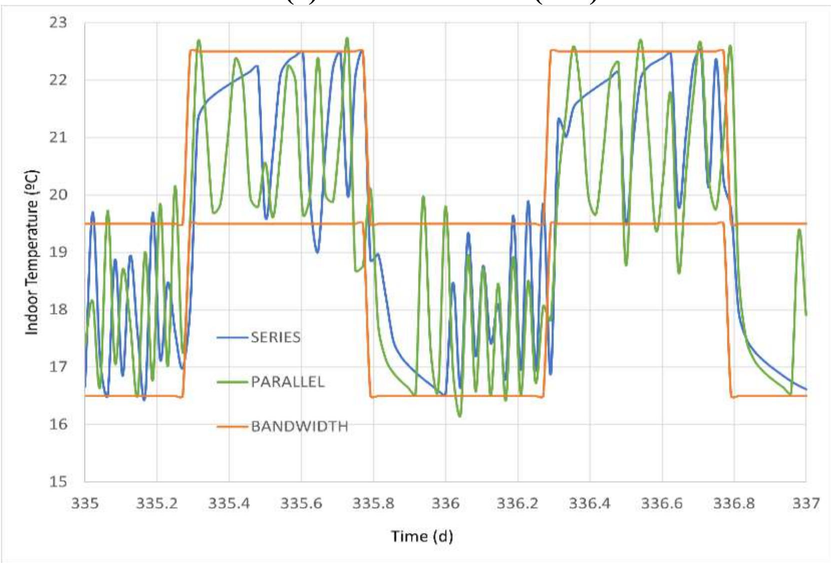
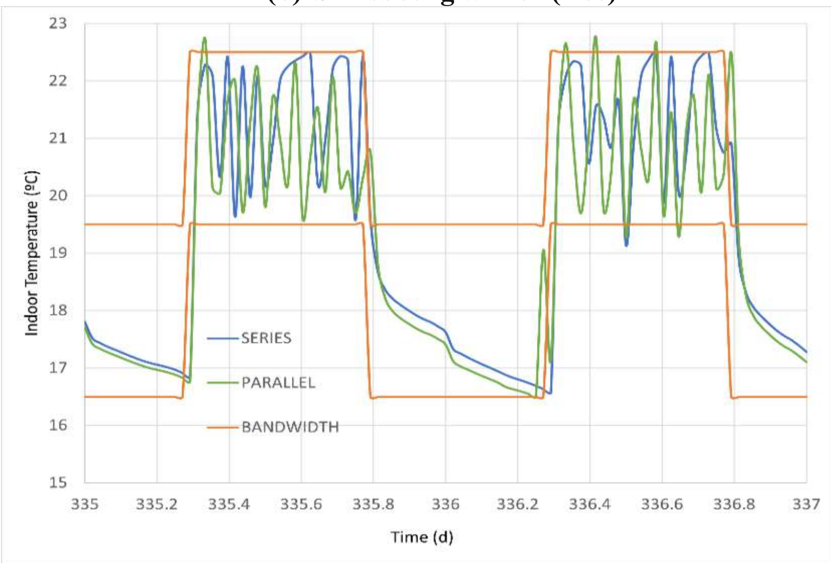


Figure 46: Indoor temperatures for two December days. Comparison between configurations

(a) Helsinki winter (Dec)



(b) Strasbourg winter (Dec)



(c) Athens winter (Dec)

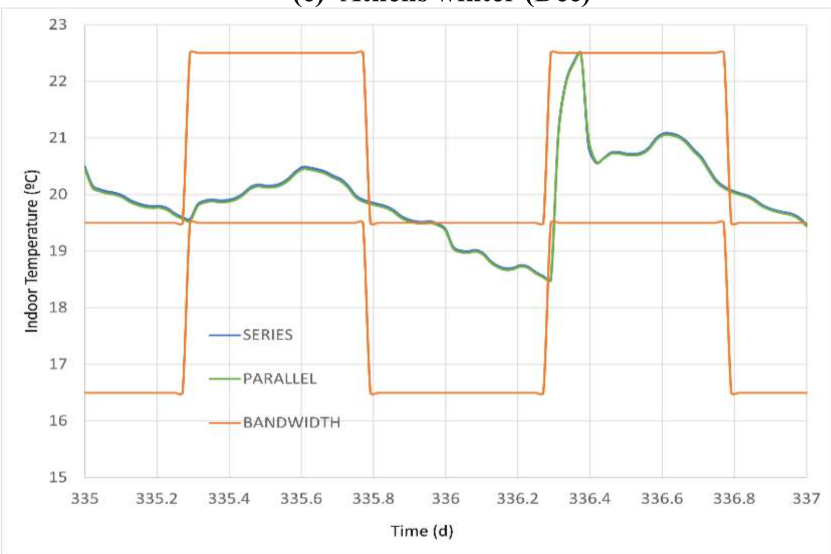
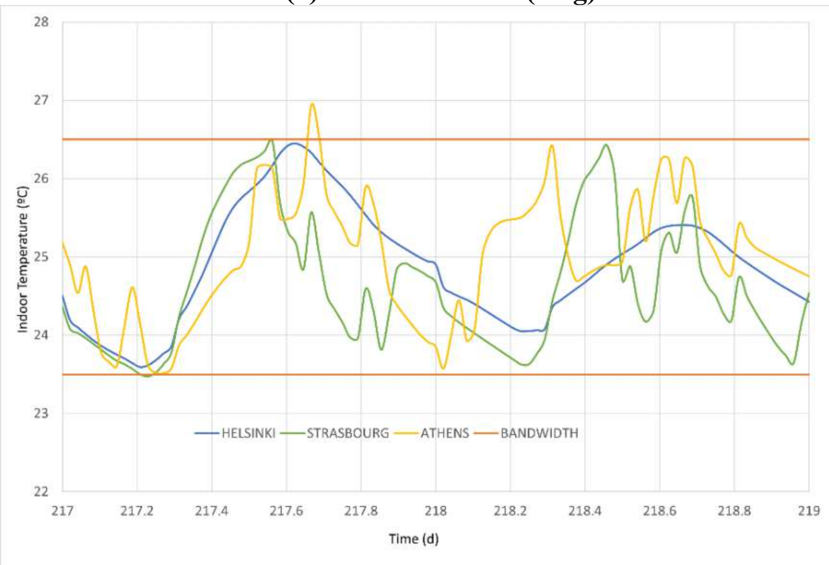
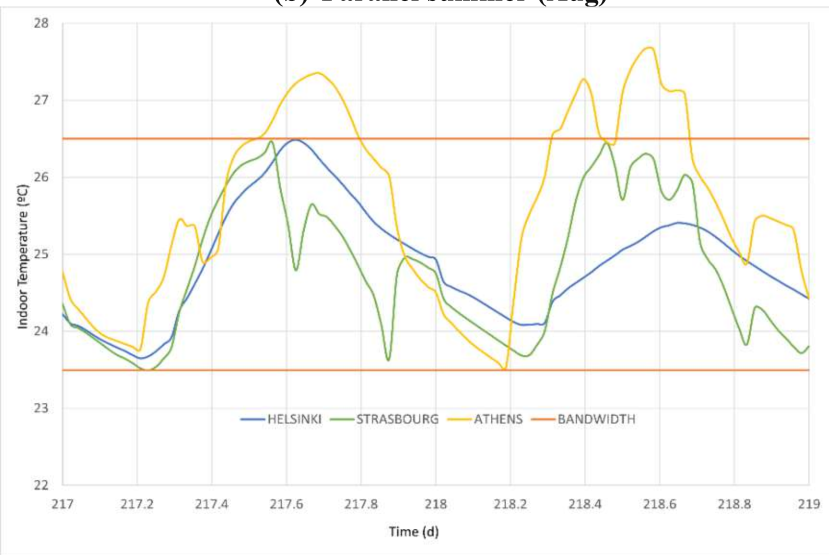


Figure 47: Indoor temperatures for two December days. Comparison between locations

(a) Series summer (Aug)



(b) Parallel summer (Aug)



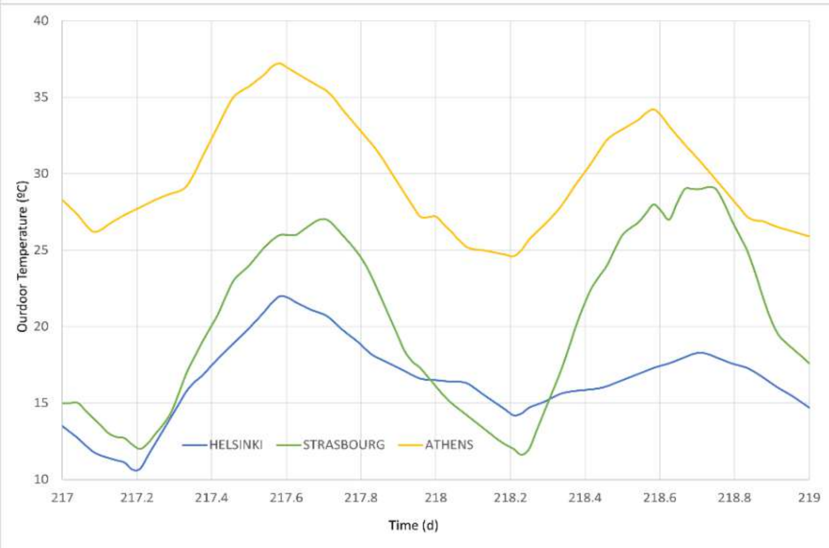


Figure 48: Indoor temperatures for two August days. Comparison between configurations

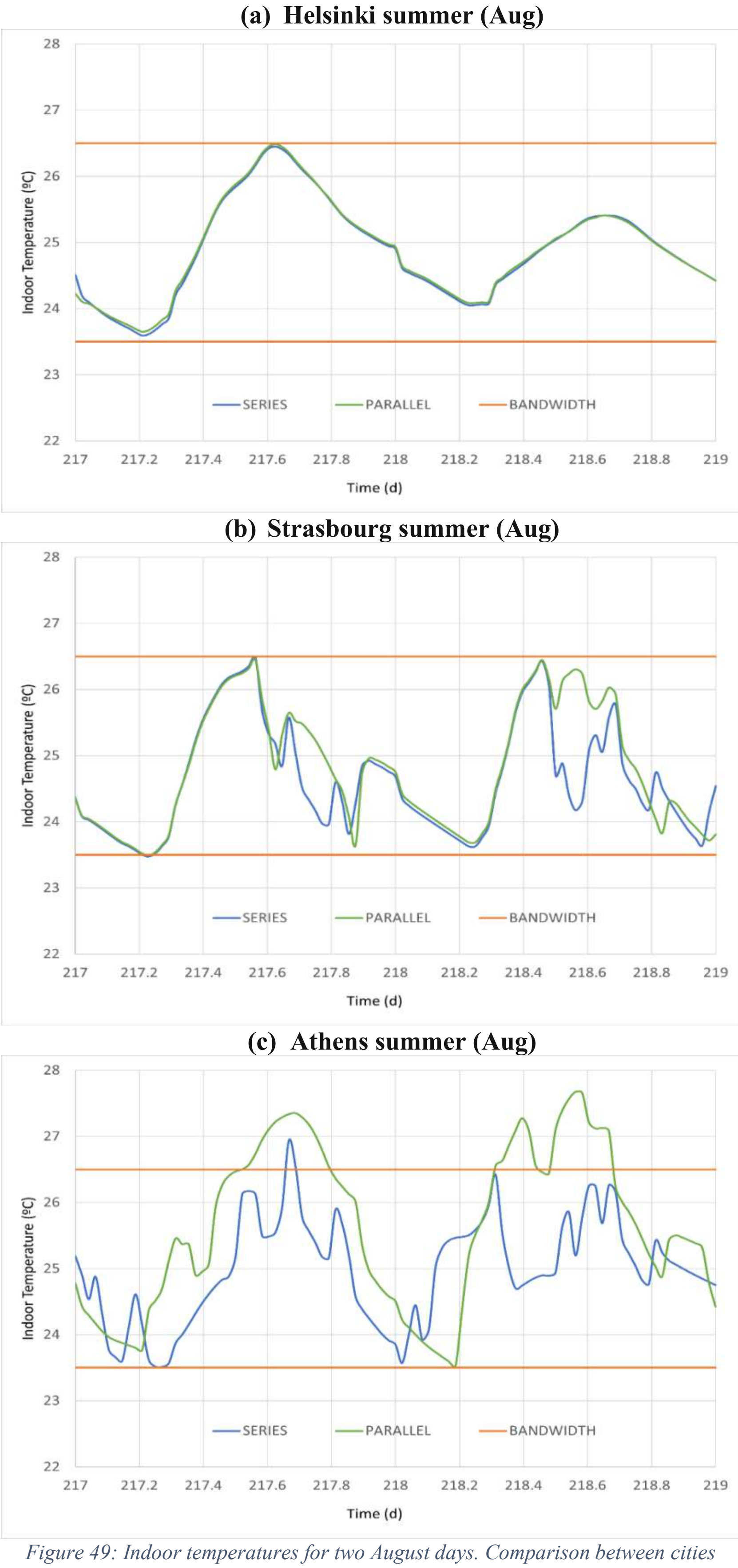
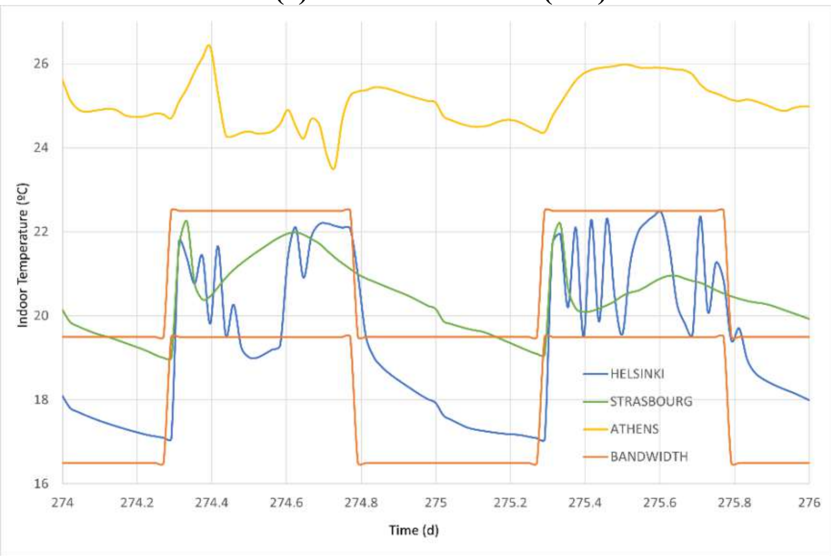


Figure 49: Indoor temperatures for two August days. Comparison between cities

(a) Series midseason (Oct)



(b) Parallel midseason (Oct)

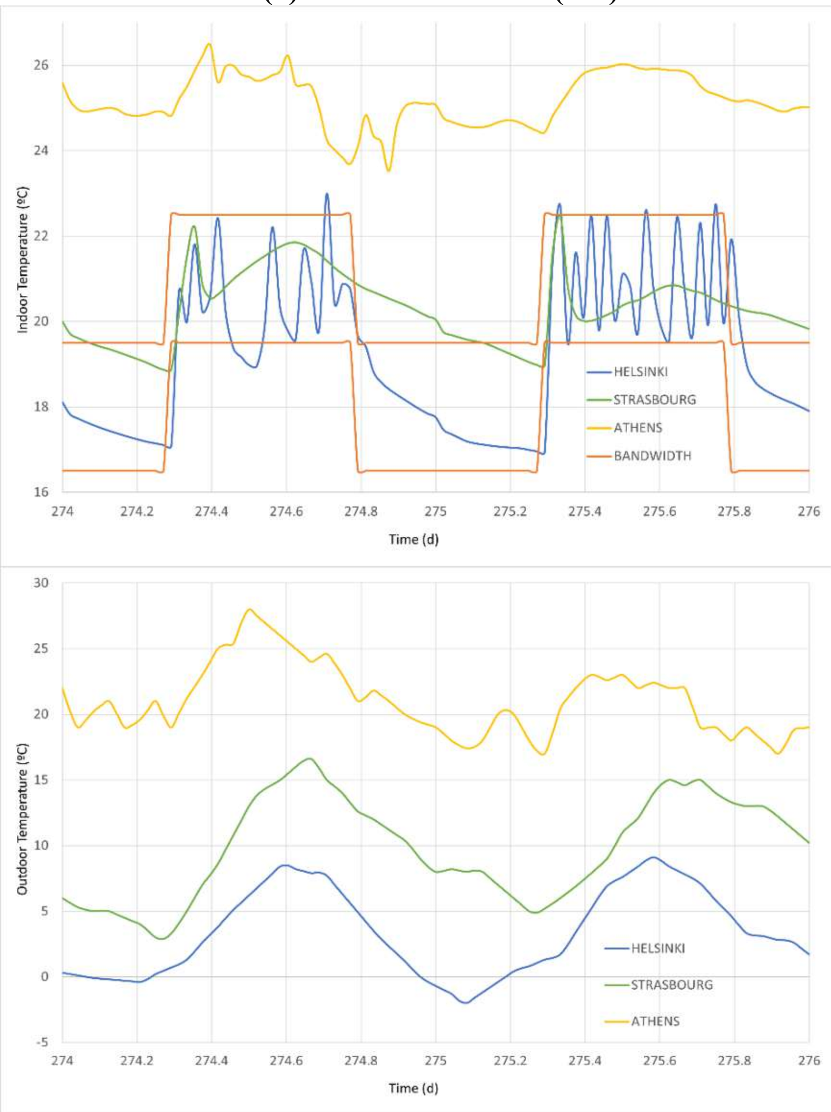
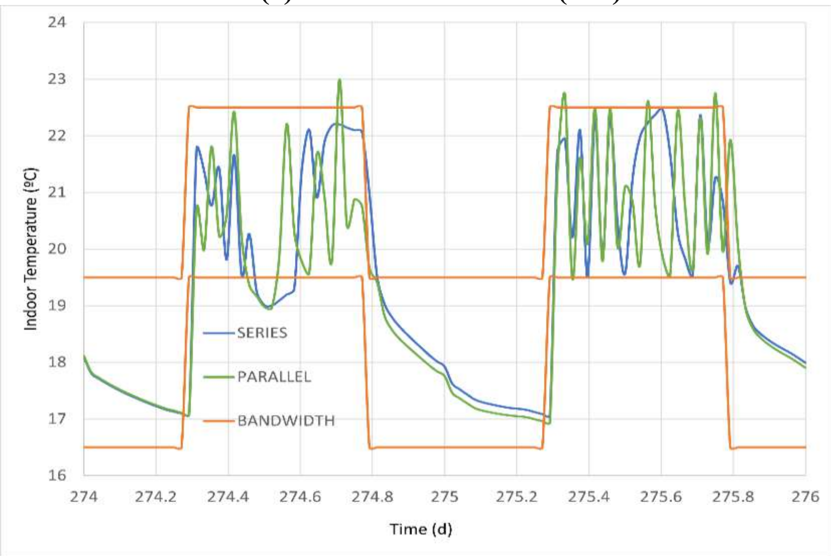
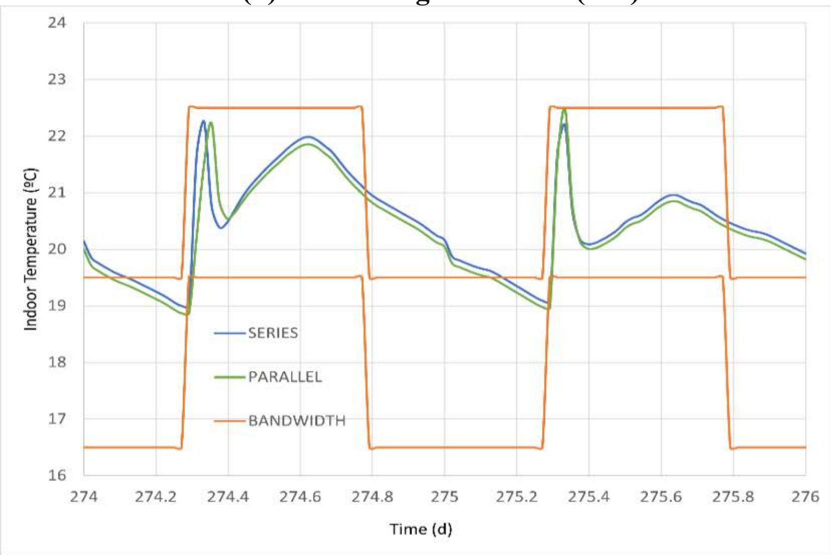


Figure 50: Indoor temperatures for two October days. Comparison between configurations

(a) Helsinki midseason (Oct)



(b) Strasbourg midseason (Oct)



(c) Athens midseason (Oct)

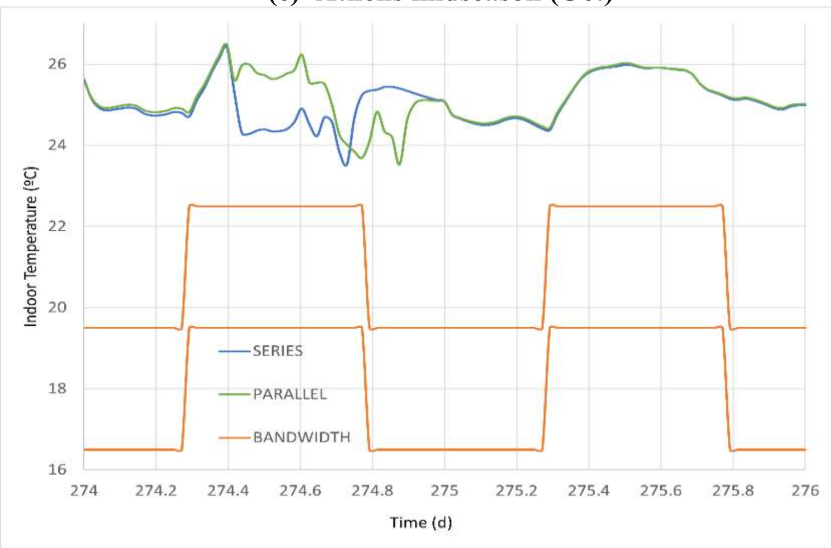


Figure 51: Indoor temperatures for two October days. Comparison between cities

Throughout this analysis, it is possible to observe what has been discussed in the analysis of indoor temperatures. In winter the temperatures are always within the desired bandwidth. The difference in the oscillations within the bandwidth can be seen especially in Helsinki, and is due to the higher supply temperature that is achieved with the system in series, which makes it better able to deal with temperature changes and not have temperature drops so often. But in spite of these differences and fluctuations, it can be observed that in all cases the temperatures are always within the desired range. For Atenas, since heating is practically not required and the change of temperatures is only due to the outdoor temperature, the behavior is the same for both configurations.

In summer, it can be observed that temperatures are generally within the desired range, especially in Helsinki and Strasbourg. In Athens, due to the controller of the first pump block, it is sometimes not able to keep the temperature within the limits (visible only in parallel as the controller is not fully optimized for this configuration). But as discussed in the analysis and the conclusion, this difference does not affect the overall performance of the system and will be considered in the further development of the system. In addition, it has also been possible to observe in more detail the behavior between summer and winter season, and how the difference in outdoor temperatures affects the needs of the building.

The last analysis to be carried out concerns the heat transmitted to the interior of the apartment in the three locations. For this purpose, Figure 52shows a duration curve with the heat transferred by the heat terminal in each of the locations, and the time that each of them is active for this operation, matching the results obtained in Table 5 and Table 10.

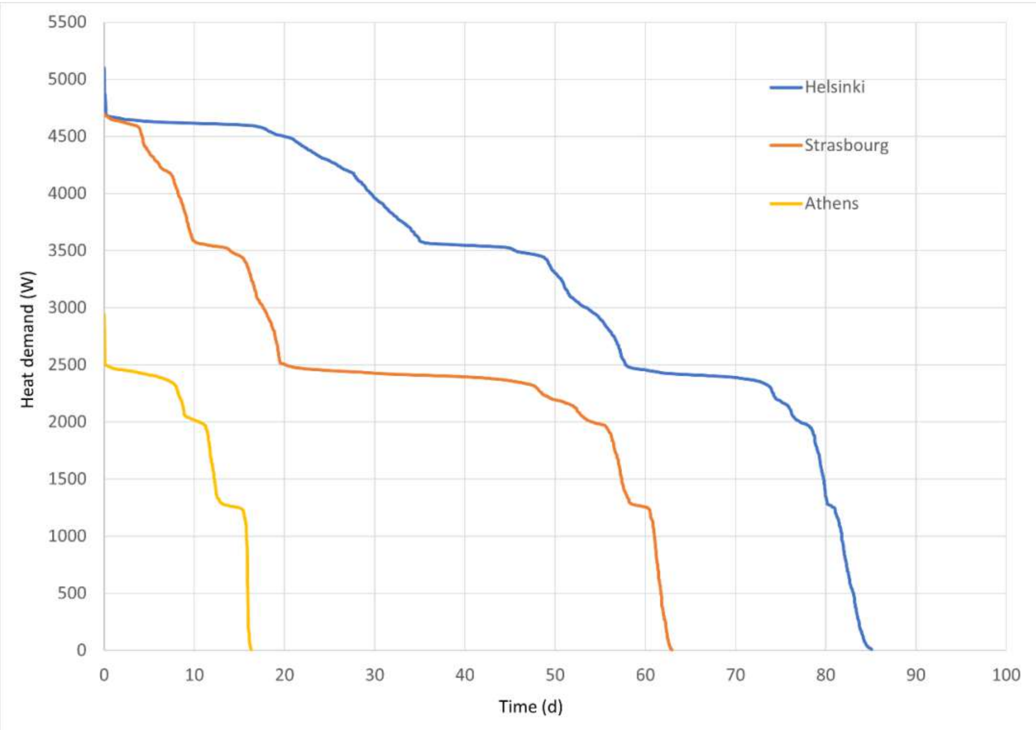


Figure 52: Duration curve of the heat demand of the apartment

ANNEX 2

Comparison of different tap water temperatures

As explained in 3.4.4, a tap water temperature of 10ºC has been used for the simulation in the three scenarios, although in Europe this temperature varies between 10ºC for the colder countries and 15ºC for the warmer ones (since having a higher outdoor temperature, the tap water delivery temperature will also be higher). This has been done in order to analyze the three locations in the most unfavorable conditions possible, thus verifying how well they perform under these conditions. In reality, a tap water temperature of around 12°C for Strasbourg and 15°C for Athens would be closer to reality.

For this reason, a brief analysis (over a period of one month) has been made in this annex varying the Strasbourg tap water temperature from 10ºC, to 12ºC and 15ºC, to see the impact of tap water temperature on the behavior of WPW-HEX and therefore on DHW delivery. The DHW production KPIs for each of the three temperatures will be analyzed here. Starting at Figure 53 with the SoC using the different temperatures. As can be seen, with a tap water temperature of 10ºC, lower peaks are reached than with the other temperatures, since when there is a demand for DHW, a higher thermal load has to be transmitted to the tap water to reach 53ºC, thus discharging the WPW-HEX further. Otherwise, the high peaks are similar at all three temperatures, although as the WPW-HEX is generally more charged with a tap water temperature of 15°C, it can be seen that slightly SoC higher values are reached. This results in a 30-day SoC average of 0.5, 0.55 and 0.56 for 10ºC, 12ºC and 15ºC respectively. Following with the KPIs and related to the SoC, the temperature distribution inside the PCM can be also seen in Figure 54.

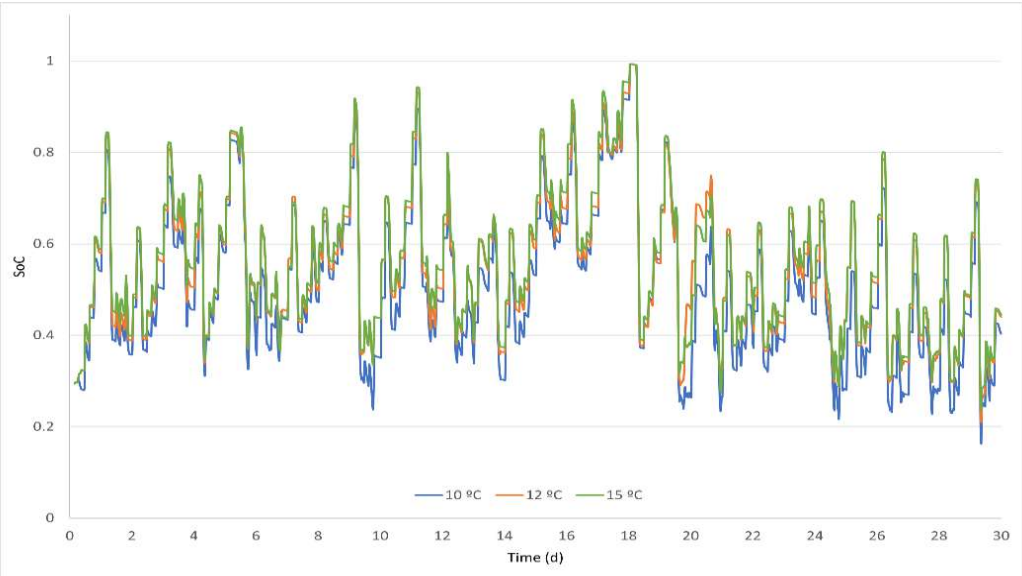
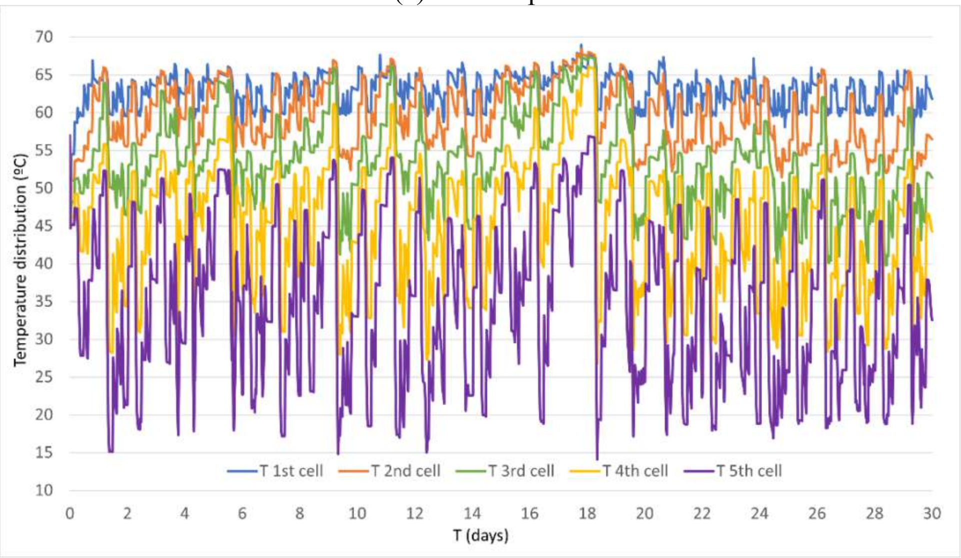
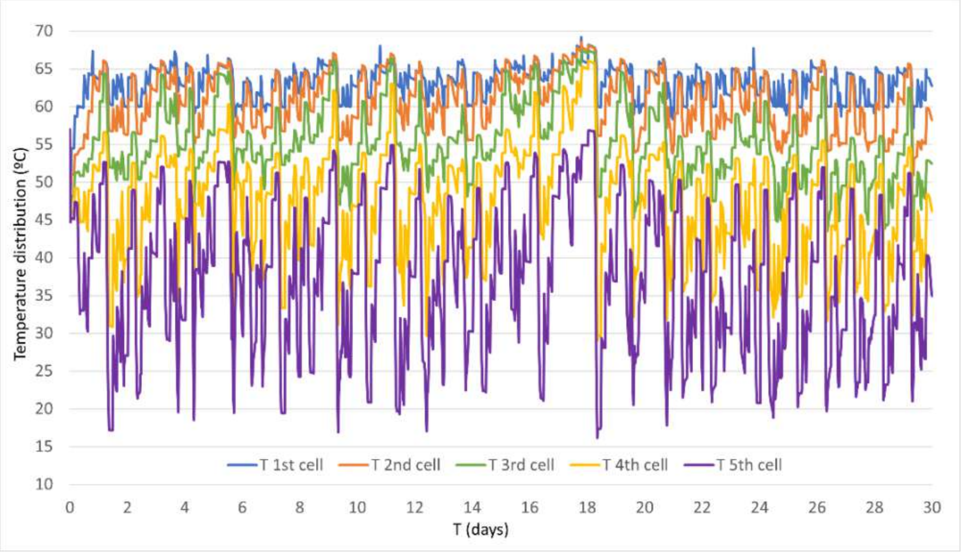


Figure 53: Monthly SoC using three different tap water temperatures

(a) 10ºC tap water



(b) 12ºC tap water



(c) 15ºC tap water

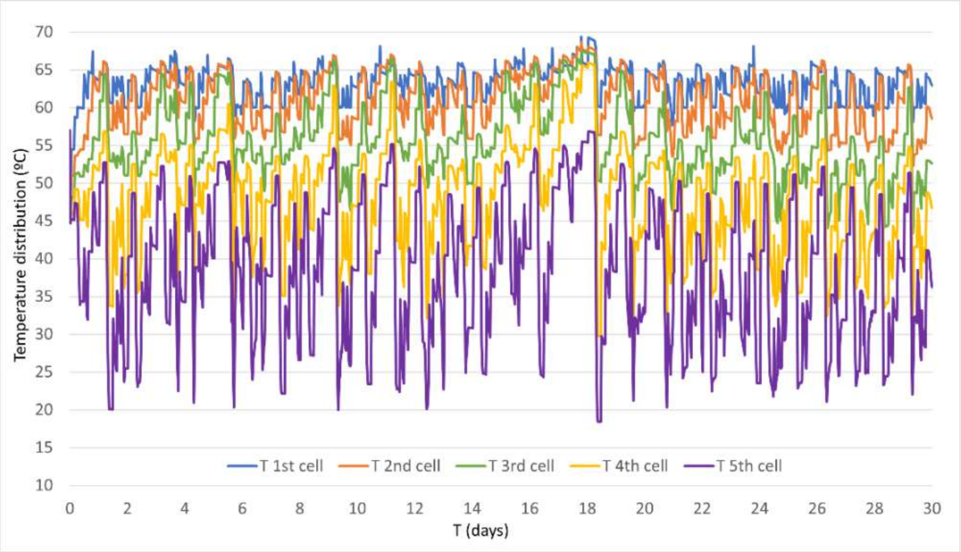


Figure 54: Monthly PCM temperature distribution with three different tap water temperatures

As can be seen at a glance, and following the SoC pattern, the maximum temperatures reached within the PCM are almost the same for all three configurations, because the water temperature arriving from the HPs is the same for all three configurations, reaching then the same maximum temperature. The difference can be seen in the rest of the cells, where as the tap water temperature increases, the lower the temperature difference with the DHW delivery temperature, the lower the temperature of the rest of the cells, creating a smaller difference between cell temperatures, and lower minimum temperatures. As can be seen at 10ºC the minimum temperature within the PCM is 15ºC, while at a tap water temperature of 15ºC the minimum temperature rises to 20ºC. This is exemplified with more detail in Figure 55, where the maximum and minimum temperatures inside the PCM for the three conditions are presented.

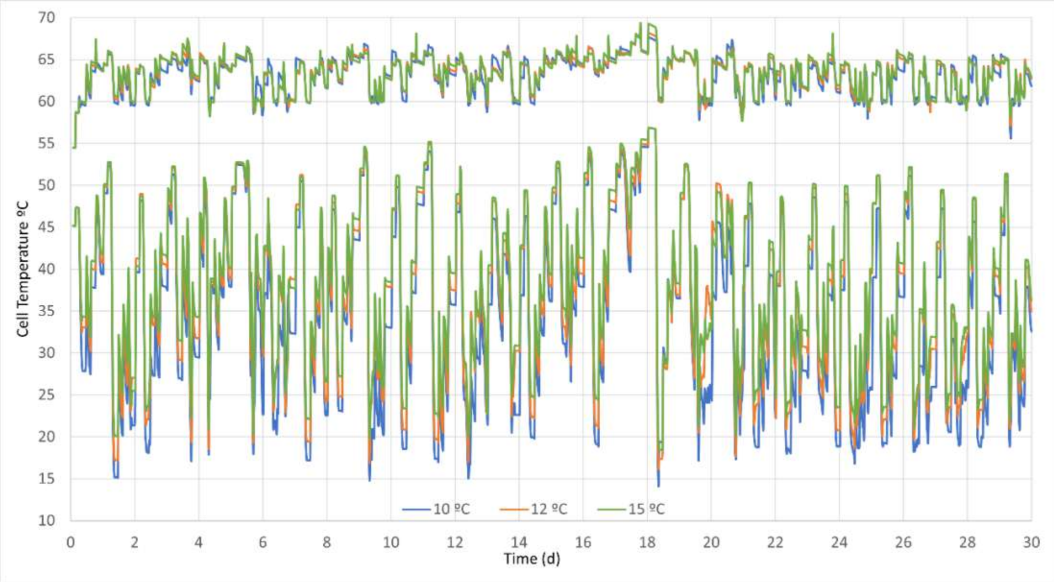


Figure 55: First and last cell PCM temperatures for the different tap water temperatures

As already mentioned, the maximum temperatures are nearly the same for the three configurations, while the difference is in the minimum temperatures observed, which are always higher with a tap water of 15ºC. This greater temperature distribution, and therefore greater SoC translates into a greater ability to provide DHW at the desired temperature and greater responsiveness, and on the other hand a lower number of charge cycles needed, and therefore lower electrical input, as can be shown in Figure 56, which shows the evolution of the total electrical input of the system over the last 30 days. Moreover, the lower number of required charging cycles will mean that the heat pumps will be available for a larger share of the time to cover the heating demand inside the building, making it possible to reach the indoor temperature setpoints more often.

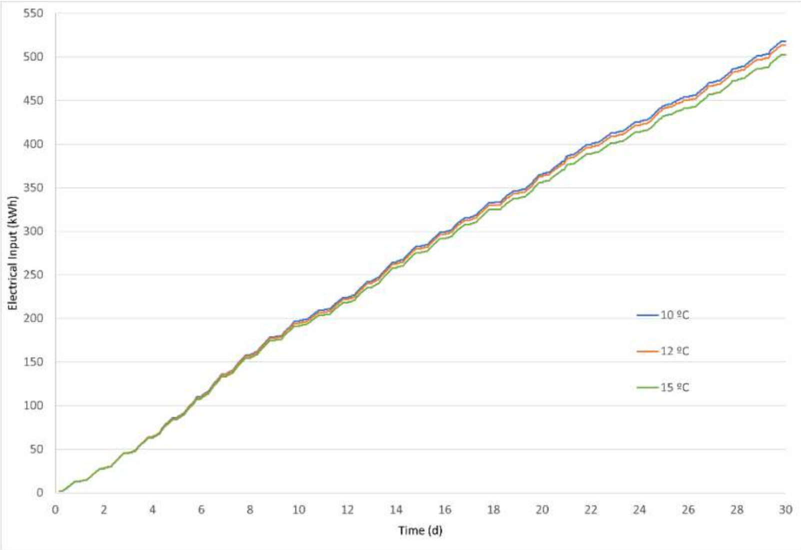


Figure 56: Electrical input required for one month with three different tap water temperatures.

At first glance it may seem that the energy savings between the three cases are small (16kWh being the maximum difference), but as can be seen, the growth is exponential, so that at the end of the year, it would mean a substantial saving of the electricity required. Furthermore, this graph represents the total energy savings, also considering the space heating. So, as mentioned above, by not having to charge the WPW-HEX, the energy could be allocated to space heating, creating that smaller difference. To see how this temperature difference affects the DHW side only, table Table 15 shows the amount of heat produced, electrical input and hours of operation of the HPs for this operation.

Table 15: Specific parameters for WPW-HEX charging operation with three different tap water temperatures

		10 ºC	12 ºC	15 ºC
WPW-HEX CHARGING	$Q_{condenser}$ (kWh/a)	448.06	423.33	268.35
	$P_{electric}$ (kWh/a)	195.14	183.73	119.71
COP		**2.30**	**2.30**	**2.24**
OPERATION TIME (Hours)		96	94	75

As can be seen, the differences between 10ºC and 12ºC are not substantial, although it does have a shorter operating time and therefore a lower electrical input with a tap water temperature of 12ºC. While with the system with a tap water temperature of 15ºC, large differences of up to 75 kWh less required and 20 hours less operation time can be observed, only in the course of one month, so that on an annual scale these differences would be much larger. This would result in large energy and cost savings, and a greater possibility to operate in space heating, as well as a higher SoC in the WPW-HEX, which would also lead to an improvement in DHW delivery. From this analysis it can be concluded that the higher the tap water temperature, the better the performance of the system. So, if the tap water temperatures in Strasbourg were adjusted to 12°C and in Athens to 15°C for the simulations (adjusting to the real behaviour), better results would be obtained.

ANNEX 3

Comparison with a 65ºC/20ºC system

For this analysis the system studied throughout the work will, which corresponds to a 45ºC/20ºC system, i.e. the supply temperature to the apartment is 45ºC and the return temperature is 20ºC (which would be associated with heating/cooling through radiant floor), will be compared with a 65ºC/20ºC system, i.e. the supply temperature will be 65ºC (that is associated with a heating/cooling system with radiators).

For this analysis the system studied throughout the work will, which corresponds to a 45ºC/20ºC system, i.e. the supply temperature to the apartment is 45ºC and the return temperature is 20ºC (which would be associated with heating/cooling through underfloor heating), will be compared with a 65ºC/20ºC system, i.e. the supply temperature will be 65ºC (this is associated with a heating/cooling system with radiators). However, as in series mode the water is heated sequentially in each of the heat pumps, it is possible to reach this final temperature.

The analysis will be carried out with the same parameters and same boundary conditions, only changing the mass flow controller for heating operation that has been seen in 3.4.2.1, to provide a mass flow at the 65ºC temperature. As the cooling and DHW side remain the same, only the parameters related to the heating delivery (mass flow to apartment, supply temperature, heat and electrical input required to carry out the heating operation, and consequently SCOP of the operation and overall SCOP of the system) will be emphasized. In this way it is possible to see the differences between the two systems and the improvements of one over the other. In Table 16 the different supply values are shown.

Table 16: Supply parameters comparation between configurations

AVERAGE VALUES	**HELSINKI**		**STRASBOURG**		**ATHENS**	
	45ºC/20ºC	**65ºC/20ºC**	**45ºC/20ºC**	**65ºC/20ºC**	**45ºC/20ºC**	**65ºC/20ºC**
Mass flow (kg/s)	0.0432	0.0220	0.0524	0.0389	0.0904	0.0881
$\vartheta_{supply,max}$ **(ºC)**	56.73	74.02	56.09	65.76	44.38	51.74
ϑ_{supply} **(ºC)**	43.31	54.14	37.93	43.32	30.93	33.42
ϑ_{return} **(ºC)**	22.08	22.64	22.38	22.88	23.18	24.11

As can be seen, the biggest difference resides in Helsinki, because as it is the location with the lowest outdoor temperature, it will also need the highest supply temperature. This is exemplified in Table 16, where the annual average supply temperature is about 10ºC higher with the 65ºC system. The behaviour in Strasbourg, being also a cold climate, but generally more temperate, the difference between temperatures is lower. Whereas in Athens, as the outdoor temperature is relatively high in winter compared to the other two locations, the supply temperature is around 30ºC in both cases. Related to this is also the water mass flow rate arriving to the apartment, since having to achieve a higher temperature lift for the system of 65°C, it is lower than with 45ºC. Along the lines of what has been explained above, it is significantly lower in Helsinki (as this is where the biggest temperature difference is seen). In Strasbourg those values are slightly lower, while in Athens are almost the same. Following the analysis, Table 17shows the performance data for each of the configurations.

Table 17: Performance comparation between configurations

		HELSINKI		STRASBOURG		ATHENS	
		45ºC/20ºC	**65ºC/20ºC**	**45ºC/20ºC**	**65ºC/20ºC**	**45ºC/20ºC**	**65ºC/20ºC**
HEATING DEMAND		7068.52	6746.87	4037.42	3816.51	790.67	691.19
HEATING OPERATION	$Q_{condenser}$ (kWh/a)	7973.88	7483.61	4667.22	4357.77	912.97	796.83
	$P_{electric}$ (kWh/a)	2615.94	2652.25	1398.34	1415.64	237.99	242.82
SCOP HEATING		**3.05**	**2.82**	**3.34**	**3.08**	**3.84**	**3.32**
HEATING OPERATION TIME (h)		3797	3520	2172	1962	445	353
ANUAL OPERATION	$Q_{condenser}$ (kWh/a)	11972.79	11716.39	8984.87	8842.22	8141.5	8076.78
	$P_{electric}$ (kWh/a)	4401.25	4496.39	3248.02	3282.55	2854.63	2859.39
SCOP		**2.72**	**2.61**	**2.77**	**2.69**	**2.85**	**2.82**
ANUAL OPERATION TIME (h)		5560	5281	4174	3954	4025	3967

As expected, the values of heat produced in the condenser are practically the same, being slightly lower for the 65ºC system due to the lower water flow rate. Following this line, the heating demand values for both cases are also similar, being lower for the 65ºC system, also due to the lower water flow rate, and to the higher heat losses with the outside as the water circulates at a higher temperature (it can be seen that the biggest difference is in Helsinki, which due to the large difference in temperature between the outside and the supply temperature is where there will be the highest heat losses).

To conclude the analysis, it can be seen that the operating time of the heat pumps (both general and heating) is shorter in the 65ºC system, because the indoor temperature is reached earlier due to the higher supply temperature. This difference, again, is especially noticeable in Helsinki, as this is where the largest temperature difference has been reported.

But at the same time, this higher supply temperature requires a higher electrical input, since in order to achieve this higher temperature difference, the heat pumps need more power, generating a higher electrical input, and consequently a higher economic cost and lower system performance. This again, is especially visible in Helsinki, due to the greater temperature difference. In Strasbourg the difference is not that big, while as has been seen throughout this analysis, in warm cities like Athens, both systems behave in much the same way.

In this way, it can be seen that the 45ºC supply temperature system (which would be equivalent to a radiant floor heating/cooling system) is more efficient, and therefore achieves both an electrical and economic reduction than the conventional radiator system (with 65ºC supply temperature). So, it is interesting to move towards these solutions and try to opt for a lower supply temperature whenever possible, which is also in line with the objectives of the 4GDH and 5GDHC.

ANNEX 4

Analysis of a system with only 2 HP blocks

As shown in 4.3.3, HPs 3 and 4 operate for a very small amount of time per year, especially on series configuration, so one might wonder if they are really necessary to satisfy the demand. To try to understand this, a simulation without those heat pumps have been carried out ins Strasbourg (as it has a milder temperature and overall similar operation times in heating and WPW-HEX charging), so it would be the most representative scenario. This will affect especially the DHW supply temperature (Figure 57), since the main function of these HPs is to cover the demand that is not possible with the first two ones (as the WPW-HEX charging operation has a higher temperature setpoint than the heating operation).

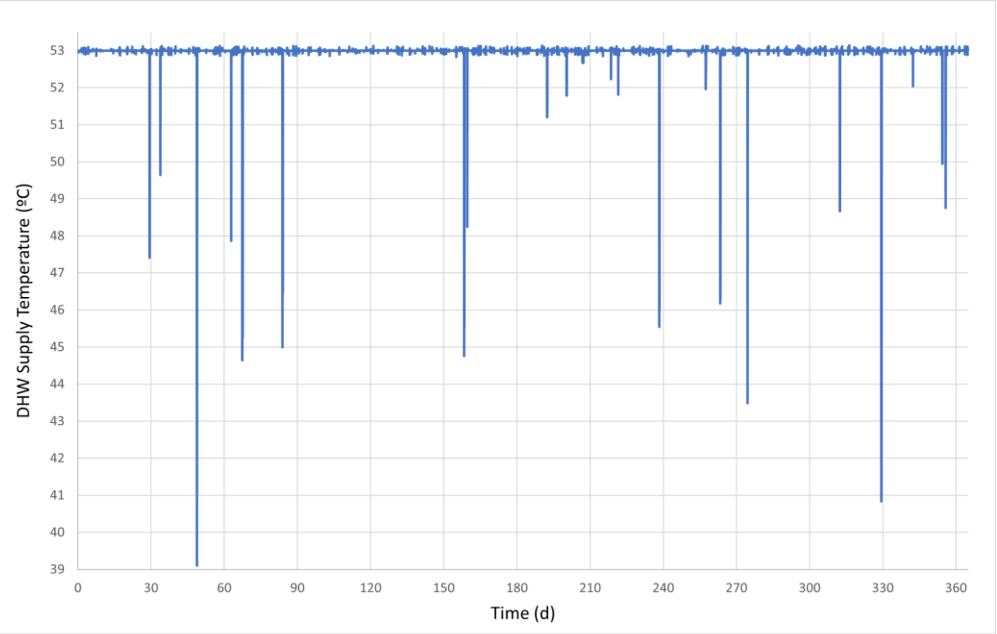


Figure 57: DHW supply temperature on Strasbourg with only two HP blocks

As can be seen, the DHW delivery temperature drops below the required temperature on several occasions during the year, with temperatures sometimes below 40ºC and for a longer period of time (for example, the drop on the 49th day goes from being around 2 hours to more than 3 hours). This is due to the low responsiveness of having only two pumps, as when the WPW-HEX is fully discharged, it will take longer to charge, making it impossible to meet the demand immediately.

For the case of indoor temperature, the analysis can be seen in Table 18. The difference is not so significant, and it is due to the fact that HPs 1 and 2 have to run longer to try to satisfy the DHW demand. This difference can be observed mainly in the indoor temperature during the day in winter, and in total, it is below comfort levels 98 hours more throughout the year, (which corresponds to no significant difference of about 3%). With this data, it can be expected that in the case of Helsinki, the removal of these two heat pumps would be much more noticeable, and for Athens it would be noticeable in short periods of time in summer.

Table 18: Indoor temperatures on Strasbourg with only two HP blocks compared with the original system

OPERATION	INDOOR TEMPERATURE (ºC)	HPs 1 2 3 4		HPs 1 2	
		Time (h)	%	Time (h)	%
WINTER NIGHT	< 16.5	12	0.26%	17	0.38%
	16.5 < ϑ< 19.5	2277	52.18%	2307	52.89%
	> 19.5	2075	47.56%	2038	46.73%
WINTER DAY	< 19.5	174	4.30%	265	6.55%
	19.5 < ϑ < 22.5	2555	63.19%	2474	61.25%
	< 22.5	1314	32.50%	1301	32.21%
SUMMER	< 23.5	1	0.14%	0	0.00%
	23.5 < ϑ < 26.5	355	99.86%	358	99.31%
	> 26.5	0	0.00%	3	0.69%

From this analysis it can be concluded that in order to satisfy the DHW demand, and therefore not affect the indoor temperature, all 4 heat pumps should be in operation. When it comes to satisfying the thermal demand of the building, for Helsinki the 4 heat pumps (or at least 3) would probably still be necessary, for Strasbourg 3 would be sufficient, while in Athens with only the first two running for heating and cooling would be enough.