POLITECNICO DI MILANO

School of Architecture, Urban Planning and Construction Engineering
Master of Science in Building and Architectural Engineering

Energy analysis of a district heating and cooling system based on a sewage water heat recovery system

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ABSTRACT

In the present thesis-work it has been analyzed the implementation of a district energy system with an important contribution of the sewage water through a vapour compression heat pump in the District IV of the city of Budapest, under the frame of the European project Heat4Cool which proposes an innovative, efficient and cost-effective solutions for the retrofit of HVAC systems. First, it has been made an overview of the current situation and the historical evolution of the district energy systems, the sewage water utilization and vapor compression heat pumps. Secondly it has been analyzed the climate of Budapest, to understand the conditions faced in the project. The buildings considered for the district energy systems have been defined and modelled with the software TRNsys in order to be able to define the energy needs through dynamic simulations. The energy system composed of sewage water heat exchanger and heat pump have been studied and calculated under the considered conditions. The final results have been compared with two different energy systems, air source heat pump and condensing boiler with chiller. The results showed a reduction of the 39% and 40% respectively in the annual energy cost of the three buildings.

SINTESI

In questo lavoro di tesi é stata analizzata l'implementazione di un sistema energetico distrettuale con un importante contributo di acque reflue per mezzo di una pompa di calore a compressione di vapore nel IV distretto della cittá di Budapest sotto la cornice del progetto europeo "Heat4Cool" che propone una soluzione innovativa, efficiente ed economica per il rinovamento di sistemi HVAC. Innanzitutto é stata fatta una panoramica della situazione attuale e dell'evoluzione storica dei sistemi energetici distrettuali, l'utilizzo delle acque reflue e delle pompe di calore a compressione di vapore. In seguito é stato analizzato il clima di Budapest, per capire le condizioni affrontate nel progetto. Gli edifici considerati per il sistema energetico distrettuale sono stati definiti e modellati con il software TRNsys per poter definire i bisogni energetici per mezzo di simulazioni dinamiche. Il sistema energetico composto dallo scambiatore di calore delle acque reflue e della pompa di calore, é stato studiato e calcolato nelle condizioni considerate. I risultati finali sono stati paragonati con due sistemi energetici differenti, la pompa di calore ad aria, e la caldaia a condensazione con refrigeratore. I risultati hanno mostrato rispettivamente una riduzione del 39% e del 40% nel costo energetico annuale dei tre edifici.

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Nomenclature

ASHP	Air source heat pump
CB	Condensing boiler
CDH	Cooling degree hours
cond	Condenser
COP	Coefficient of Performance
cpw	Water specific heat
Dint	Interior diameter
DN	Nominal diameter
EER	Energy Efficiency Ratio
evap	Evaporator
GW	Government Window
HDH	Heating degree hours
HP	Heat pump
HX	Heat exchanger
kWhele	Electric kilowatt hour
kWhth	Thermal kilowatt hour
$\dot{m}$	Mass flow rate
MO	Mayor's Office
NMH	New Market Hall
NTU	Number of Transfer Units
P	Pump
Pcond	Condenser power
Pevap	Evaporator power
Sew	Sewage water
SWHP	Sewage water heat pump
T	Temperature
Tci	Cold inlet temperature
Tco	Cold outlet temperature
Tenv	Environment temperature
Thi	Hot inlet temperature
Tho	Hot outlet temperature
Tin	Inlet temperature
Tout	Outlet temperature
TZ	Thermal Zone
U-value	Thermal transmittance
ΔT	Temperature differential
ΔTML	Mean logarithmic temperature
ΔTML,c	Mean logarithmic temperature corrected
ε	Efficiency
ψ	Linear thermal transmittance

1 Introduction

1.1. General framework

In the last years the awareness towards the conservation of the environment has been increasing as society has become more worried about the future of the planet and the possibilities of the new generations. The increase in the world population and the development of emerging countries with elevated populations have led to a huge increase in the energy consumption, and this to question the viability of the actual energy models and the limits of the existing resources. Consequently, the researches and innovations related with sustainability and more efficient ways to produce energy have been multiplied.

An important part of the energy consumption corresponds to buildings. In Europe, buildings consume around the 40% of the energy produced and are responsible of the 36% of the CO2 emissions (1). And the most important part of the building energy consumption corresponds to the heating and cooling energy needs. As shown in the IEA (International Energy Agency) Tracking Clean Energy Progress 2017, in OECD (Organization for Economic Co-operation and Development) countries 45% of building final energy use accounts for space heating (2).

1.2. District Systems

In this context, district heating and cooling systems can be an effective way to reduce building energy consumption. District heating and cooling systems consist in distributing the energy produced by a centralized generation system to a group of buildings located in the same area, through buried pipes. The main idea is to avoid the individual generation systems in each flat, in this way is possible to have a better control over the emissions, as well as to increase the efficiency of the generation system or to implement sustainable systems that would only be affordable in the case of a considerable consumption of energy because of the high initial investment costs or the need of big areas to install the system.

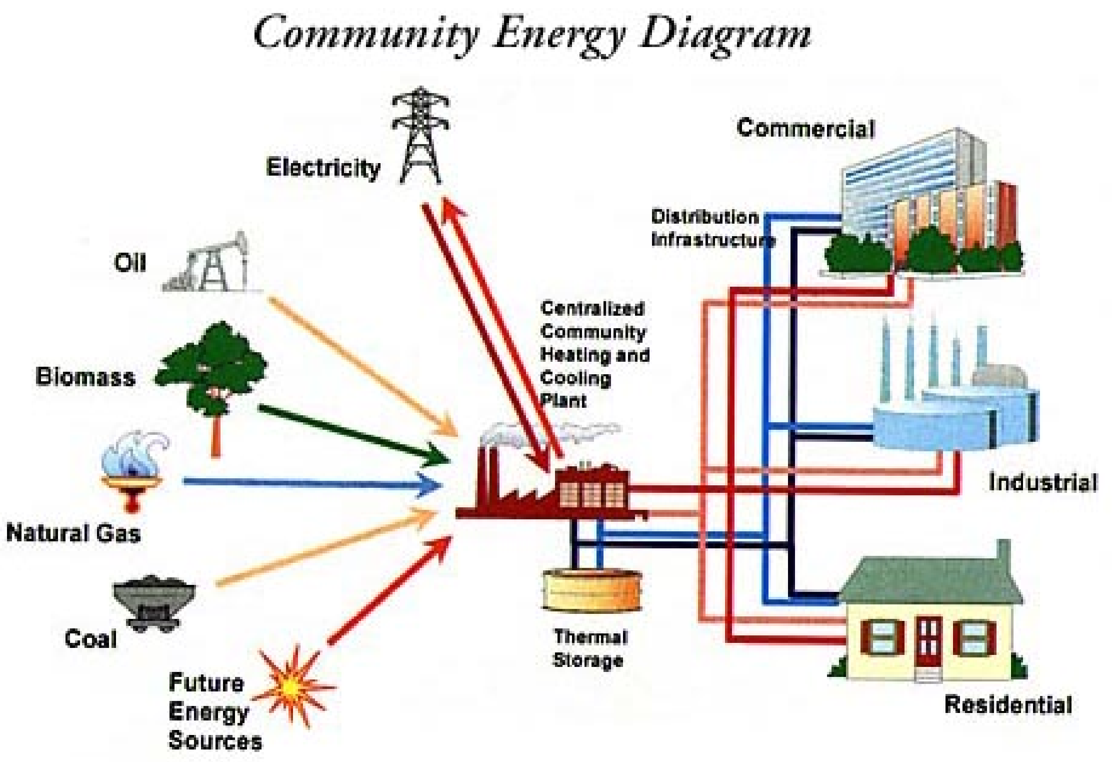

Figure 1.1: District system scheme (3)

District energy systems are not new and in order to make a brief historical introduction is necessary to separate heating from cooling systems. In Europe in the 14th century a geothermal district heating system was operating in France (4). Since then 3 district heating system generations have been developed. The first one around 1880s with steam as the heat carrier fluid. In the second one hot pressurized water mostly over 100ºC was used and was developed in the 1930s. The third generation was the most used from 1970s, and the heat carrier fluid was again pressurized water, but in this case the temperature was often below 100ºC which increases the efficiency of the generation system, and the main difference to achieve the temperature reduction was the use of pre-insulated steel pipes. Currently the fourth generation is being developed, its main characteristics are the reduction of the water temperature to 30-70 ºC, and the importance to incorporate renewable resources as generation systems. About district cooling, three generations can be considered, similar to the previously mentioned. The first one in the late 19th century used refrigerant as distribution fluid, the second one took place in the 1960s where the distribution fluid changed to cold water and the third generation appeared in the 1990s also using cold water but with a more diversified cold supply (5).

Nowadays the number of district heating systems is estimated to be 80 000 around the world, while the number of district cooling systems is unknown. The energy delivered from these systems can be estimated to be 11.5 EJ for heating and 300 PJ for cooling, being in both cases less than the 10% of the total energy supply to buildings (6).

As energy generators have been used several types of sources and systems for district heating. Fossil fuels such as natural gas, coal or oil are the most extended ones (90% of the world district systems), mainly because of its implementation in the previous century, when their cost was lower, and the impact generated in the environment not so much considered. But has to be mentioned that a big part of the energy coming from the fossil fuels is waste heat from the generation of electricity, the so-called cogeneration plants (6). However, in the last years the trend has changed, and renewable energy sources are chosen for the new systems, and in some cases are proposed to replace the old ones. The most extended renewable sources for district heating systems are ground source heat pumps, solar thermal energy and biomass, and waste heat from electricity supply plants from renewable resources.

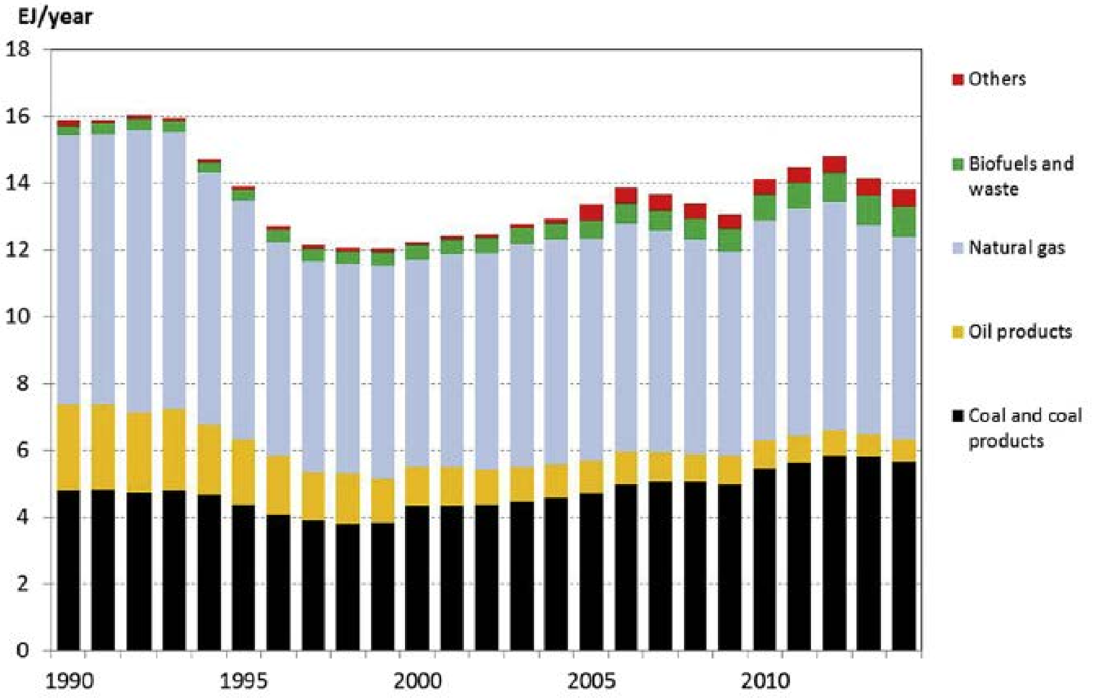

Figure 1.2: Heat supplied into all district heating systems in the World 1990-2014 (6)

For district cooling there are no statistics to determine the proportion of the supply methods used. In any case, the cold supply is managed mainly by heat exchangers using excess cold resources, absorption chillers from excess heat resources, mechanical chillers and cold storages (6).

The use of district energy systems has several benefits:

- the increase of the efficiency of the generation systems, which reduces the energy costs, as well as the environmental impact;
- also permits to have a better control of the CO2 emissions and helps to reduce them;
- allows the implementation of renewable energy sources that would be impossible to implement in individual flats;
- the fact of not having generation system in each individual flat is safer;
- the district systems are the best option to take advantage of the waste heat of different plants;
- the generation system can be closer to energy source reducing the losses.

However, the implementation of district energy systems has its difficulties. They usually have a higher initial cost. It is necessary to find the appropriate site to place the plant, which is not always possible (4).

1.3. HEAT4COOL Project

Heat4Cool is a project initiated in 2016 and expected to continue until 2020 which has received funding from the European Union's Horizon 2020 program for energy efficiency and innovation action. The project title is "Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system" and it is framed in the topic "Integration of advanced technologies for heating and cooling at building and district level".

Figure 1.3: H4C logo

The Heat4Cool project proposes an innovative, efficient and cost-effective solution to optimize the integration of a set of rehabilitation systems in order to meet the net-zero energy standards. The project develops, integrates and demonstrates an easy to install and highly energy efficient solution for building retrofitting.

The project aims to reach an optimal solution combining:

- gas and solar thermally driven adsorption heat pumps, which permits the full integration with existing natural gas boilers to ensure efficient use of current equipment;
- solar PV assisted DC powered heat pump connected to an advanced modular PCM heat and cold storage system;
- Self-correcting intelligent building energy management system (SCI-BEMS);
- energy recovery from sewage water with high performance heat exchangers.

For it Heat4cool will implement four benchmark retrofitting projects in four different European climates, Valencia (Spain), Sofia (Bulgaria), Chorzow (Poland) and Budapest (Hungary), aiming to achieve a reduction of at least 20% in energy consumption in a technically, socially, and financially feasible manner and is expected to demonstrate a return on investment lower than ten years.

The results expected from this project are:

- high possibility of replication across Europe, aiming to contribute to a large-scale market deployment before 2025, with the support of dedicated tool kits, which would be easy to install and would require a limited workforce;
- the creation of cost-effective, highly energy-efficient equipment with target reduction of energy consumption of 20-30 % (including renewable);
- payback period of below 10 years;
- best practice examples for the construction sector based on innovation and competitiveness, with benefits both for the citizens and the environment.

The project is divided in 8 main work packages that can be seen in the figure below, plus one more work package regarding the ethics requirements (WP9).

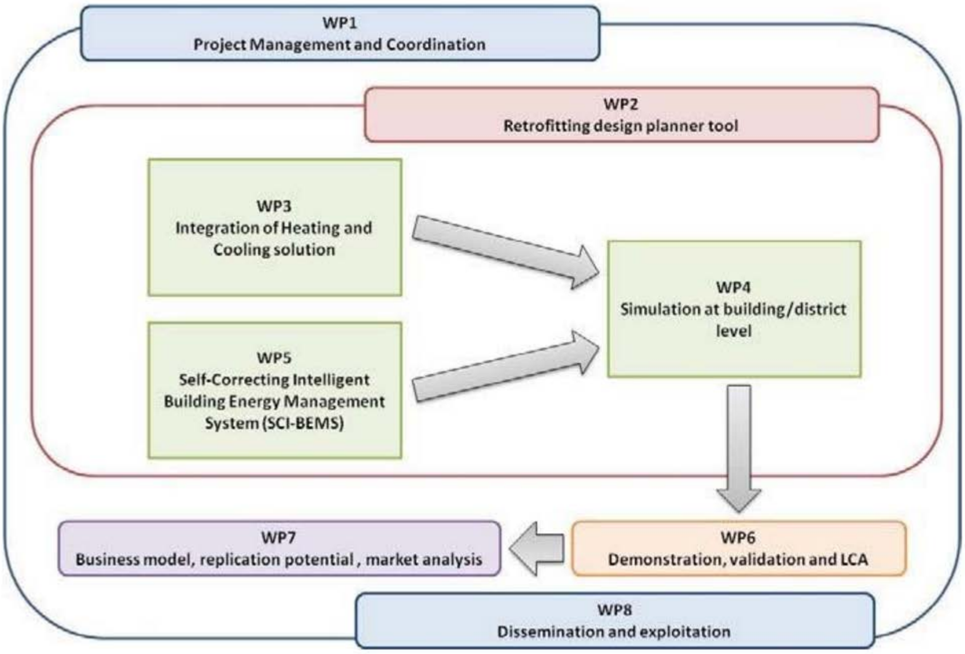

Figure 1.4: H4C work packages

The project counts on the participation of thirteen partners. In particular Politecnico di Milano leads Work Packages 1, 4 and 9, and takes part in 2, 3, 5, 6 and 8.

1.4. Thesis objects and structure

This thesis is included as a part of the WP4 of the H4C Project "Simulation at building/district level". More specifically this thesis aims to simulate three buildings that form a district heating system located in the IV District of the city of Budapest (Hungary).

Figure 1.5: Budapest's District IV

Most of the necessary data to elaborate this thesis has been facilitated by Thermowatt, another one of the thirteen Heat4Cool partners, which has a very relevant part in the mentioned work package.

For the simulation it is first necessary to model the buildings, which has been carried out with the software TRNSYS 18 (7) and TRNBUILD. After the modelling the simulation allows to calculate the heating and cooling needs of the district system.

It has also been studied the energy system that will supply the demand of the buildings. This system is composed of a sewage water heat pump and a sewage heat exchanger that allows the system to take the energy from the discharged water.

Finally, a comparative analysis among other possible energy systems has been carried out, in order to evaluate the potential benefits that could imply the proposed energy system.

The thesis is divided in seven chapters.

Chapter 1: Introduction (the present one), where it is explained the general framework and object of the thesis.

Chapter 2: Technologies under investigation, it is explained the actual situation of the technologies that will be used in the thesis.

Chapter 3: Weather data analysis, where it is analyzed the Budapest weather.

Chapter 4: Building modelling, where are described the different buildings that form the district system and the main characteristics that have been taken into account for the modelling.

Chapter 5: Building energy demand, are exposed the results as energy balances and needs of the simulation of the buildings.

Chapter 6: District energy system, in this chapter is explained the energy system and its main components.

Chapter 7: Comparative analysis, where the solution is compared with other possibilities.

2 Technologies under investigation

2.1 Sewage water

The sewage water is the waste water that comes out of the drain. This water if it comes from the shower or from different machines is usually at higher temperature than the ambient due to a heat that has been applied to it, and it is wasted once the water is drained.

To understand the sewage water potential, it is important to first talk about the urban water cycle (UWC), which is the path that the water follows for the human utilization. In this path a considerable amount of energy is supplied to the water. The cycle is divided in three parts: before consumption, during consumption and after consumption, and the energy supplied depends on the part of the cycle the water is at. The energy needed before and after consumption is mainly from the pumps used for the water catchment, supply, distribution and transportation, while the energy needed for the water use is mostly to heat it. Different analysis' have been carried out to estimate the amount of energy needed and its percentage. For example, in USA and Netherlands the energy needed before and after consumption represent only the 20% of the energy while during consumption represents the 80%. This means that the water heating represents the most important part of the energy supplied to the UWC, and the majority of this heat remains in the water after its use and it is drained to the sewer (8).

Other consideration that has to be taken into account is that due to the environmental situation previously mentioned, in the new buildings, energy performance is much better because of the implementation of techniques oriented to save as much energy as possible, motivated also because of new and stricter regulations. These techniques are focused mainly in the envelope behavior and the use of the renewable energy sources, but little progress has been made in the energy lost via the sewage system. This energy represents around the 15% in relatively new buildings but rises to around 30% in low energy buildings. All this lead to the fact that nowadays sewers represent the largest source of heat leakages in buildings (9).

For all these reasons the heat recovery from the sewage water has increased in importance in the last years, although the first plant appeared probably in 1975 (10), and its use it has not been widely extended yet, but there are different successful examples of how to implement this technology.

The main characteristic of the sewage water that makes it a good possibility as an energy source is its temperature. The temperature of the sewage water has a low variation along all the year. Depends on the place, for example in Switzerland the temperatures are around 10ºC in winter and around 25ºC in summer, and an energy source with a small temperature variation along the year is very useful for different systems.

The way for taking advantage of this energy source usually implies the use of a heat exchanger that can be coupled with other generations systems. According to the location of the heat exchanger it can be classified in three types: inside the building, in the sewer and in the waste water treatment plant.

The heat exchanger can be placed inside the building, usually directly after the shower, washing matching or dishwasher. It is used directly after being drained and helps reducing the energy needed to heat the water. In this first stage the water still has nearly all its energy, so the loses are reduced a lot. The main disadvantage is the space needed to place it, and usually in existing buildings there is no place for it.

When the heat exchange is placed in the sewer it is usually coupled to a heat pump and its use is for space heating and cooling. The main advantage of this location is its closeness to where the energy is required, that can be crucial in the effectiveness and the viability of the system. The main disadvantage is that in the water there is a solid fraction. When this solid fraction it is deposited in the heat exchanger can reduce its efficiency drastically. For this reason, the heat exchanger used in the sewers are equipped with different systems that allow to remove the screen that can be formed.

Finally, the heat exchanger can be located in waste water treatment plants, the advantage of locating it here is that water, as it has been treated, does not have the solid part that can affect the performance of the heat exchanger. In the other hand its main disadvantage is that in general the waste water treatment plants are far from the point where the energy is needed, and the loses of energy through the path the water must follow are considerable compared with other to possible locations. Therefore, it is more useful to use for the heat needed in the same plant processes.

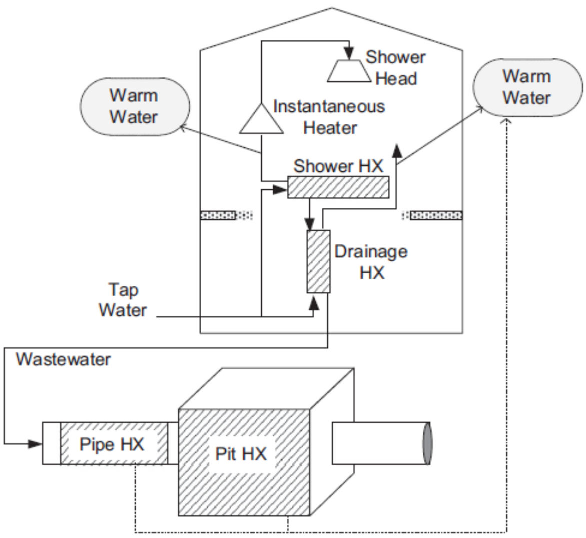

Figure 2.1: Heat exchanger possible location (8)

For the present project it has been used a shell and tube heat exchanger and the choice has been to locate it in the sewer, because there is an important pipe collecting the sewage water of the district passing close to the buildings that are object of study.

2.2 Heat pump

This project aims to provide an important part of the space heating and cooling with the energy contained in the sewage water. It is not possible to obtain this energy only with a heat exchanger due to the large needs of the affected buildings, the variability of the sewage water conditions, the distance between sewer and buildings, and because the temperature of the sewage water is not high enough to achieve it. Thus, it is necessary to use a complementary system that helps to take advantage of the sewage water energy.

The proposed solution is to use a water-water heat pump connected to the sewage water heat exchanger, that can help to satisfy both, heating and cooling needs.

Nowadays, the heat pump can be considered under given circumstances a renewable energy according to Directive 2009/28/CE, so the use of the heat pump is becoming more and more popular. But not always has been like that. This is possible thanks to the advances made since its appearance. The first practical vapor-compression machine was built in 1834 and was for ice production. Since then, several developments in a lot of different aspects have helped to convert the heat pumps in a reliable energy generation system, and as it has been said, in some cases environmentally friendly, which explains its expansion in the last years.

Heat pump functioning is based in the 1st and 2nd laws of the thermodynamics. The principle is moving heat from inside to outside or vice versa according to seasonal needs. For this purpose, it is used heat absorbed and released in evaporation and condensation by a refrigerant adapted to the functioning temperatures. As this heat flux is not natural (heat needed in winter and cold needed in summer) is necessary to provide energy to the system to achieve it. According on how to provide energy to the cycle heat pumps can be classified as mechanical heat pumps (vapor-compression cycle) or thermal heat pumps (absorption cycle). In this thesis the chosen one is based in the vapor-compression cycle. Generally speaking, the heat pump is a cycle based in the ideal reverse Rankine cycle, and composed of two heat exchangers which work as condenser and evaporator, in the case of reverse heat pumps they can switch to work as the opposite depending on the season and if it is needed heating or cooling inside the building. The other parts are the compressor (which is the main electricity consumer of the system) and an expansion valve to close the cycle.

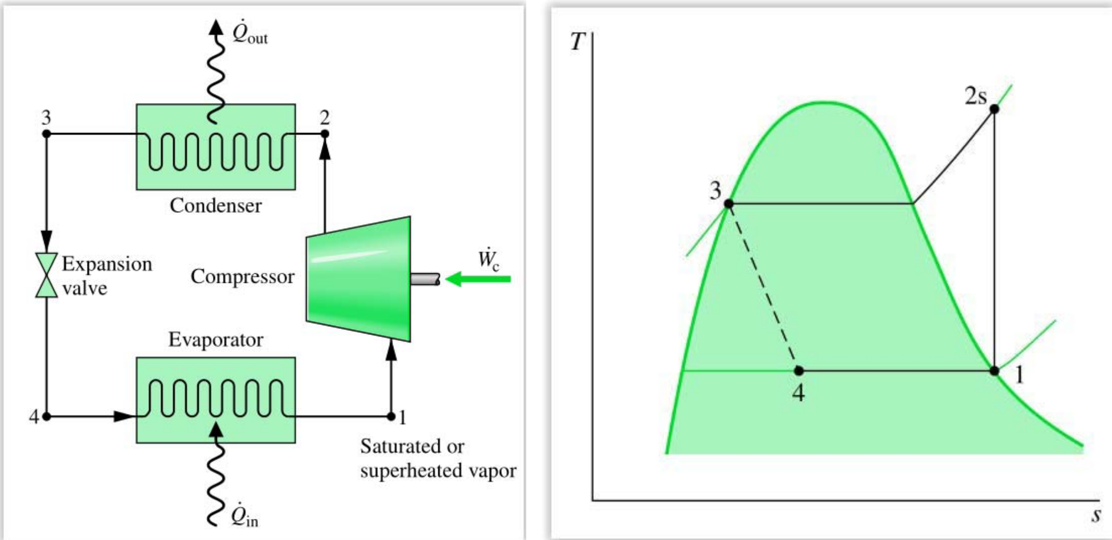

Figure 2.2: Vapor compression cycle (11)

According to the source where heat is taken or released the heat pumps can be classified in:

- Air source heat pumps: are the most common type because they are easy to install in individual rooms. They use the outside air as the source to exchange heat with the refrigerant. Their COP is usually lower than the others 2 types, because depends on the outside temperature which is not at the optimal temperature for the functioning.
- Water source heat pumps: use water as source, usually taken from groundwater. It is more difficult to find it as a source and depends on the location. As water has a higher heat capacity better than air, the temperatures are more stable during the year, increasing the COP.
- Ground source heat pumps: are basically water heat pumps, their characteristic is that the water exchange heat with the ground, whose temperature remains nearly constant during the year. They are the heat pumps with higher installation cost which is their biggest disadvantage.

Focusing on the vapor-compression heat pumps, other important thing to take into account is the compressor. As the main electricity consuming part of the cycle the development of different types has improved a lot the performance of the heat pumps. The compressors' function is to increase the refrigerant pressure, so it facilitates the condensation by increasing the condensation temperature.

Nowadays the heat pump compressors can be divided in two main types: positive displacement compressors and flow compressors.

The main features of the positive displacement compressors the possibility of achieving a high compression ratio with a single-stage compressor, the lack of restrictions on the operations because of the suction pressure and the not need of continuity in transporting refrigerant. Within this group are reciprocating compressors, rotary compressors, scroll compressors and rotary screw compressors.

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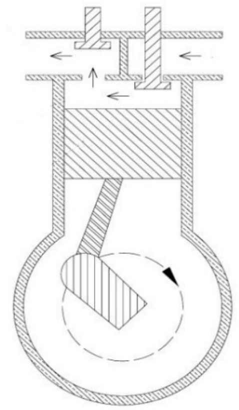
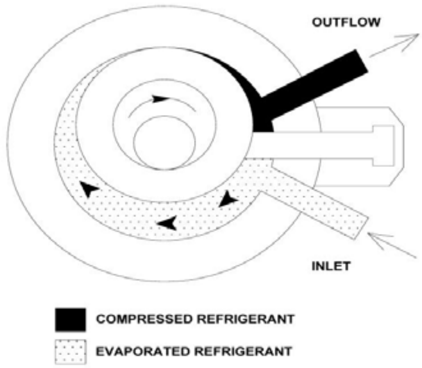
<tr><td></td><td>
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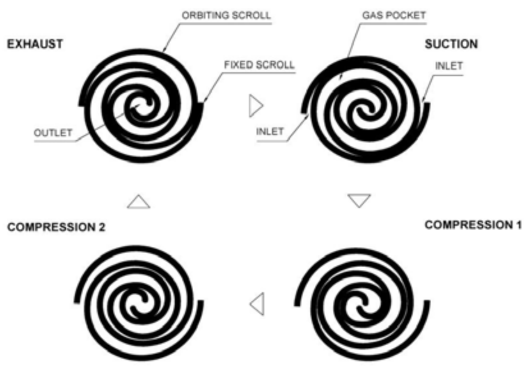
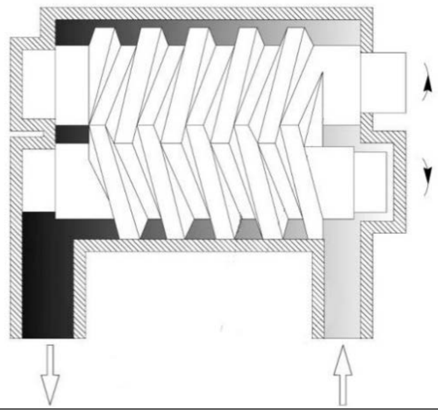
<tr><th>Scroll compressor</th><th>Screw compressor</th></tr>
<tr><td>
</td><td></td></tr>
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Table 2.1: Compressor types (12)

As flow compressors stand out centrifugal compressors. The principal characteristics are the factor reduced compression and the increased flow rate of the compressed refrigerant.

The first compressor was the reciprocating or piston compressor, based on cycles of suction, discharge and extrusion of water vapor of working factor. Apart from improving this type of compressor, the different types appeared with different features that helped with the improvement.

Rotary compressor	Scroll compressor	Screw compressor
Eliminate crankshaft Compact construction Reduce the noise	Less moving parts Smaller Resistant to water hammer Less vibration Increased service life	No flow pulsation/vibration No working valves No water hammer Variable power 20-100%

Table 2.2: Compressor types advantages (12)

3 Budapest weather analysis

3.1 Introduction

Before running any simulation, it is necessary to understand the climate conditions that are faced in the project. Thus, an analysis of the weather of the region of Budapest has been carry out.

Budapest is the capital and most populous city of Hungary, country located in central Europe. That is why its climate is humid continental characterize by his large seasonal temperature differences.

For analyzing the climate, Meteonorm weather file of Budapest has been used. The weather file includes hourly weather data of the region of Budapest along the year, obtained through averaging data of different years in order to be as accurate as possible. This data has been collected in Budapest-Lorinc station (Station 128430), whose exact location can be seen in the map below:

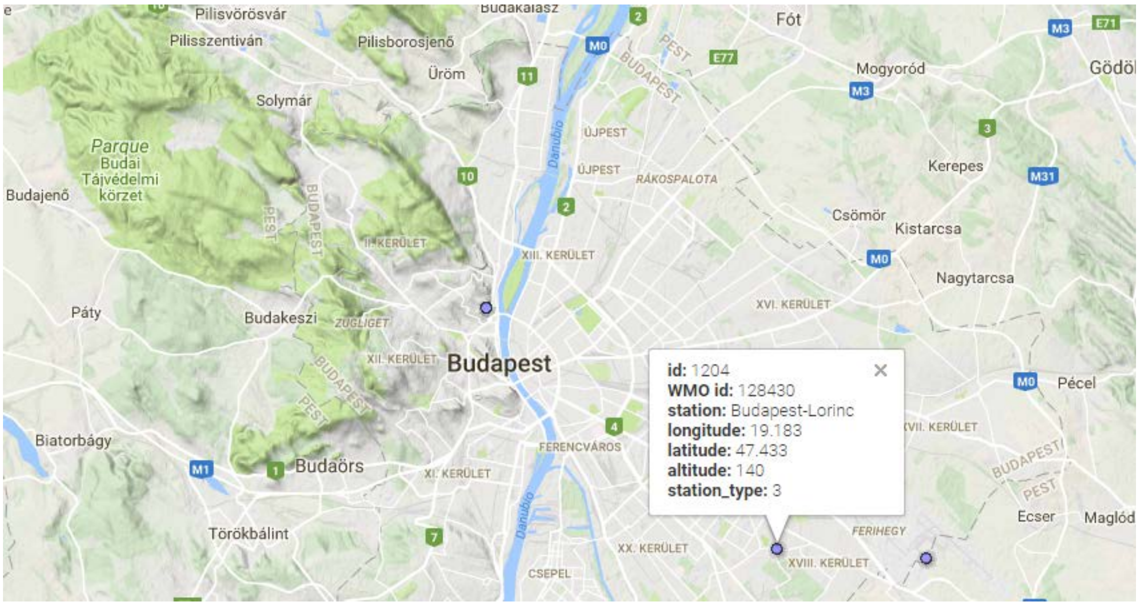
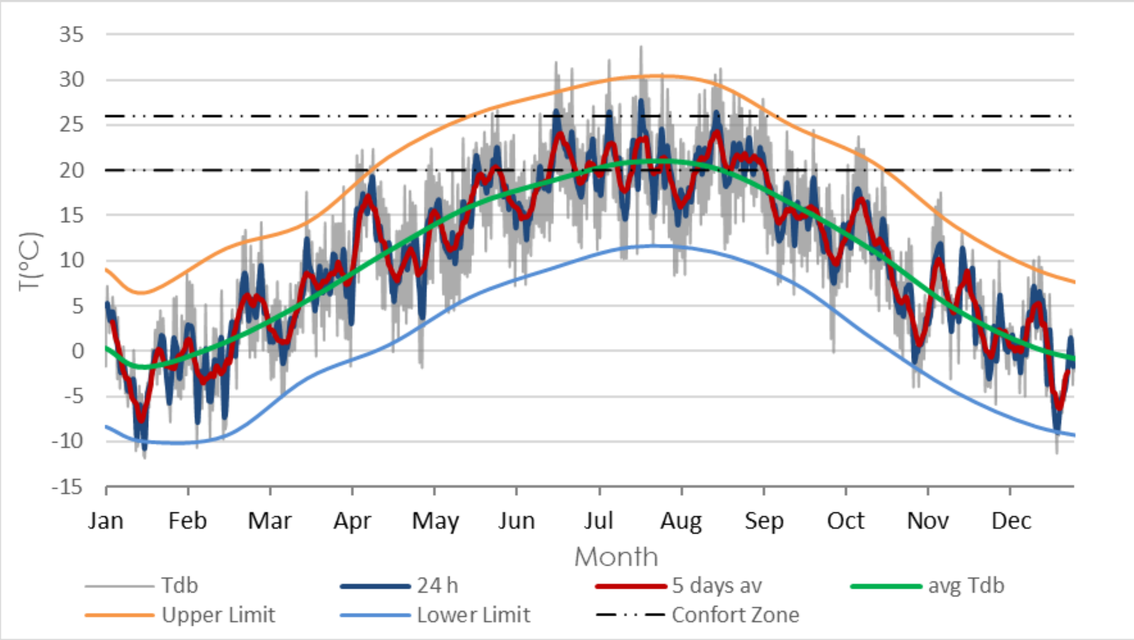


Figure 3.1: Budapest-Lorinc weather station

3.2 Temperature

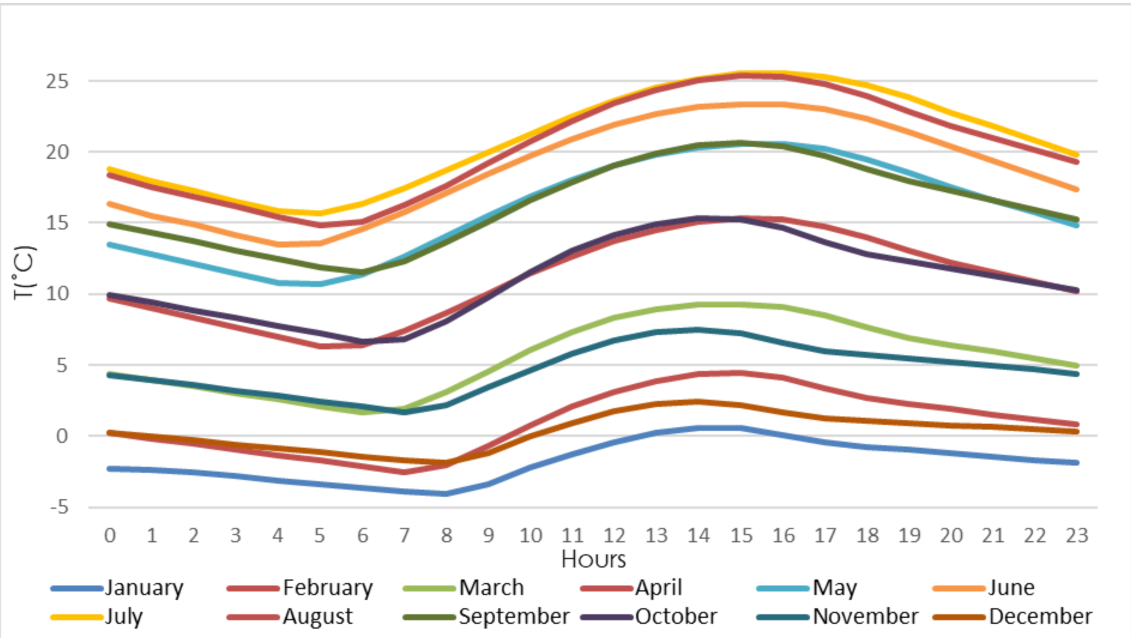
In the graph are shown the hourly dry bulb temperature, its monthly average and different moving averages (24hs and 5 days). This helps to understand the temperature along the year as well as to have an idea of how it varies during smaller periods of time.



Graph 3.1: Dry bulb temperature

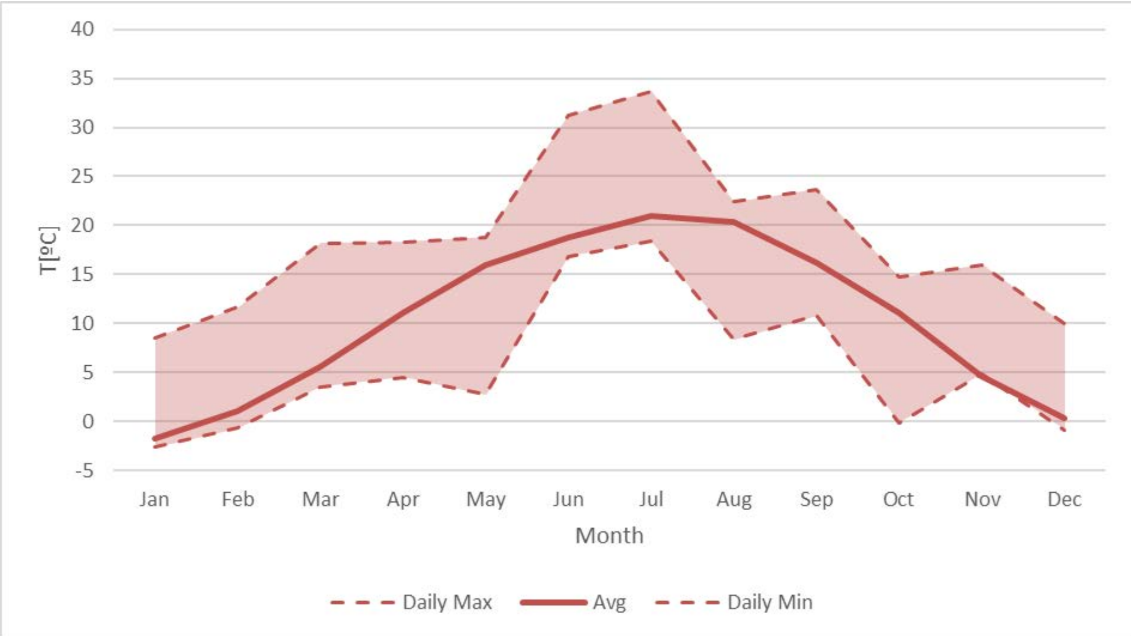
In the graph it can be seen that Budapest is in general a cold city specially in the winter months when temperatures below -10ºC can be reached. In the other hand in summer the temperature can go above the 30ºC. In the hourly data the fluctuating trend between day and night can be appreciated. In the monthly average the ranges are between nearly -2ºC in January to 21ºC in July. The annual average temperature is around 10ºC. This graph gives a general vision of the type of climate of Budapest.

In the next graph are shown the monthly average of the temperature at each hour.



Graph 3.2: Temperature monthly hourly average

With this graph it is possible to understand the fluctuation of the temperature during the day and also helps to compare the different months. So, as it has been said previously it can be observed that the coldest month is January, and the warmest July. Also, it can be seen that the coldest hours are the first in the morning and varies depending on the month. In the other hand the warmest hours are between 14:00 and 16:00 and again depends on the month.

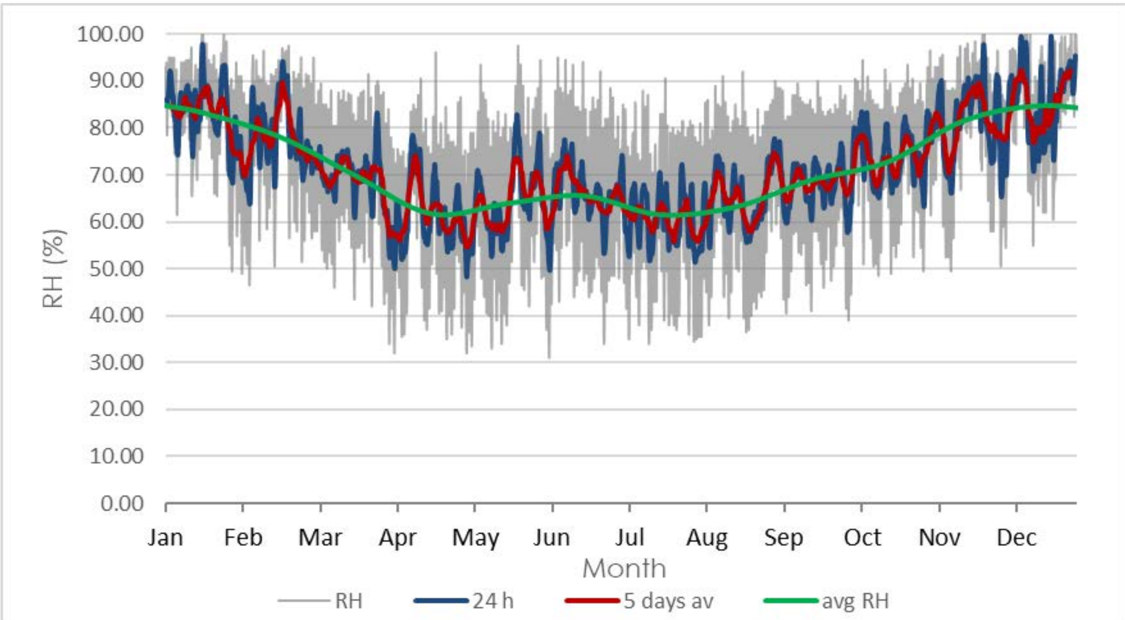


Graph 3.3: Temperature monthly daily maximum variation

In this graph is shown the maximum daily differences that can be reached each month.

3.3 Relative Humidity

The next graph shows the hourly relative humidity along the year.



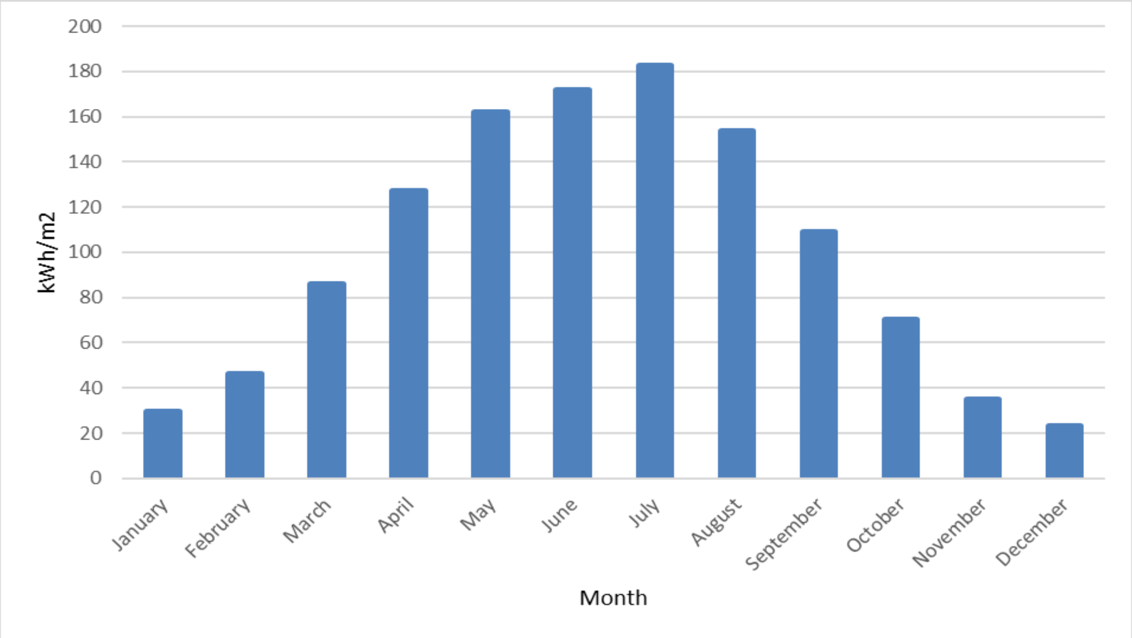
Graph 3.4: Relative humidity

As it can be seen Budapest is a humid city specially during the winter months, which enforces the thermal effect. The relative humidity is higher in winter months due to the air capacity to allow the vapor content which is reduced as the temperatures decrease. The main reason of the humidity in Budapest because it is crossed by the Danube.

3.4 Solar radiation

The solar radiation is a very important factor to take into account when it comes to weather analysis because it helps to understand the effect of the sun in the climate.

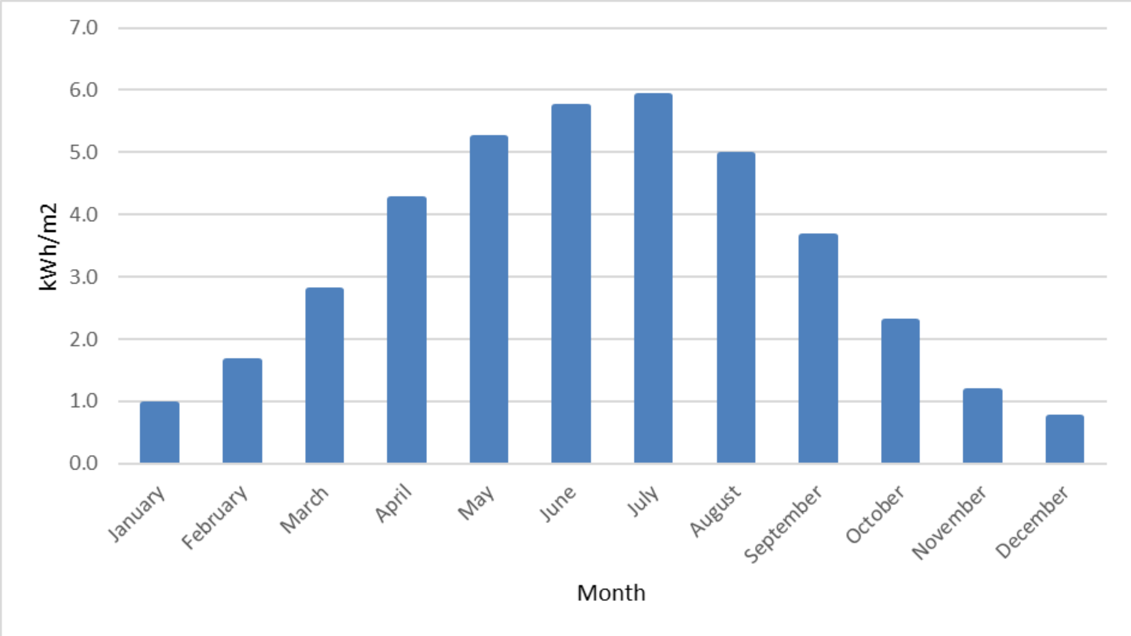
In the first graph is shown the monthly total horizontal radiation.



Graph 3.5: Monthly total horizontal radiation

It can be appreciated that the graph follows the same trend as the dry bulb temperature. The total yearly horizontal radiation amounts to 1197 kWh/y.

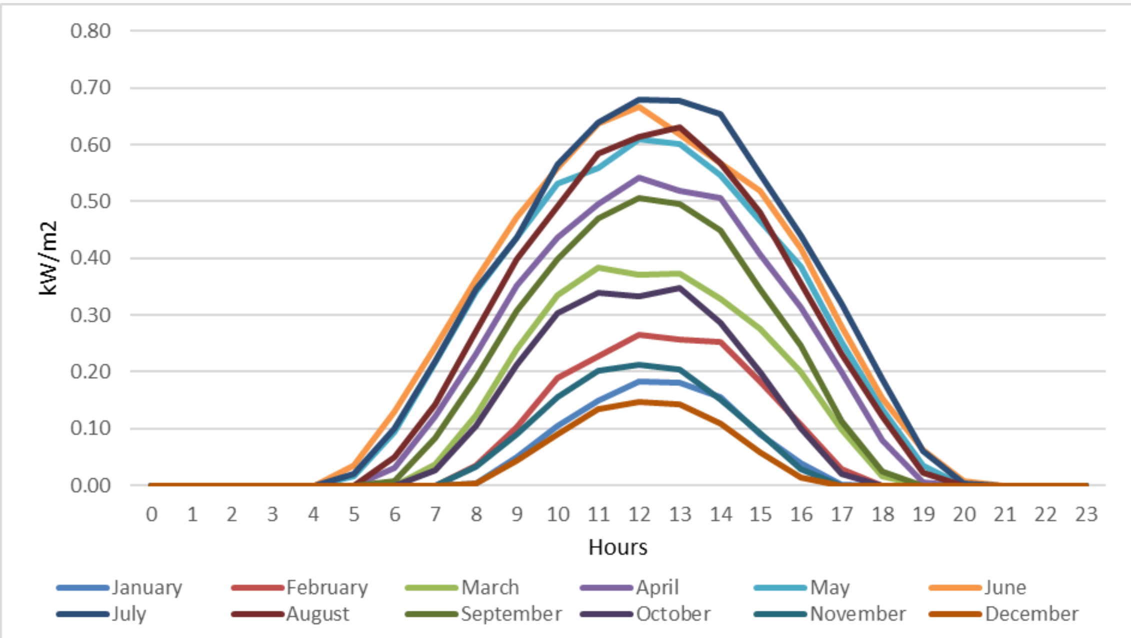
In the next graph is shown the monthly average of the daily available energy. With this graph it is possible to have an idea of the global (which includes the direct and diffuse radiation) irradiation that reaches a horizontal surface in terms of energy (kWh/m2). In this case it is shown the total monthly radiation of each month divided by the number of days.



Graph 3.6: Monthly average of the daily available energy

As expected the available energy in the summer months is much higher than the winter ones, close to 6 kWh/m2 in July, and lower than 1 kWh/m2 in December. This is caused by the position of the earth respect to the sun and the location of Budapest in the globe (North hemisphere). The solar annual average is 3.3 kWh/m2.

In the next graph are represented the monthly hourly values, which give a more accurate vision of what happen with the radiation during the day and help to understand better the previous graph.



Graph 3.7 Monthly hourly radiation values

In the graph is clearer the reason why the radiation in the summer months is higher than the one in the winter ones. The sun rises earlier and sets later in these months being up for more hours and reaching higher values in the midday hours.

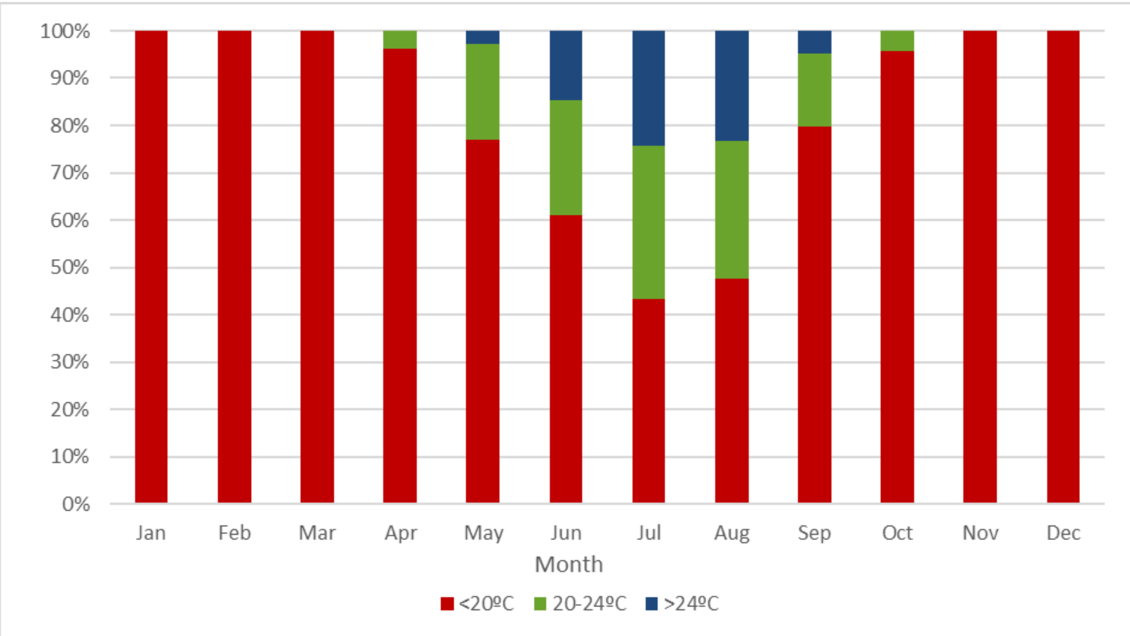
In the next graph is shown the same in a color map which is more intuitive.

Hourly average kWh/m2	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
January	0.00	0.00	0.00	0.00	0.05	0.10	0.15	0.18	0.18	0.16	0.09	0.04	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.04	0.10	0.19	0.23	0.26	0.26	0.25	0.18	0.11	0.03	0.00	0.00	0.00
March	0.00	0.00	0.04	0.12	0.24	0.33	0.38	0.37	0.37	0.33	0.28	0.20	0.10	0.02	0.00	0.00
April	0.00	0.03	0.12	0.23	0.35	0.44	0.50	0.54	0.52	0.51	0.41	0.31	0.20	0.08	0.00	0.00
May	0.02	0.09	0.22	0.34	0.44	0.53	0.56	0.61	0.60	0.55	0.47	0.39	0.25	0.14	0.04	0.00
June	0.04	0.13	0.24	0.36	0.47	0.56	0.64	0.67	0.62	0.57	0.52	0.42	0.28	0.15	0.06	0.01
July	0.02	0.10	0.22	0.34	0.44	0.57	0.64	0.68	0.68	0.65	0.55	0.44	0.32	0.19	0.06	0.00
August	0.00	0.05	0.14	0.27	0.40	0.49	0.58	0.61	0.63	0.57	0.48	0.36	0.23	0.12	0.02	0.00
September	0.00	0.01	0.08	0.19	0.31	0.40	0.47	0.51	0.50	0.45	0.34	0.25	0.11	0.02	0.00	0.00
October	0.00	0.00	0.03	0.11	0.21	0.30	0.34	0.33	0.35	0.29	0.20	0.10	0.02	0.00	0.00	0.00
November	0.00	0.00	0.00	0.03	0.09	0.16	0.20	0.21	0.21	0.15	0.09	0.03	0.00	0.00	0.00	0.00
December	0.00	0.00	0.00	0.00	0.04	0.09	0.13	0.15	0.14	0.11	0.06	0.01	0.00	0.00	0.00	0.00

Graph 3.8: Monthly hourly radiation values

3.5 Comfort zone hours

A comfort zone must be defined. This means a range of temperatures that are considered to be acceptable for living and working in comfort conditions. These conditions vary depending on the location and its climatic characteristics. For this project will be consider a comfort zone ranging between 20ºC and 24º according to the European Normative (13). This means that the minimum temperature during the working hours would be 20ºC and the maximum temperature 24ºC. With these boundaries it has been analyzed the Budapest temperature, and the results in percentage are shown in the graph.



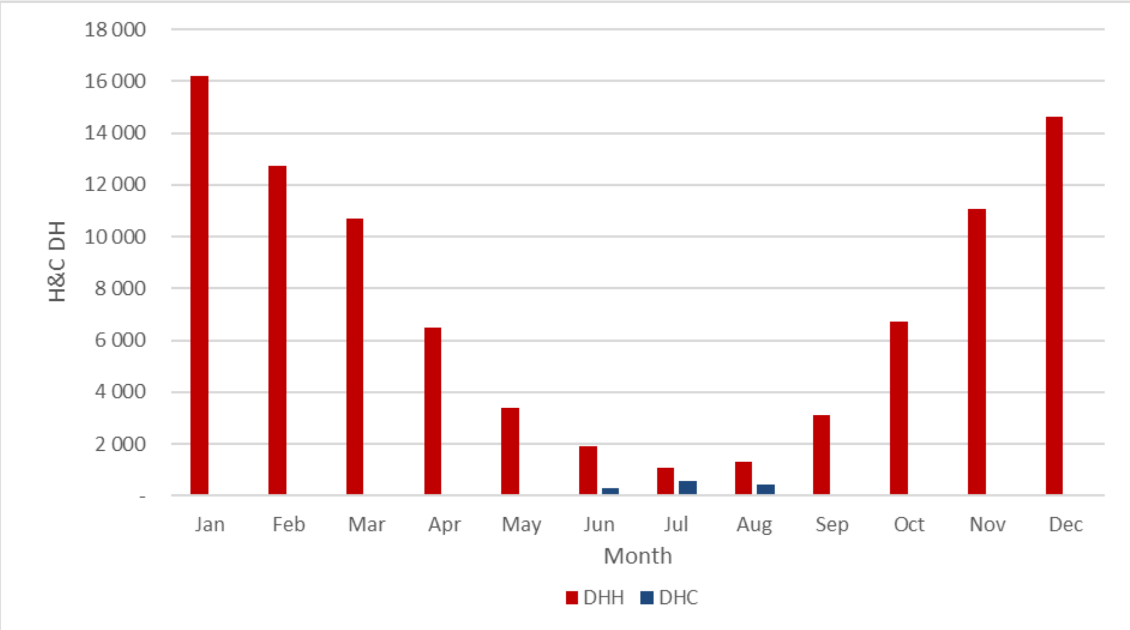
Graph 3.9: Comfort zone hours percentage

A quick look is enough to understand that the main problem to solve in Budapest will be the heating needs, because the temperature is generally under 20ºC, also that the months with the highest percentage of hours in the comfort zone are from May to September, and finally that the only months with important cooling needs are from June to August but even these months have heating needs that even surpass the cooling ones.

In any case this graph is only for having a general overview of the situation, because there are other things to take into consideration for the definition of heating and cooling needs. First of all is the indoor temperature the one used for this definition which is affected by a lot factors and the outdoor temperature is only one of them. Others can be the different loads that act in the building or the office working schedule

3.6 Heating and Cooling Degree Hours

Finally to finish the weather analysis of Budapest, the heating and cooling degree hours (HDH, CDH) have been calculated. Heating and cooling degree-hours are defined as the sum of the differences between hourly average temperatures and the base temperature (20-24ºC). It is important to differentiate between the degree hours, and the degree days. The degree hours are least 24 times higher than the degree days, which at the end is other way to represent the difference between the actual conditions and the comfort conditions.



Graph 3.10: Heating and Cooling Degree Hours

The total heating degree hours are 3642.29 while the cooling degree hours are only 14.80.

As shown in the graph and has been said other times during the analysis, the final conclusion is that Budapest is a cold city and the main issue to deal with are the heating energy needs.

4 Building modelling

4.1 Introduction

Three buildings located in the district IV of Budapest have been analyzed energetically, in order to figure out the energy consumption, and if it is possible to use a sewage water heat recovery to provide the heating and cooling needs of the buildings.

The three buildings are the District IV Mayor's Office (middle) and the Government Window (right) and the New Market Hall (right)

Figure 4.1: Buildings analyzed

The buildings data that it is presented in this chapter have been provided by Thermowatt.

For the analysis it has been used the software TRNSYS. And in order to model the building it has been used TRNBuild a program that simplifies the process of designing the building in TRNSYS.

For the model it has been necessary to introduce the data detailed below.

4.2 Government Window

4.2.1 *Building description*

Figure 4.2: Government Window

The Government window is a public building. It accommodates the operation and administration office of government issued documents as well as offers customer service for the inhabitants of District 4. Offices and meeting rooms are the main type of rooms.

The building was constructed in 2001, it has 5 floors, basement and a basilica level. Its main facade faces West, 15 °turned clockwise so that the orientation is 15° North-West (considering North as 0°). Its walls are 0.38 m thick brick blocks, the average inside height is 2.8 m. The building has not been renovated since construction.

4.2.2 *Thermal zones*

The building has been divided in 2 thermal zones in order to consider 2 different types of windows disposed in different floors and orientations. The thermal zone 1 is compounded by the ground and the first floor, and the thermal zone 2 by the second third and fourth floors.

4.2.3 *Stratigraphy*

The exterior walls have been considered of brick blocks, with mineral wool as insulation.

According to the data provided the values reached are:

- For the external walls: U-value 0.6 W/m2K, thickness 0.38 m.
- For the roof: U-value 0.25 W/m2K, thickness 0.4 m.
- For the floor: U-value 0.92 W/m2K, thickness 0.6 m.

The window information provided is:

- Type 1: U-value 0.5 W/m2K.
- Type 2: U-value 1 W/m2K.

4.2.4 *Surfaces dimensions*

The external walls have been considered according to their orientation.

<u>Thermal zone 1</u>

- North walls area: 2 floors; 21x3.1 m (130.2 m2). Boundaries: Climatized space (20-24ºC)
- East walls area: 2 floors; 44x3.1m. Boundaries: half of the area (136.4m2) has been considered in contact with climatized space (20-26ºC), and the other half (136.4m2) with the exterior. The windows for this orientation are type 2, and it has been assumed a 20% window area (27.28m2).
- South walls area: 2 floors; 20x3.1m (124 m2). Boundaries: Exterior. Window type 1, assuming a 20% window area (24.8m2).
- West walls area: 2 floors; 44x3.1m (272.8 m2). Window type 1, 88m2.
- Ground Floor area: 495 m2. Boundaries: ground.

<u>Thermal zone 2</u>

- North walls area: 3 floors; 21x3.1m (195.3 m2). Boundary: climatized space (20-26ºC).
- East walls area: 3 floors; 44x3.1m. Boundaries: half of the area (204.6 m2) has been considered in contact with climatized space (20-26ºC), and the other half (204.6 m2) with the exterior. The windows for this orientation are type 2, and it has been assumed a 20% window area (40.92m2).
- South walls area: 3 floors; 20x3.1m (186 m2). Boundaries: Exterior. Window type 2, assuming a 20% window area (37.2m2).
- West walls area: 3 floors; 44x3.1m (409.2). Window type 2, assuming a 30% window area (122.76 m2).
- Roof area: 450 m2. Boundaries: exterior.

4.2.5 *Schedules*

The schedules provided for heating, cooling, ventilation occupancy and internal gains are:

Heating: Mon-Fri; 06:00-18:00.

Cooling, ventilation, occupancy, internal gains: Mon-Fri; 07:00-18:00.

In the information provided it is written that when the heating and cooling is not ON, it is OFF or attenuated. But it is not specified if it is attenuated the setback temperature. So, it has been assumed that, out of the schedules the systems are OFF.

4.2.6 *Internal Gains*

- Occupancy TZ 1: 49 people.
- Occupancy TZ 2: 80 people.
- People: Seated, light work, typing: Sensible 75 W/pers; latent 75W/pers.
- Light & equipment: 5 W/m2.

4.2.7 *Ventilation*

The information provided says that the building has an intermittent ventilation; but is not specified the air rate. It has been assumed 0.4 ach for ventilation with the schedule previously mentioned, and 0.25 ach for Infiltration. The infiltration has been considered for the 24 hours including weekends.

4.2.8 *Heating & Cooling*

The set points considered have been:

Heating set point: 20ºC.

Cooling set point: 24ºC.

4.3 Mayor's office

4.3.1 *Building description*

Figure 4.3: Mayor's Office

The Mayor's Office building is a public building that accommodates the headquarters for the main operation and administration bodies of the District 4 Municipality and it is composed mainly by offices and meeting rooms.

The building was built in 1899-1900, it has 3 floors, 2 inner garden areas and offices along the inner corridors. Its main facade faces East, 15 °turned clockwise so that the orientation is -75° South-East (considering South as 0°). Its walls are 0.6-0.7 m thick brick walls with no insulation, the average inside height is 4.2 m. The building was completely renovated in 2010-2011, during which there were new facilities put into service and the building construction was renovated as well as completely repainted. However, since it is an architecturally protected building, it was not a possibility to put insulation on the outside walls.

4.3.2 *Thermal zones*

In this case it has been considered only one thermal zone.

4.3.3 *Stratigraphy*

The exterior walls have been considered of clay blocks.

According to the data provided the values reached are:

- For the external walls: U-value 0.85 W/m2K, thickness 0.65 m.
- For the roof: U-value 0.4 W/m2K, thickness 0.2 m.

- For the floor: U-value 1.24 W/m2K, thickness 0.8 m.

The window information provided is:

- Type 1: U-value 1.5 W/m2K.
- Type 2: U-value 0.5 W/m2K.

4.3.4 *Surfaces dimensions*

Thermal zone 1

Due to the lack of information regarding the area of each type of window and being only written that all surfaces have both types of window, it has been assumed a 20% the glazed area, from which 12.5% is type 1 windows and 7.5% is type 2 windows.

Other problem regarding the Mayor's Office information received is that it has not been taken into account the internal courtyard of the building which implies a higher external wall area.

In the data below this last point has been considered and the area of the external walls has been increased.

- North walls area: 642.6 m2. Window type 1: 80.3m2. Window type 2: 48.2m2.
- East walls area: 1071.9. Window type 1: 134m2. Window type 2: 80.4m2.
- South walls area: 642.6 m2. Window type 1: 80.3m2. Window type 2: 48.2m2.
- West walls area: 1071.9. Window type 1: 134m2. Window type 2: 80.4m2.
- Roof area: 1430 m2.

Boundaries for all above described: exterior.

- Ground area: 1200 m2. Boundaries: ground.

4.3.5 *Schedules*

Heating: Mon-Fri; 05:30-18:00.

Cooling, ventilation, occupancy, internal gains: Mon-Fri; 07:00-18:00.

In the information provided it is written that when the heating and cooling is not ON, it is OFF or attenuated. But it is not specified if it is attenuated the setback temperature. So, it has been assumed that, out of the schedules the systems are OFF.

4.3.6 *Internal Gains*

- Occupancy TZ: 134 people.
- People: Seated, light work, typing: Sensible 75 W/pers; latent 75W/pers.
- Light & equipment: 5 W/m2.

4.3.7 *Ventilation*

The information provided says that the building has no ventilation; but is not specified the air rate. It has been assumed 0.4 ach for ventilation with the schedule previously mentioned, and 0.25 ach for Infiltration. The infiltration has been considered for the 24 hours including weekends.

4.3.8 *Heating & Cooling*

The set points considered have been:

Heating set point: 20ºC.

Cooling set point: 24ºC.

4.4 New Market Hall

4.4.1 *Building description*

As it has been said the third building is under construction at this time. However, it will be finished by the time of the functioning of the district heating system. The New Market Hall is designed to be a mixed typed building (commercial building and cultural institution) with 4 floors and 2 levels of underground parking garage. It will be a complex market hall and event center: market hall with food and goods market space, shops on level 0 and level 1, conference and event center with theatre, event spaces and conference rooms, managing and functional offices on level 2 and level 3.

Figure 4.4: New Market Hall

Since it is under construction some information is missing by the time this thesis is written, so it has been assumed.

4.4.2 *Thermal zones*

The building has divided in 2 thermal zones according to its 2 different uses. The first thermal zone TZ 1 corresponds to the ground and first floor, which are the market floors. The second thermal zone TZ 2 corresponds to the second and third floor, floors used as offices.

4.4.3 *Stratigraphy*

The New Market is a new building, so it is better insulated compared with the previous two buildings.

The exterior walls have been considered of clay blocks, with mineral wool as insulation.

The U-values in this case are:

- For the external walls: U-value 0.28 W/m2K, thickness 0.47 m.
- For the roof: U-value 0.25 W/m2K, thickness 0.4 m.
- For the floor: U-value 0.3 W/m2K, thickness 0.5 m.

Regarding the windows the building is composed in some surfaces by a curtain wall.

The curtain wall and the windows has been considered with a U-value of 0.5 W/m2K.

4.4.4 *Surfaces*

Thermal zone 1

- North walls area: 2 floors; 604.7 m2. Boundaries: Exterior. Window area: 45%.
- East walls area: 2 floors; 723 m2. Boundaries: Exterior. Window area 90%.
- South walls area: 2 floors; 629.3 m2. Boundaries: Exterior. Window area 50%.
- West walls area: 2 floors; 722.1 m2. Window area 5%.
- Ground Floor area: 4555.4 m2. Boundaries: ground.
- Roof area: 2011 m2. Boundaries: exterior.

Thermal zone 2

- North walls area: 2 floors; 262.4 m2. Boundary: Exterior. Window area 45%.
- East walls area: 2 floors; 486 m2. Boundaries: Exterior. Window area 90%.
- South walls area: 2 floors; 455.7 m2. Boundaries: Exterior. Window area 50%.
- West walls area: 2 floors; 520 m2. Boundaries: Exterior. Window area 5%.
- Roof area: 450 m2. Boundaries: exterior.

4.4.5 *Schedules*

In this case as the building has 2 different uses the schedules applied have to be different as well. One for each thermal zone.

Thermal zone 1

As it has been explained the thermal zone one includes the ground floor and the first floor, and they are part of the market. The schedule chosen has been the same as the Budapest’s Central Market.

Monday: 6:00-17:00.

Tuesday-Friday: 6:00-18:00.

Saturday: 6:00-15:00.

Applied for heating, cooling, ventilation, occupancy and internal gains.

Thermal zone 2

Thermal zone 2 is composed by the second and third floors, both used as offices, so it has been applied the same schedules as the previous buildings.

Heating: Mon-Fri; 06:00-18:00.

Cooling, ventilation, occupancy, internal gains: Mon-Fri; 07:00-18:00.

4.4.6 *Internal gains*

It has been necessary to consider different gains for each thermal zone due to the different use of them.

Thermal zone 1

- Occupancy TZ1: 1750 people (4 m2/person).
- People: Walking, standing: Sensible 145 W/pers; latent 145W/pers.
- Light & equipment: 5 W/m2.

Thermal zone 2

- Occupancy TZ2: 400 people.
- People: Seated, light work, typing: Sensible 75 W/pers; latent 75W/pers.
- Light & equipment: 5 W/m2.

4.4.7 *Ventilation*

In this case it has been considered a mechanical ventilation because it is a new building. As it is considered mechanical ventilation the indoor air quality requirements have to be controlled. The values have been taken from the ASHRAE 62.1-2012 (14).

Thermal zone 1

For the market the requirements are:

- 3.8 l/s per person.
- 0.3 l/s per m2

Thermal zone 2

For the office the requirements are:

- 2.5 l/s per person.
- 0.3 l/s per m2

It has been considered an infiltration of 0.2 ach, active for 24 hours including weekends.

4.4.8 *Heating and Cooling*

The comfort zone has been defined as the previous buildings for both thermal zones:

Heating set point: 20ºC.

Cooling set point: 24ºC.

5 Building energy balances and needs

5.1 Introduction

With the data detailed in the previous section energy analyses have been carried out. As it has been said for the analysis it has been used the software TRNSYS. With it, have been analyzed the energy balance and the heating and cooling needs of the three buildings. It has to be pointed out that the analysis refers to maintaining the temperature of the buildings in the comfort zone (20-24ºC) in the considered scheduled, considering the different loads taken into account. Also, it has not been considered yet the energy system used, neither its efficiency. Thus, the system has infinite capacity for this initial analysis.

The energy balance of each building has been calculated with the formula:

$$\frac{dE_{cv}}{dt} = \dot{Q}_p + \dot{Q}_{sol} + \dot{Q}_A - \dot{Q}_{trans} - \dot{Q}_v - \dot{Q}_{inf} + \dot{Q}_{sys}$$

Where:

- $\dot{Q}_p$: gains due to the people in the building.
- $\dot{Q}_{sol}$: gains due the solar radiation.
- $\dot{Q}_A$: gains due to the appliances and equipment.
- $\dot{Q}_{trans}$: losses due to transmission.
- $\dot{Q}_v$: losses due to ventilation.
- $\dot{Q}_{inf}$: losses due to infiltration.
- $\dot{Q}_{sys}$: power supplied by the system in order to keep the energy balance.

The result of the balance must be 0 when the energy system (consider for this calculation an ideal plant) is ON in order to maintain the comfort conditions inside the control volume, which is the building.

The cooling and heating needs are what compensate the balance.

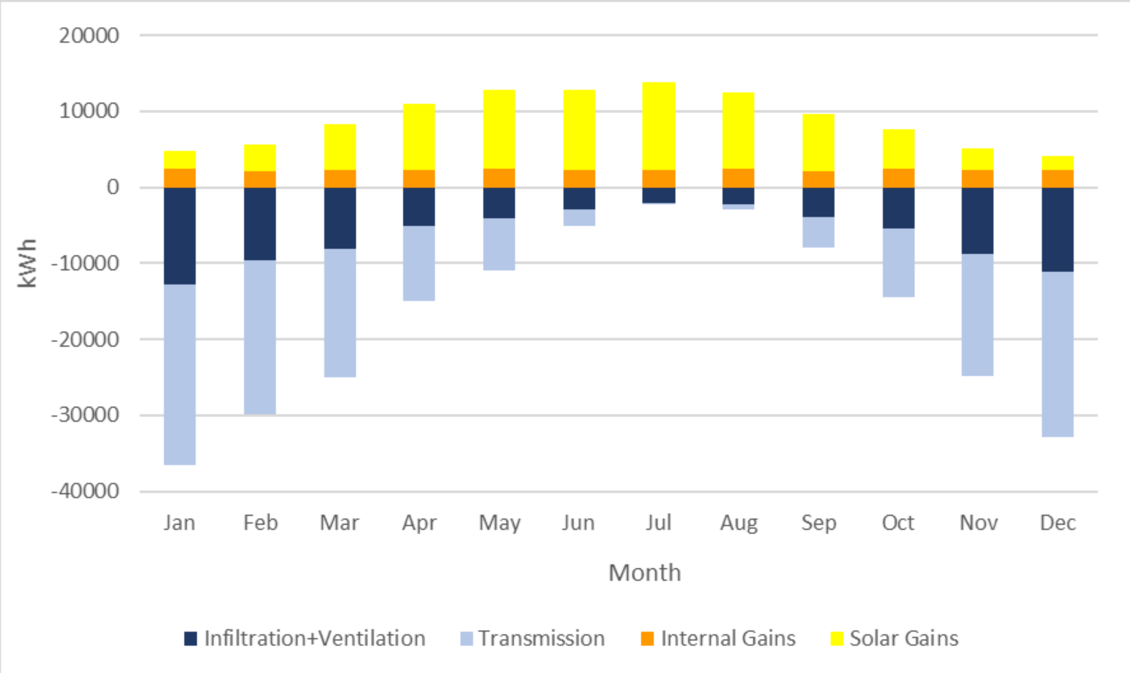
The balances of each building are shown in the next graphs. Infiltration and ventilation have been considered in the same group. And the people, equipment and appliances gains have been all considered as internal gains.

The result in terms of heating and cooling needs are shown in total and with reference to the floor are of the building in order to make different appreciations and understand the situation of each building.

5.2 Government Window

5.2.1 *Energy balance*

The results for the Government Window energy balance are shown in the next graph:



Graph 5.1: Government Window energy Balance

It can be appreciated that the solar gains are the predominant gains in the Government Window, especially in the summer months when the solar gains are at least 3 times higher than the internal gain. While in winter the total gains are equally divided between solar and internal.

In the case of the losses the ones with more incidence in the results are the ones due to the transmission which are 2 times higher in the coldest months than the infiltration and ventilation losses. This difference can be explained by the fact that it is not consider a mechanical ventilation, limiting the outside air entering the building and so the ventilation losses.

5.2.2 *Energy demand*

As it has been explained the energy demand it has been calculated as the energy needed to keep the energy balance as zero. Thus, the heating and cooling needs are the result of energy balance.

In the table 3 can be seen the results of heating and cooling needs monthly and totals, and in absolute values and per square meter.

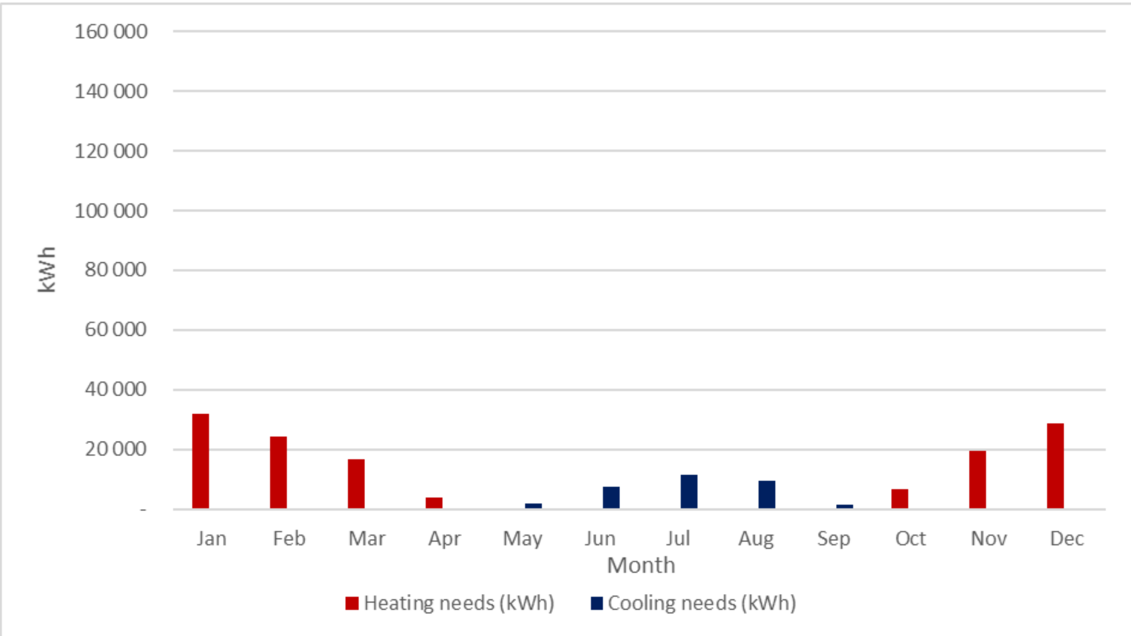
Area (m2)	2 295			
Month	Heating needs (kWh_{th})	Cooling needs (kWh_{th})	Heating needs (kWh_{th}/m2)	Cooling needs (kWh_{th}/m2)
Jan	31 843.74	-	13.88	-
Feb	24 201.75	-	10.55	-
Mar	16 593.22	-	7.23	-
Apr	3 991.26	-	1.74	-
May	135.14	1 992.77	0.06	0.87
Jun	-	7 629.31	-	3.32
Jul	-	11 580.41	-	5.05
Aug	-	9 550.36	-	4.16
Sep	-	1 693.61	-	0.74
Oct	6 694.16	-	2.92	-
Nov	19 673.05	-	8.57	-
Dec	28 610.05	-	12.47	-
Year	131 742.37	32 446.45	57.40	14.14

Table 5.1: Government Window energy needs

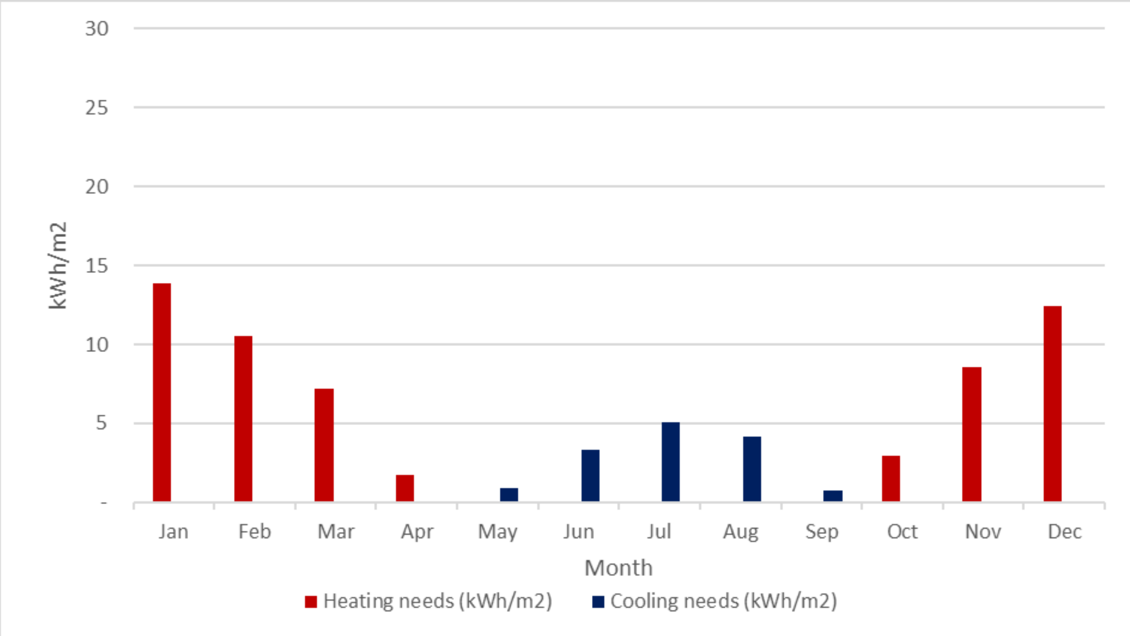
As expected the heating needs are much higher than the cooling needs due to the Budapest climate. The months of January and February have the highest heating needs, and in terms of cooling July and August are the hottest months.

Considering the whole year, the total heating needs are 132 MWh while the cooling needs 32MWh. In reference to the building floor area, which is the best way to analyze the building performance, the results are 57.40 kWh/m2 for heating and 14.14 kWh/m2 for cooling.

The results are also represented in graphs 9 and 10. The axis are the same for the 3 buildings in order to ease the comparison between them. That is why these graphs look disproportionate.



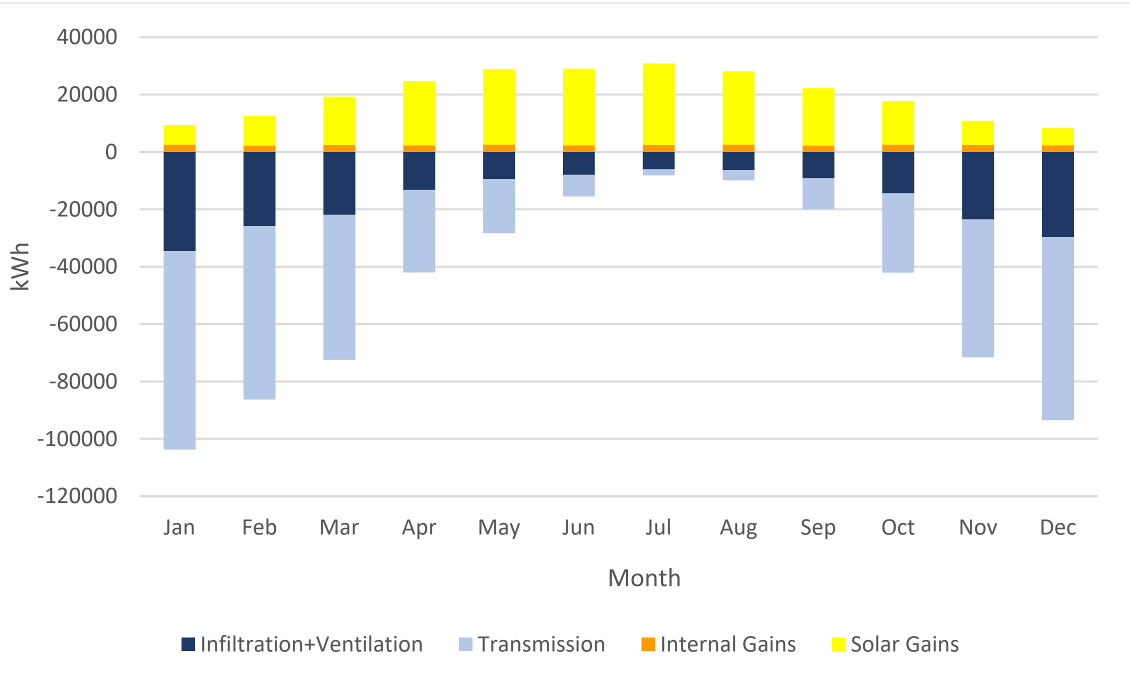
Graph 5.2: Government Window energy needs



Graph 5.3: Government Window energy needs per square meter

5.3 Mayor’s office

The Mayor’s office results from the energy balance are shown in the graph below:



Graph 5.4: Mayor’s Office energy balance

The results are in the same line as the Government Window, solar gains and transmission losses are higher than internal gains and ventilation losses. In this case the internal gains have even less incidence compared with the other gains and losses. It can also be appreciated how the difference between the transmission and ventilation losses has been increased, being the transmission close to 3 times higher than the ventilation losses in the coldest months. This is not only because of the lack of mechanical ventilation, but also because of the low insulation of the Mayor's Office, increasing the transmission losses.

5.3.1 *Energy demand*

After the energy balance the heating and cooling needs can be calculated.

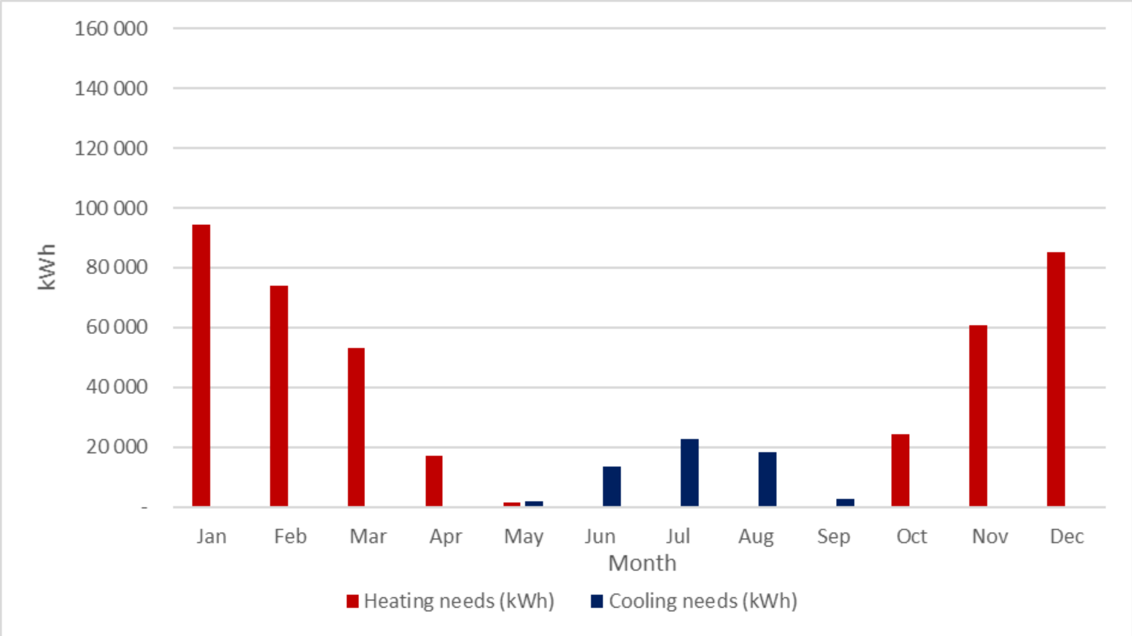
The results for the Mayor´s Office are shown in table 4.

Area (m2)	3 600			
Month	Heating needs (kWh_{th})	Cooling needs (kWh_{th})	Heating needs (kWh_{th}/m2)	Cooling needs (kWh_{th}/m2)
Jan	94 282.81	-	26.19	-
Feb	73 805.33	-	20.50	-
Mar	53 217.53	-	14.78	-
Apr	17 257.70	-	4.79	-
May	1 479.14	2 017.65	0.41	0.56
Jun	-	13 561.20	-	3.77
Jul	-	22 727.38	-	6.31
Aug	-	18 291.42	-	5.08
Sep	471.38	2 833.51	0.13	0.79
Oct	24 281.26	-	6.74	-
Nov	60 726.68	-	16.87	-
Dec	85 192.05	-	23.66	-
Year	410 713.87	59 431.15	114.09	16.51

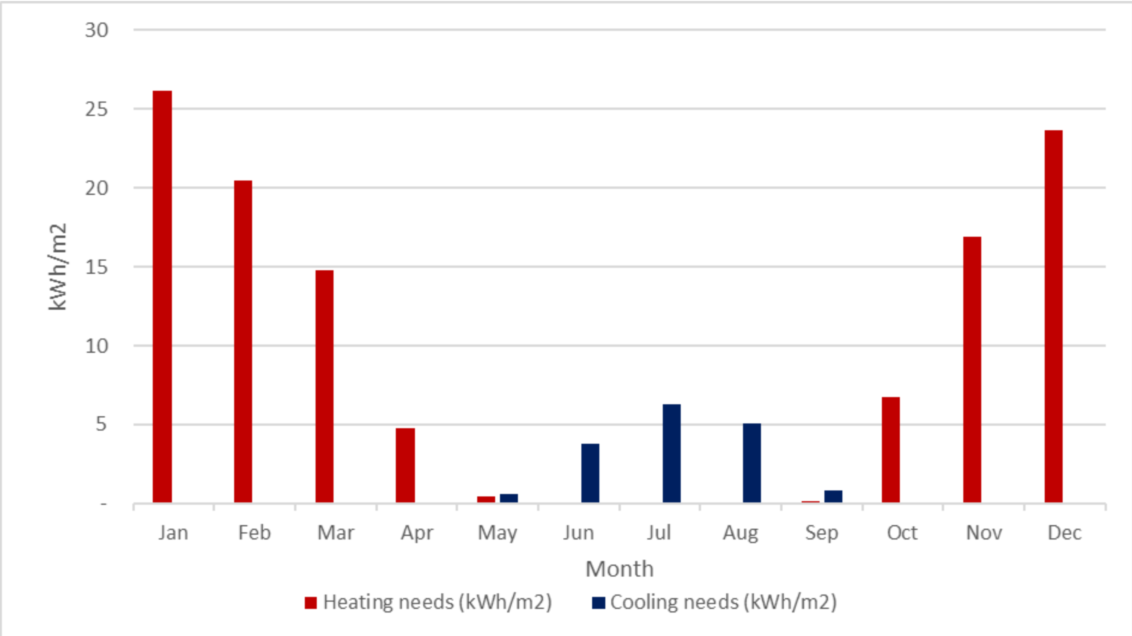
Table 5.2: Mayor's Office energy needs

The pattern is logically the same as for the Government Window but can be appreciate a considerable increment of the energy needs, from 132 MWh to more than 410 MWh. The cooling needs are more than 59 MWh. The increment is logical considering that is a bigger building but considering the results per square meter can be appreciated that the difference is even higher regarding the heating needs, which are nearly 115 kWh/m2, while the cooling needs are very similar to the ones of the Government Window. This is caused because of the characteristics of the building. As it has been said earlier, the Mayor's Office has a poor insulation in the outside walls, problem that cannot be fixed due to fact that it is an architecturally protected building.

In the graphs 11 and 12 the results are shown graphically.



Graph 5.5: Mayor's Office energy needs

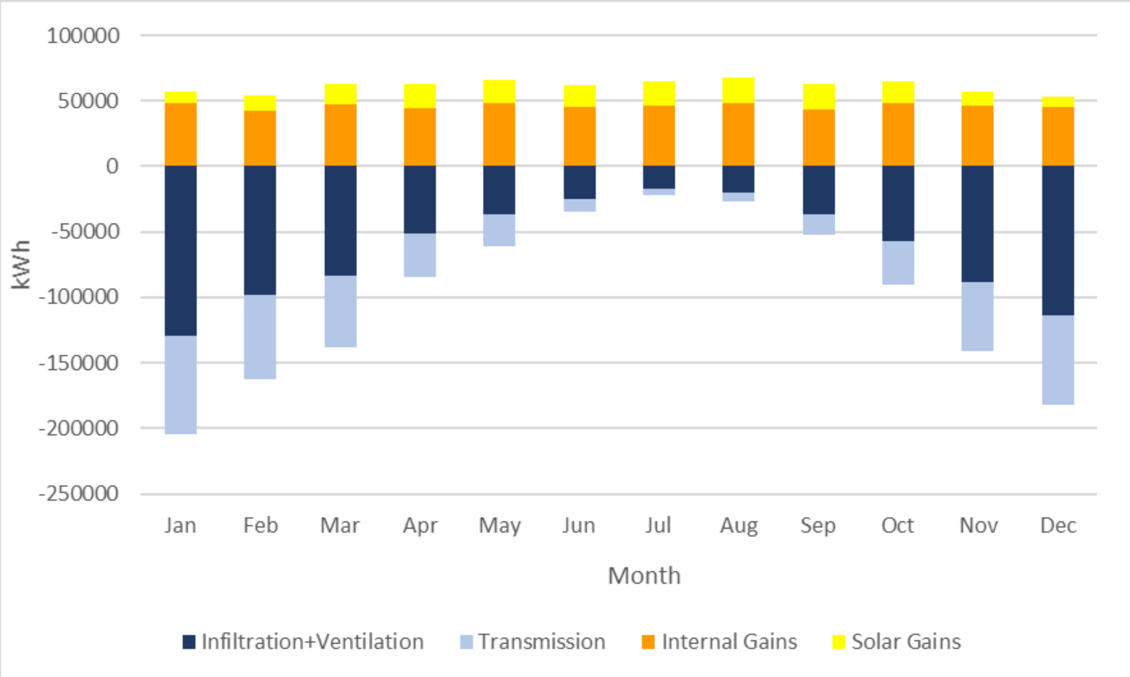


Graph 5.6: Mayor's Office energy needs per square meter

5.4 New Market Hall

5.4.1 *Energy Balance*

The results of the New Market energy balance hall show a relevant difference with the balances of the Mayor's Office and Government Window.



Graph 5.7: New Market Hall energy balance

In this case the internal gains have are much higher than the solar gains. And in the part of losses can be appreciated how the ventilation and infiltration losses are higher than the transmission ones.

The explanation of the change in the gains is that as the there is a different use of the building, in this case is a market, there are much more people to be considered in the analysis, causing an important increment in the internal gains, close to 5000 kWh, and constant during the year.

Regarding the losses, as is a new building it is better insulated (UA=0.28W/m2K) reducing the transmission losses. Besides that, in this case it has been considered mechanical ventilation, which was not considered in the previous cases. As mechanical ventilation is considered and in order to respect the indoor air quality requirements, the ventilation losses have increased considerably compared with the transmission losses (3 times higher).

5.4.2 *Energy demand*

After the energy balance, the energy heating and cooling needs can be presented.

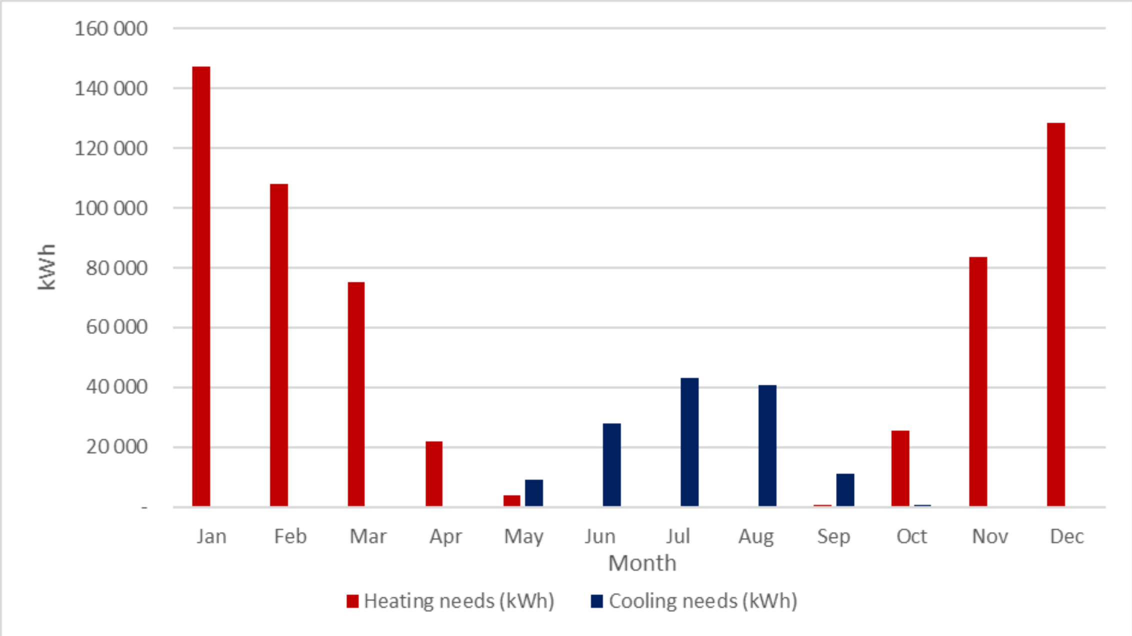
In table 5.3 are shown the results of the third building analyzed, the New Market Hall.

Area (m2)	12 000			
Month	Heating needs (kWh_{th})	Cooling needs (kWh_{th})	Heating needs (kWh_{th}/m2)	Cooling needs (kWh_{th}/m2)
Jan	147 229.03	-	12.27	-
Feb	108 133.30	-	9.01	-
Mar	75 026.57	-	6.25	-
Apr	21 814.89	56.01	1.82	-
May	3 857.06	8 982.76	0.32	0.75
Jun	-	27 834.01	-	2.32
Jul	-	43 219.78	-	3.60
Aug	-	40 833.84	-	3.40
Sep	516.86	11 289.29	0.04	0.94
Oct	25 709.48	748.47	2.14	0.06
Nov	83 474.24	-	6.96	-
Dec	128 527.99	-	10.71	-
Year	594 289.43	132 964.15	49.52	11.08

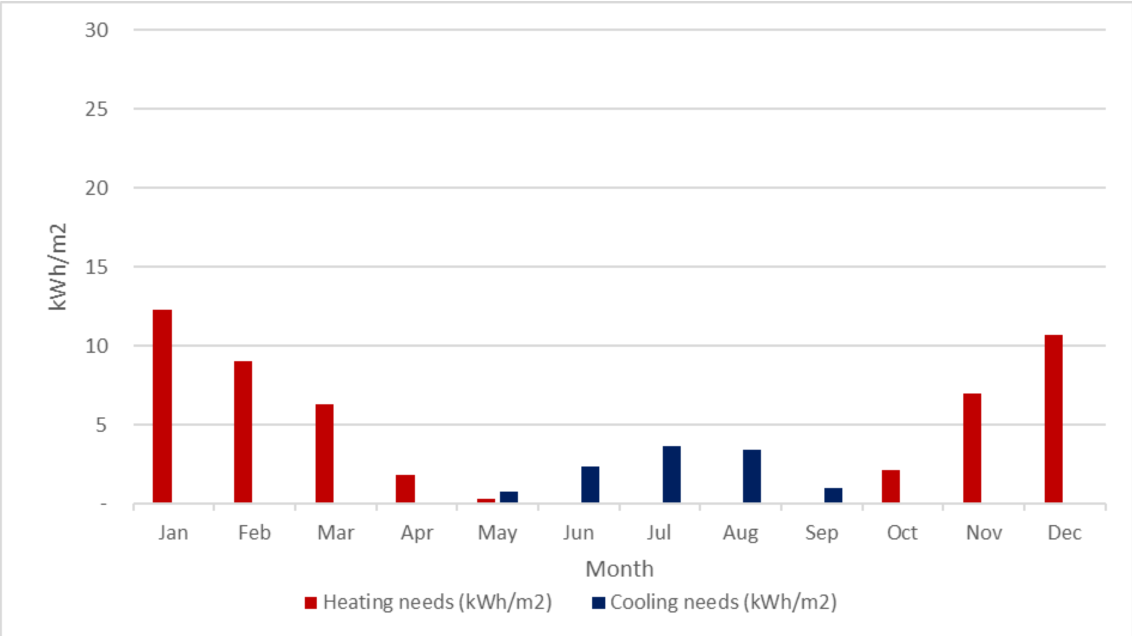
Table 5.4: New Market Hall energy needs

Again, the pattern is the same as the previous two buildings. In this case the both heating and cooling needs are higher in absolute terms, logical considering is much bigger building. The total heating needs are 594 MWh and the total cooling needs 77MWh. The area referenced results are 49.5 kWh/m2 for heating and 6.43 kWh/m2 for cooling. Lower in both cases that the results observed in the other 2 buildings. The explanation is that as it is a new building the insulation is higher reducing considerably the heat and cool needed for each square meter.

The results are shown graphically below.



Graph 5.8: New Market Hall energy needs

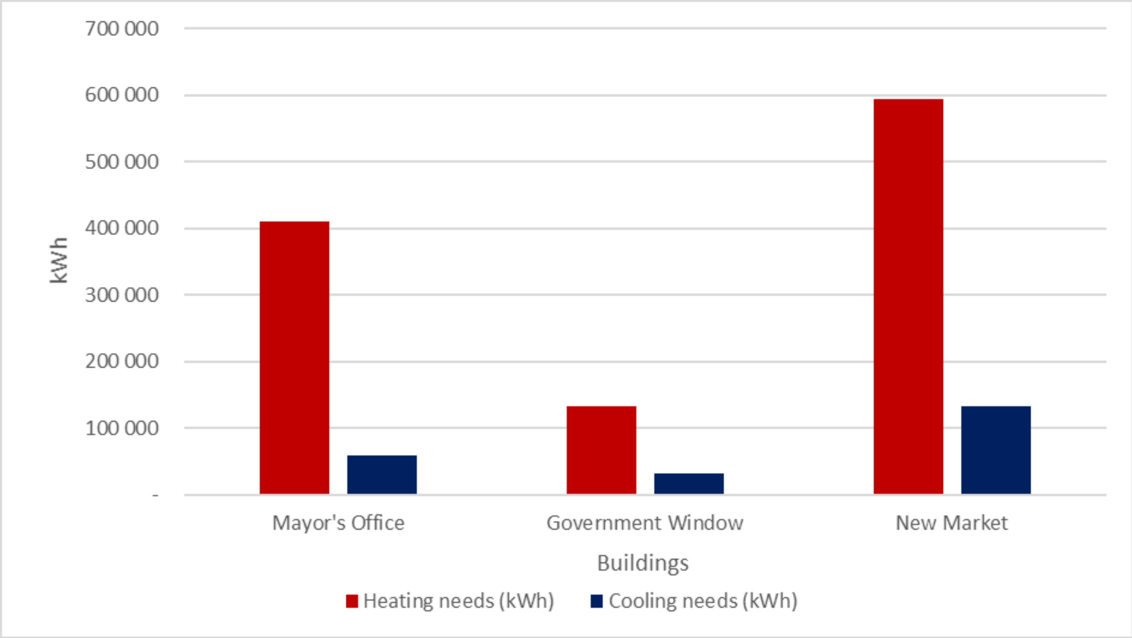


Graph 5.9: New Market Hall energy needs per square meter

5.5 Building energy needs comparison

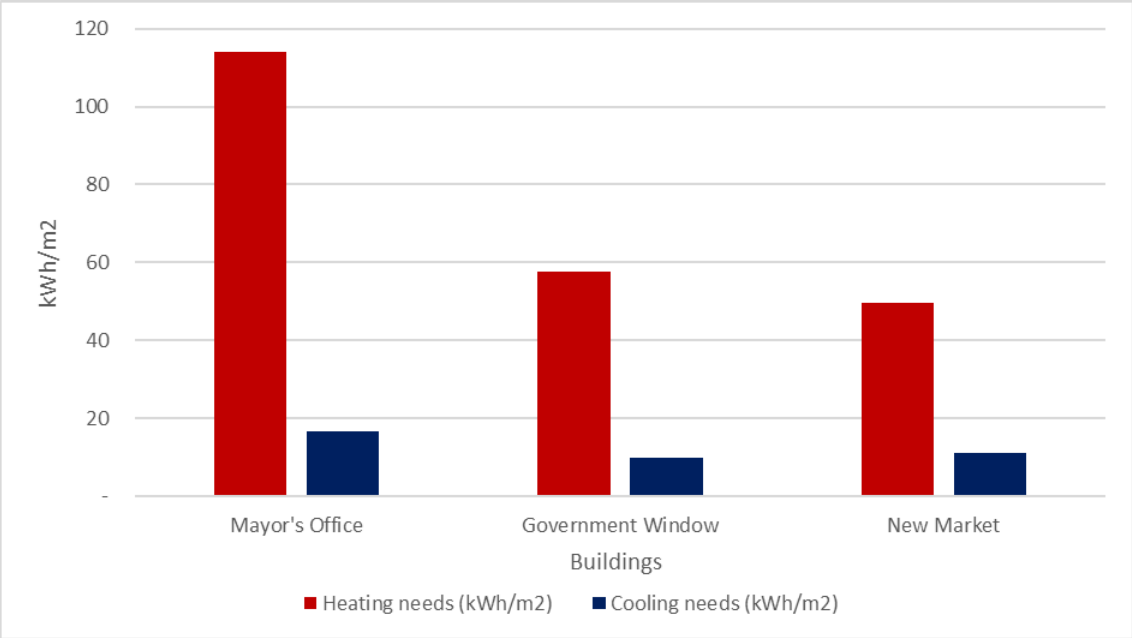
In this section the total results of the heating and cooling needs are compared, in order to have an overall view of the three buildings and how they behave.

The graphs 15 shows the total heating and cooling needs of each building.



Graph 5.10: Energy needs comparison between buildings

The graph 16 shows the heating and cooling needs per square meter of each building



Graph 5.11: Energy needs comparison between buildings per square meter

As it has been said the New Market Hall is the building with the higher total heating and cooling needs as expected due to its size. But at the same time is the one with lowest values per square meter, which means that is the most energetically efficient of the three, which is logical because is the newest.

In the other hand the Mayor’s Office is the less efficient of the three having the higher values referred to the area of the building. In this case is because of its low insulation when it was constructed in the beginning of the 20th century.

The Government Window being the smallest of the three buildings has less heating and cooling than the other two buildings, and it is more efficient than the Mayor's Office but less than the New Market Hall.

So, it can be clearly seen the relation between the year of construction and the energy efficiency of the buildings.

5.6 District network heating and cooling needs

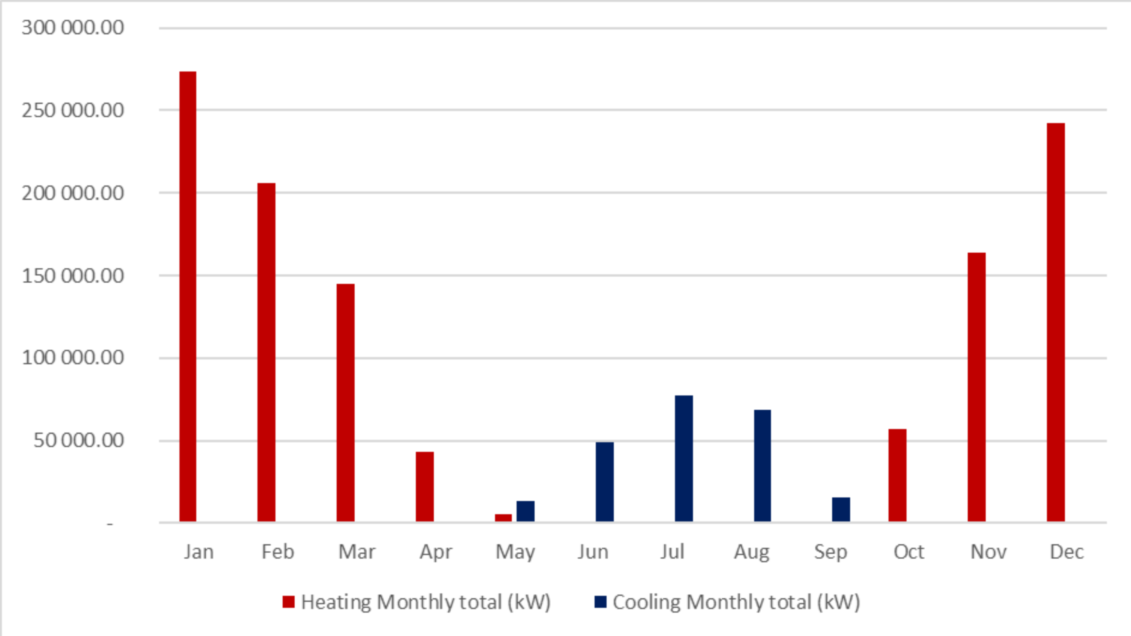
As it has been explained at the beginning the district energy systems are composed of different buildings that share the generation subsystem. For this project, the three buildings presented previously form the district system.

To determine the heating and cooling needs of the district system it is necessary to sum the individual needs of each building. In the total of the year it will be necessary more than 1140 MWh for heating and more than 134 MWh for cooling.

In the following table and graph are presented the monthly district heating and cooling needs.

Month	Heating Monthly total (kWh_{th})	Cooling Monthly total (kWh_{th})
Jan	273 355.58	-
Feb	206 140.37	-
Mar	144 837.32	-
Apr	43 063.85	56.01
May	5 471.35	12 993.18
Jun	-	49 024.51
Jul	-	77 527.56
Aug	-	68 675.61
Sep	988.24	15 816.41
Oct	56 684.90	748.47
Nov	163 873.97	-
Dec	242 330.08	-
TOTAL	1 136 746	224 842

Table 5.5: District heating and cooling needs



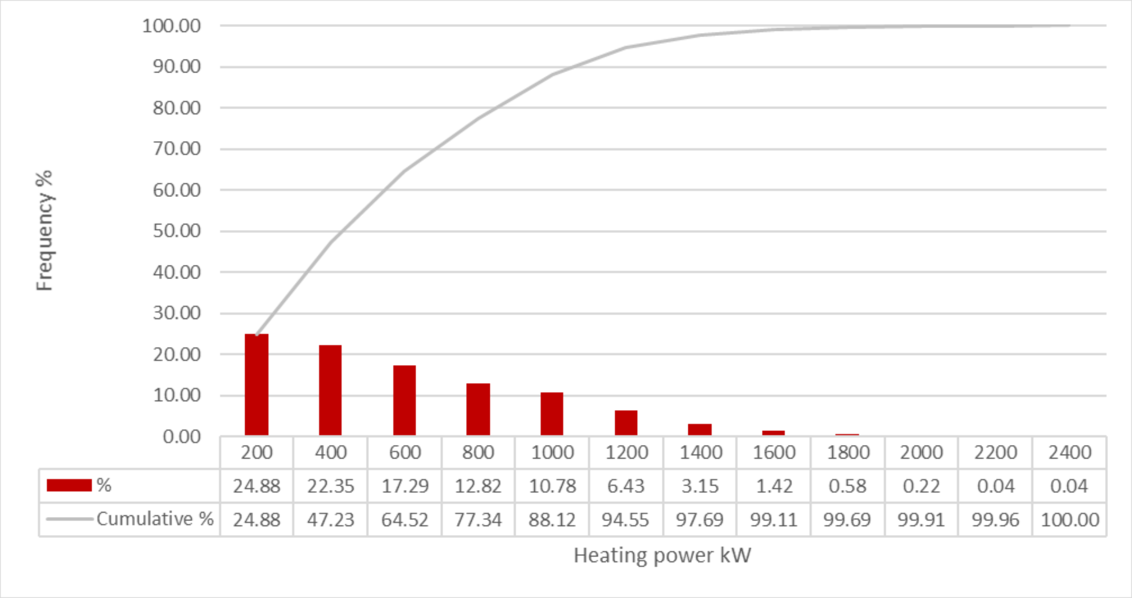
Graph 5.12: District heating and cooling needs

But to design the suitable energy system it is important to focus in the power needed in each time interval. The time intervals have been defined of one hour. So, the heating power is the mean value over that interval.

The maximum heating power needed considering the three buildings corresponds to January 15th, when are needed more than 2260 kW. Regarding the cooling power more than 675 kW are needed on July 23rd. These values are the maximum power needed at certain time interval, but they do not necessarily represent the typical functioning point, in fact they rarely do.

To understand how the system will work in normal situation it has been analyzed the power needed by all the buildings at every interval during the year. In the next graphs is presented the frequency in percentage of the power needed by the system when it is working for heating and cooling.

For heating the results are:

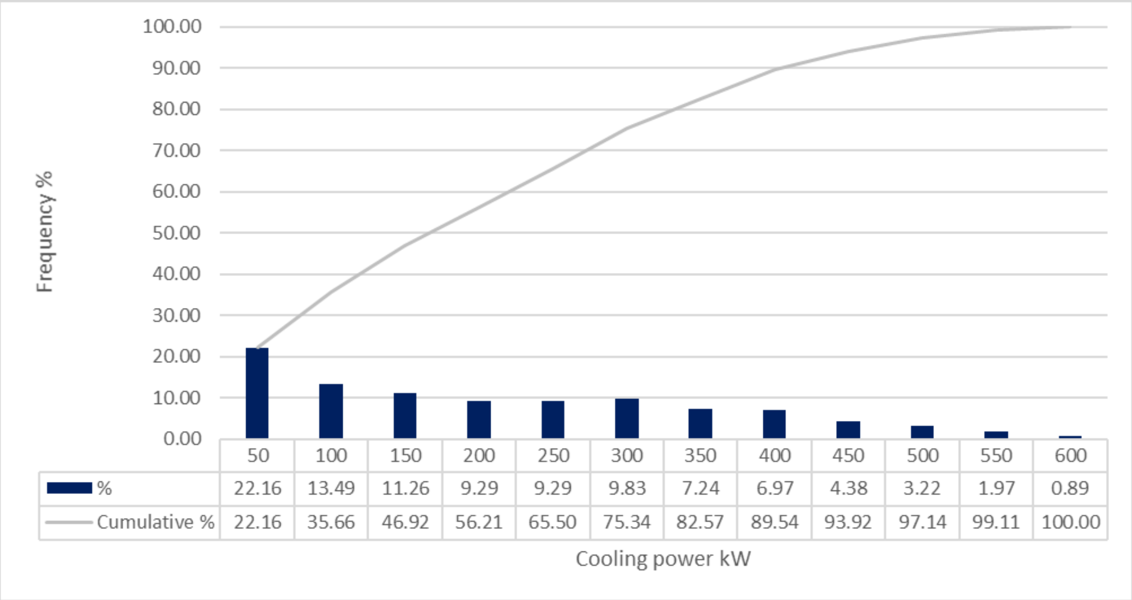


	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
%	24.88	22.35	17.29	12.82	10.78	6.43	3.15	1.42	0.58	0.22	0.04	0.04
Cumulative %	24.88	47.23	64.52	77.34	88.12	94.55	97.69	99.11	99.69	99.91	99.96	100.00

Graph 5.13: Heating power needed frequency in percentage

It is possible to observe that the 88% of the year are need less than 1000 kW, and close to the 50% are needed less than 400 kW. In the other side, more than 2000 kW, as the maximum previously commented, are needed less than the 1% of the time

In the case of the cooling power needed:



	50	100	150	200	250	300	350	400	450	500	550	600
%	22.16	13.49	11.26	9.29	9.29	9.83	7.24	6.97	4.38	3.22	1.97	0.89
Cumulative %	22.16	35.66	46.92	56.21	65.50	75.34	82.57	89.54	93.92	97.14	99.11	100.00

Graph 5.14: Cooling power needed frequency percentage

Again, can be seen that the maximum cooling power needed is only in a few cases a year. In this case close to the 75% of the time are needed less than 300 kW and the 77% of it less than 200 kW are needed. While more than 400 kW are required less than the 18% of the time.

Is important to have all this into consideration in order not to oversize the energy system to install, which could cause a poor performance.

As it has been said the generation system will be a heat pump that will be explained and detailed later. The initial idea in this thesis is to provide the heating and cooling demand with this heat pump. The heat pump nominal power is around 800 kW for heating and cooling, enough to cover the maximum cooling needs, but not enough to cover the maximum heating needs. In order to solve this, it is proposed to use the heat pump constantly at nominal power and take advantage of the district system thermal inertia when the need surpasses the heat pump nominal power. Later are shown the calculations to see if it is possible.

6 District energy system

6.1 Introduction

As it has been said one of the main advantages of the implementation of a district system is to have a common generation system, giving the opportunity to use solutions that would be too expensive for individual use. In this case the idea is to recover part of the heat lost in the sewage system. With this purpose is going to be used a generation system composed by a sewage heat exchanger and a water heat pump. Other important elements that have to be taken into account are the pipes. They are necessary to carry the power generated in the engine house to the building conforming the district system.

In the figure below can be observed the district system layout. With the 3 buildings, the forward and return pipelines, the engine house and the sewer.

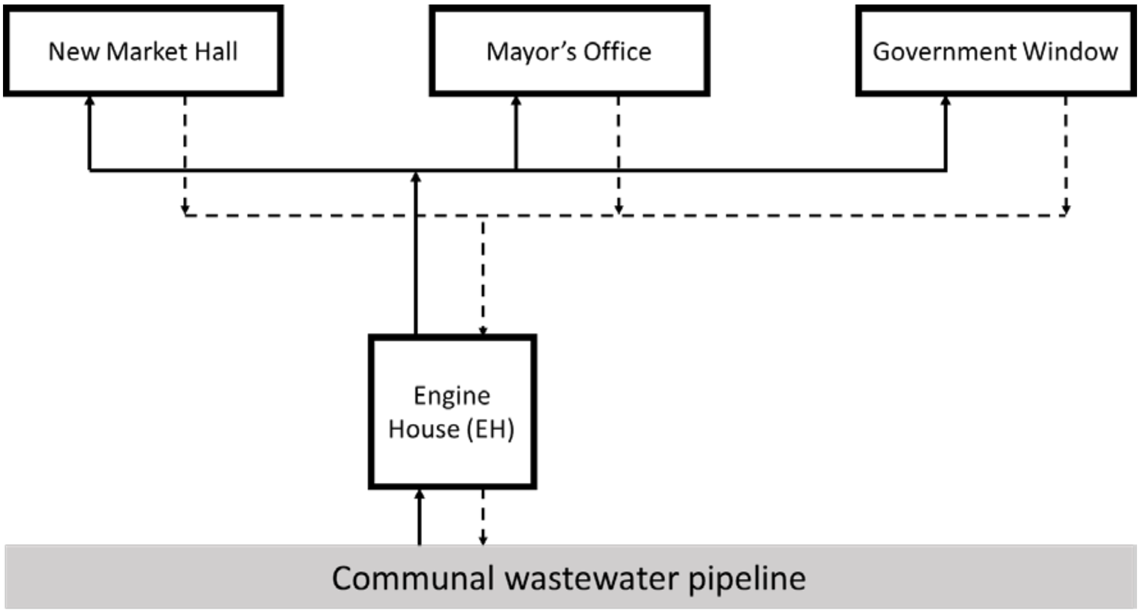


Figure 6.1: District energy system layout

In the next figure is shown with more detail the engine house and its components:

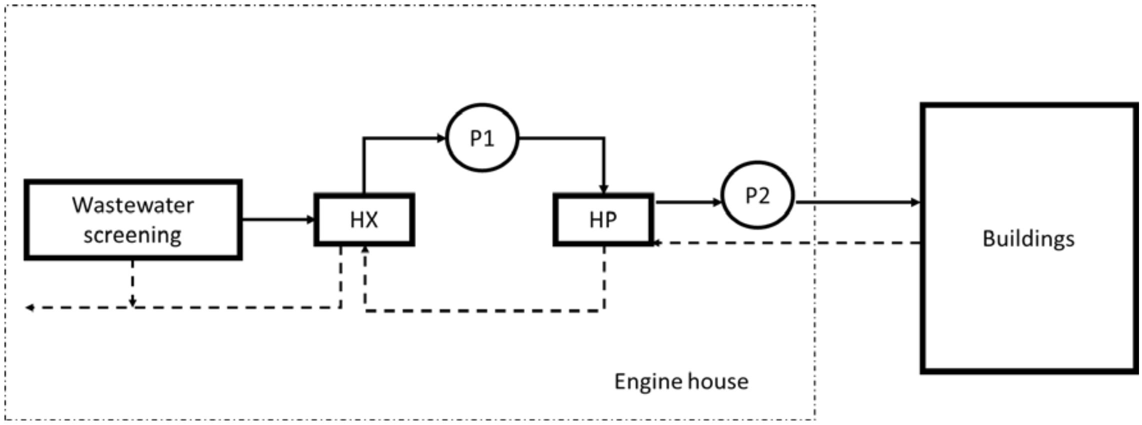


Figure 6.2: Engine house components

In the engine house can be found the wastewater screening station, used for filtering the sewage water, and returning the solid particles and sludge to the sewer. The heat exchanger (HX) necessary to extract the heat contained in the wastewater. The heat pump (HP), the element responsible for providing the energy to the buildings. Finally, 2 hydraulic pumps (P1 and P2) in charge of making the water flow through the system.

As it has been said, one of the advantages of using a heat pump is its reversibility, allowing to operate in winter and summer, fulfilling the heating and cooling demand. It is important as well the low variation in the sewage temperature between seasons, which allows the system with high efficiency as it will be explained later. The functioning of sewage heat exchanger coupled with the heat pump in heating and cooling season is shown in the figure below.

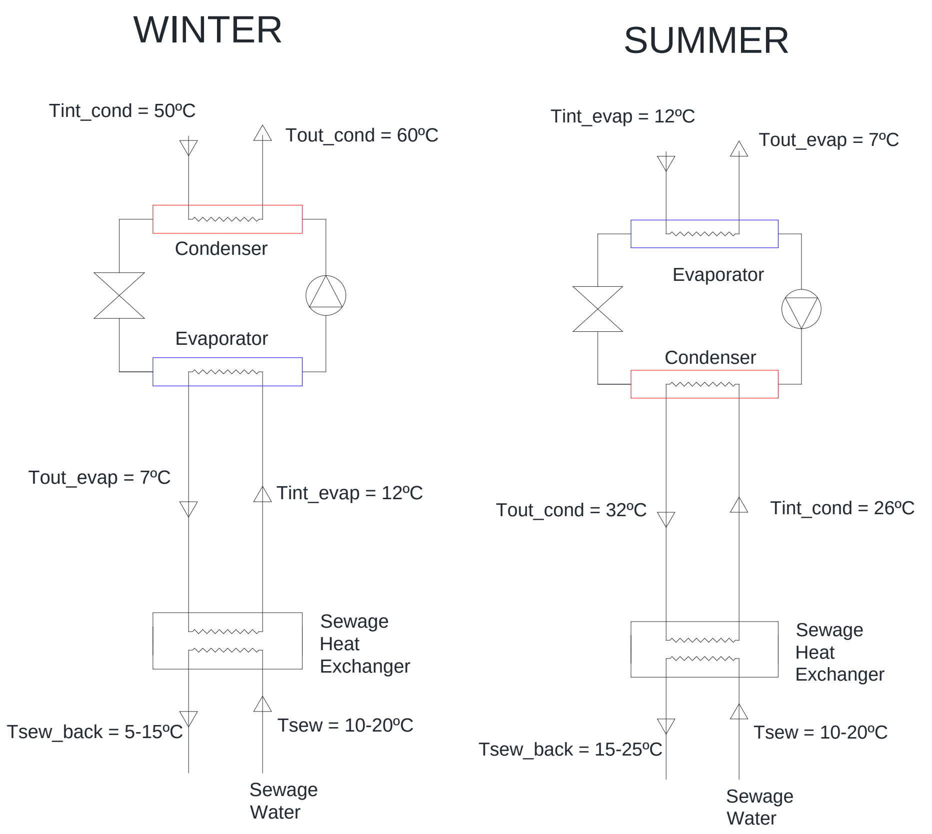


Figure 6.3: Heat exchanger heat pump functioning scheme in winter and summer

As it can be seen change the heat pump mode depending on the season it has to be inverted the direction of the flow, inverting the condenser and the evaporator. It is important to notice that the sewage water through the heat exchanger works as a source in the heating period, and as a sink in the cooling period.

6.2 Heat Pump

The heat pump is the generation system selected, mainly for its consideration as a renewable source of energy and for being the best solution to recover the heat from the sewage coupled with a heat exchanger.

The model selected by Thermowatt for this purpose is the 30XWHP0712 from Carrier (15), a water-to-water heat pump with twin-rotor screw compressors with nominal heating and cooling capacities of around 800kW.

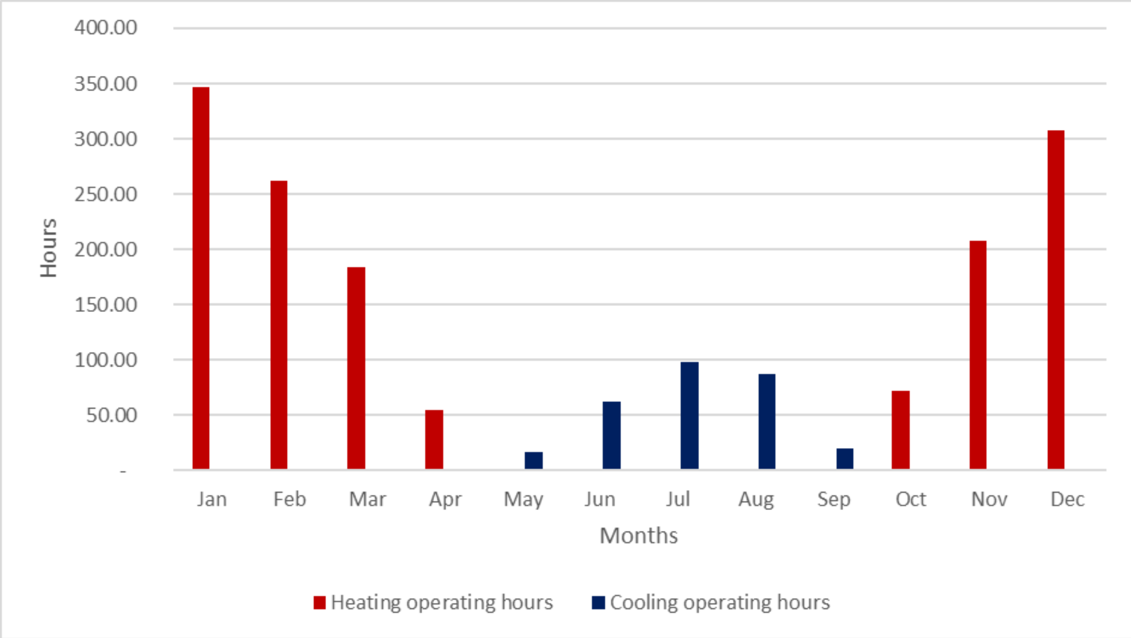
Figure 6.4: Heat pump 30XWHP0712 model

It has been selected for being water-to-water, a requirement given the working conditions (sewage water and district system), and for its twin-rotor screw compressors, which as it has been explained previously are the best compressors for high outputs.

The nominal heating power of the heat pump is 788.33 kW and the nominal cooling power 738.9 kW. In the previous chapter has been seen the power needed monthly, yearly and the maximums in an hour. The nominal power of the heat pump covers the majority of the demand as it has been seen in the frequency charts, but not the maximums peaks of power. The idea for this energy system is to make it work always in nominal conditions and to take advantage of the thermal inertia of the system to compensate in both cases, when the demand is higher and when the demand is lower. When the demand is lower than the heat pump nominal power is obvious that can be covered. But when the demand is higher than the power provided in nominal conditions it would be necessary to predict the situation and to use the thermal inertia of the system.

It has been used the operating heating and cooling hours, calculated as the division of the monthly needs under the nominal power, as an approach to verify the feasibility of the system.

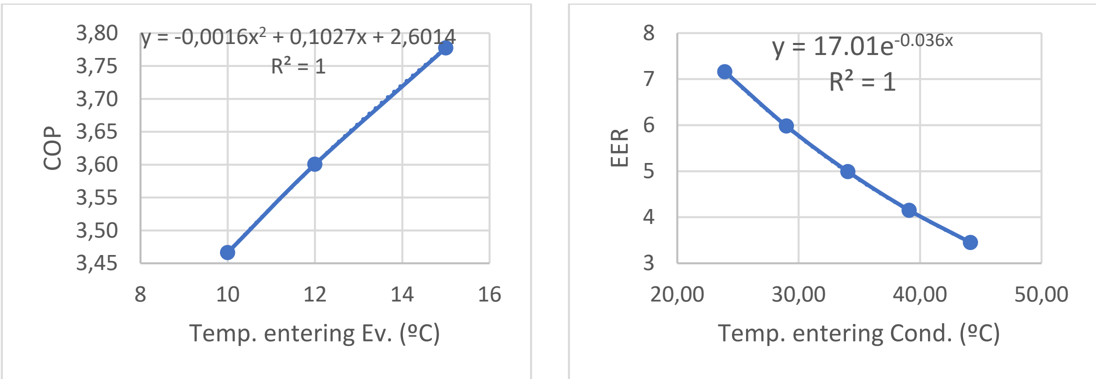
In the graph below it can be appreciated how the hour follow the same pattern of the needs, and how in any case it is surpassed the 600 hundred hours which would have meant the impossibility of the system to cover the needs.



Graph 6.1: Heat pump operating hours

Other point to take into account when talking about the heat pump is its reaction to the temperature coming from the sewage part, because is the principal reason to use this system, the heat recovered from the sewer.

Using the heat pump datasheet given by the supplier it has been possible to establish a relation between the heat pump COP/EER and the temperature coming from the sewage heat exchanger. These relationships are shown in the graph below:



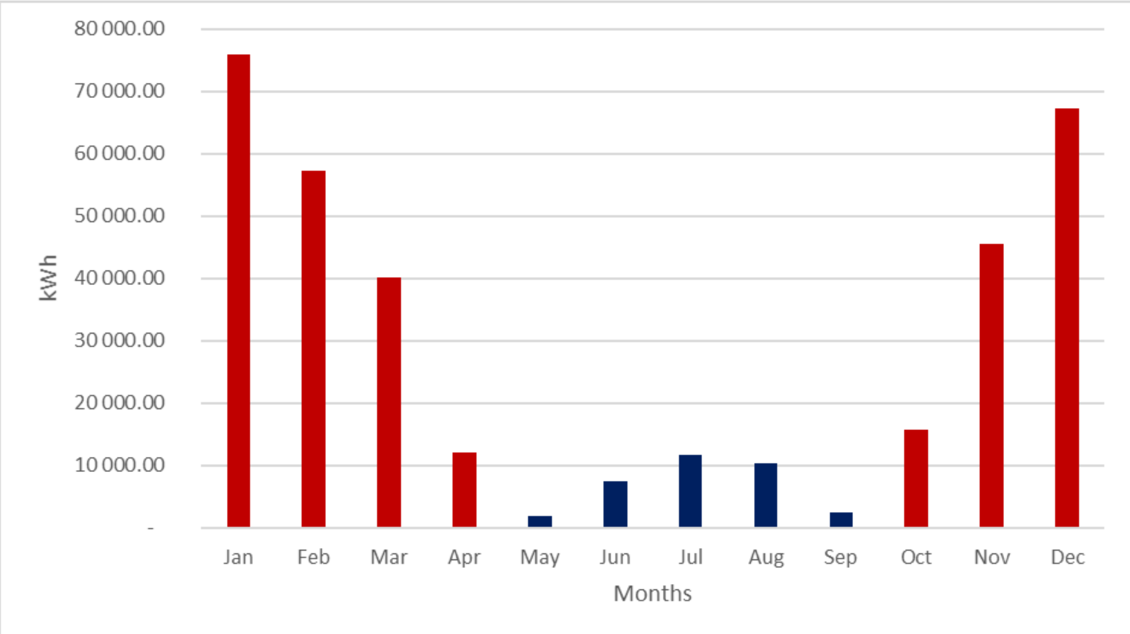
Graph 6.2: COP and EER heat pump variation with temperature

With these graphs and the energy needs of the building it is possible to calculate the heat pump electrical consumption. It has to be highlighted that this consumption it is only of the heat pump and under given circumstances, which are the nominal conditions.

Months	Tin HP (ºC)	COP	EER	Heating Monthly total (kWh_{th})	Cooling Monthly total (kWh_{th})	Electric Consumption (kWh_{ele})
Jan	12.00	3.603		273 355.58	-	75 860.46
Feb	12.00	3.603		206 140.37	-	57 207.19
Mar	12.00	3.603		144 837.32	-	40 194.63
Apr	12.00	3.603		43 063.85	-	11 950.89
May	26.00		6.671	-	12 993.18	1 947.65
Jun	26.00		6.671	-	49 024.51	7 348.67
Jul	26.00		6.671	-	77 527.56	11 621.21
Aug	26.00		6.671	-	68 675.61	10 294.32
Sep	26.00		6.671	-	15 816.41	2 370.85
Oct	12.00	3.603		56 684.90	-	15 730.95
Nov	12.00	3.603		163 873.97	-	45 477.60
Dec	12.00	3.603		242 330.08	-	67 250.40
					TOTAL	347 254.81

Table 6.1: Heat pump electric consumption in nominal conditions

The heat pump energy consumption is more than 347 MWh. The results are shown graphically below.



Graph 6.3: Heat pump electric consumption in nominal conditions

Again, it can be seen how the pattern is the same as the previously seen.

6.3 Heat exchanger

The heat exchanger is in charge of provided the energy taken from the sewer line. It has been selected a shell and tube heat exchanger model. Which consist of a large number of tubes contained in a tank (shell), and the axes of the shell and the tubes are in parallel.

The heat is exchanged between the fluids flowing inside the tubes and the fluid flowing through the volume of the shell.

Shell and Tube Heat Exchangers are one of the most popular types of exchanger due to the flexibility the designer has to allow for a wide range of pressures and temperatures. In this case the selected model has 2 shell passes.

In the figure below can be observed the design of the heat exchanger selected.

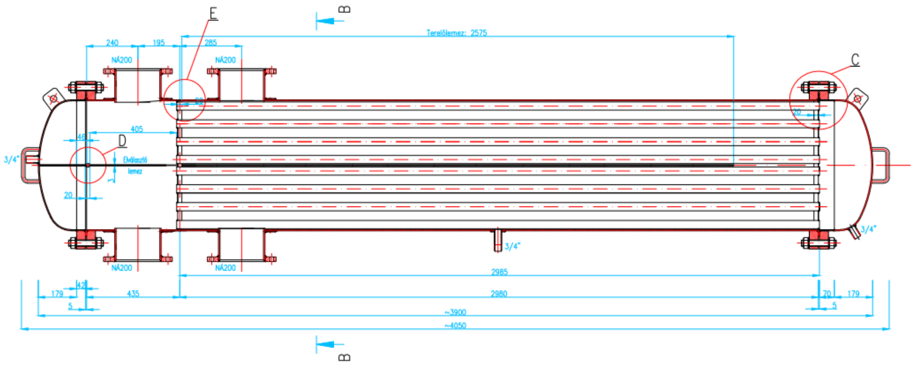


Figure 6.5: Heat exchanger

For this application (sewage water), it is very important to consider the possible loss of efficiency due to the deposition of solid particles coming from the sewer. To avoid this, the system has a previous filter that does not allow the sludge to access the heat exchanger. The screening is crucial in order to prevent the heat-exchanger from obstruction.

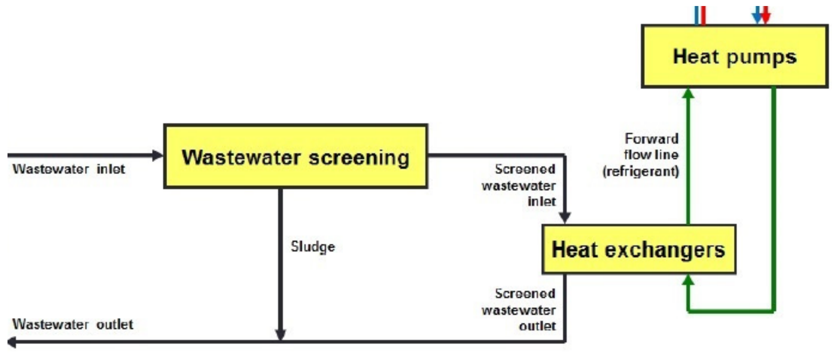


Figure 6.6: Wastewater screening system scheme

In addition, the supplier ensures that the heat exchanger is self-cleaning without any internal moving part (16).

Despite this and considering that the loss of efficiency due to deposition is one of the main problems of the sewage water recovery systems, some calculations on how the loss of efficiency could affect the performance of the heat exchanger have been carried out.

6.3.1 *Calculations*

The first calculations regarding the heat exchanger have been the ones related to the loss of efficiency because of the screen that could be formed. The mean logarithmic temperature method and the NTU method have been used for this purpose.

The sewage water temperature it is a determinant factor for the heat exchanger calculations. Thermowatt has provided wastewater temperature averages of different years. For the first calculations it has been chosen last year temperature averages. The average temperature of the sewage water in the heating period was 15ºC and in the cooling period was 19ºC. Also, the nominal data of the heat pump is assumed as the initial situation.

The calculations have been made separately for the heating period and for the cooling period.

For the heating period the starting point is the one shown on the scheme:

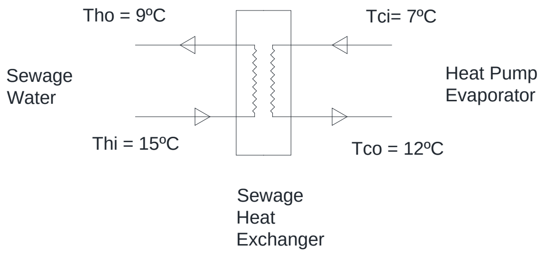


Figure 6.7: Heat exchanger scheme in heating period

The nominal power of the evaporator in these conditions is 590.90 kW, and its flow 28.23 l/s.

To calculate the mean logarithmic temperature, it is necessary to know that the heat exchanger works in counterflow, in order to determine the temperatures as follows:

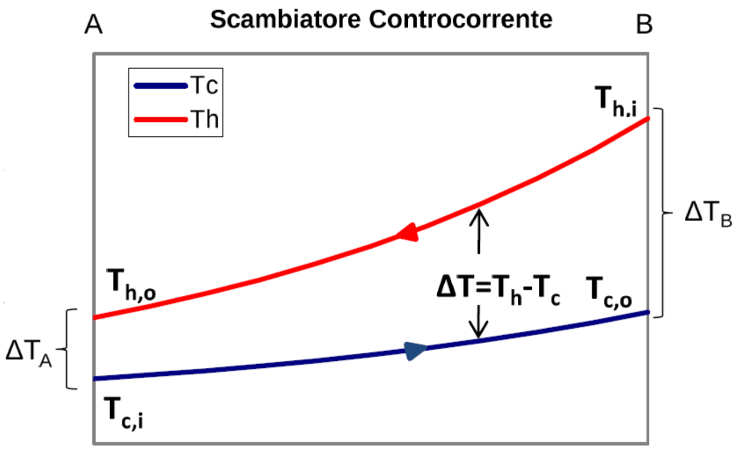


Figure 6.8: Counter flow scheme to calculate the mean logarithmic temperature

Applying the formula:

$$\Delta T_{ML} = \frac{\Delta T_B - \Delta T_A}{ln\left(\frac{\Delta T_B}{\Delta T_A}\right)} = \frac{(15-12)-(9-7)}{ln\left(\frac{15-12}{9-7}\right)} = 2.47ºC$$

For the shell and tube heat exchanger of two shell passes a correcting factor should be applied.

Knowing that: $t_1 = T_{Ci}$; $t_2 = T_{CO}$; $T_1 = T_{hi}$; $T_2 = T_{2hO}$ it is possible to calculate:

$$R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{15-9}{12-7} = 1.2; \quad P = \frac{t_2 - t_1}{T_1 - t_1} = \frac{12-7}{15-7} = 0.63$$

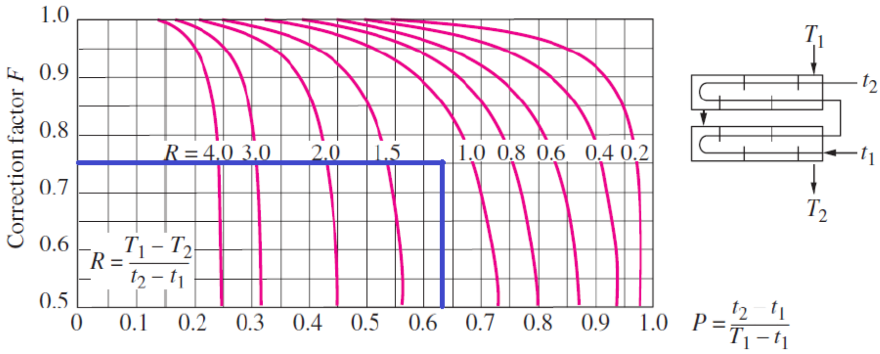


Figure 6.9: Mean logarithmic temperature for shell and tube heat exchanger with 2 water passes correction factor table

Getting graphically a correcting factor F=0.75.

So, the logarithmic mean temperature corrected is $\Delta T_{ML,C} = 1.85\ ºC$.

With the logarithmic mean temperature is possible to calculate the UA of the heat exchanger with the formula:

$$UA = \frac{P_{evap}}{\Delta T_{ML,C}} = \frac{590.9}{1.85} = 318.92\ kW/ºC$$

The UA value allows to calculate the NTU and this to calculate the efficiency. The UA value is what will be changed in order to try to understand the effect of the screen formed in the heat exchanger.

First it has to be calculated the initial conditions that will be common to all the scenarios.

$$\dot{m}_h = \frac{P_{evap}}{\Delta T_{evap} * c_{pw}} = \frac{590.9}{6 * 4.19} = 23.50\ kg/s$$

$$C_{min} = min(c_{pw} * \dot{m}_h, c_{pw} * \dot{m}_c) = (4.19 * 23.50, 4.19 * 28.23) = 98.47$$

$$NTU = \frac{UA}{C_{min}} = \frac{318.92}{4.19 * 23.5} = 3.24$$

$$c = \frac{C_{min}}{C_{max}} = \frac{4.19 * 23.5}{4.19 * 28.23} = 0.83$$

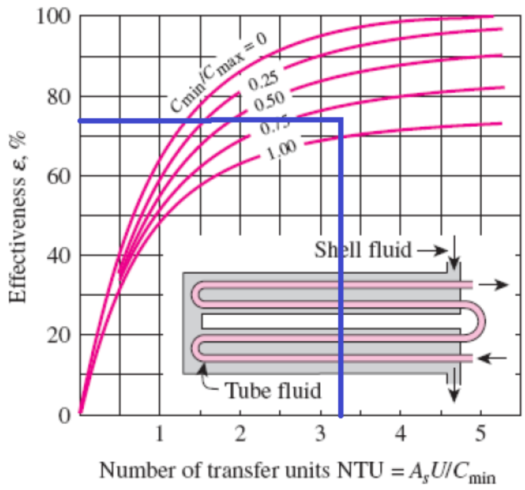


Figure 6.10: Shell and tube 2 passes efficiency table

It can be appreciated in the graph that the initial efficiency of the heat exchanger is around 0.75.

For the cooling period the same calculations have been carried out, in this case the initial conditions are shown in the next scheme:

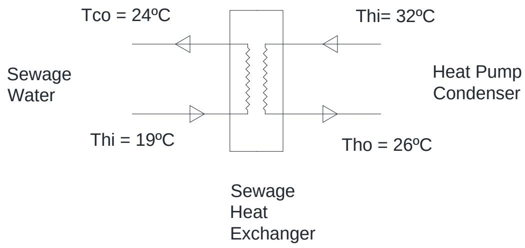


Figure 6.11: Heat exchanger scheme in cooling period

The nominal power of the condenser in these conditions is 861.60 kW, and its flow 34.44 l/s.

Applying again the formula:

$$\Delta T_{ML} = \frac{\Delta T_B - \Delta T_A}{ln\left(\frac{\Delta T_B}{\Delta T_A}\right)} = \frac{(32-24)-(26-19)}{ln\left(\frac{32-24}{26-19}\right)} = 7.49ºC$$

For the shell and tube heat exchanger of two shell passes a correcting factor should be applied.

Knowing that: $t_1 = T_{Ci}$; $t_2 = T_{CO}$; $T_1 = T_{hi}$; $T_2 = T_{2hO}$ it is possible to calculate:

$$R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{32-26}{24-19} = 1.2; \quad P = \frac{t_2 - t_1}{T_1 - t_1} = \frac{24-19}{32-19} = 0.38$$

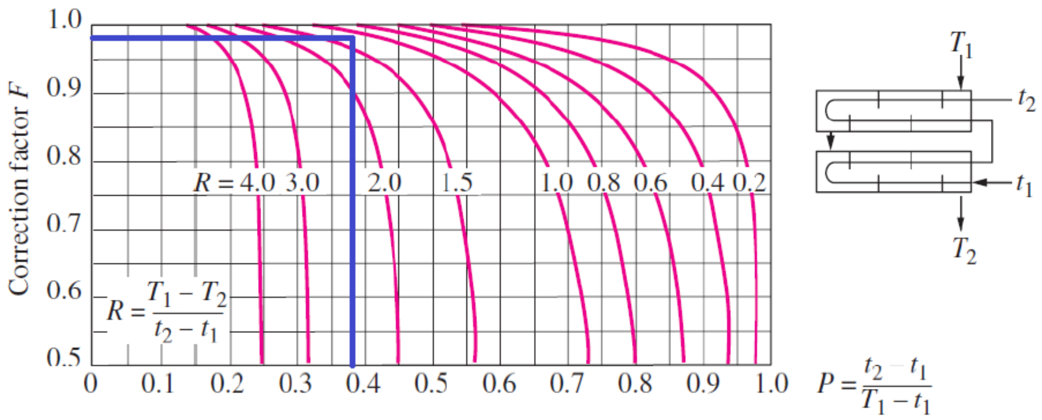


Figure 6.12: Mean logarithmic temperature for shell and tube heat exchanger with 2 water passes correction factor table

Getting graphically a correcting factor F=0.97.

So, the logarithmic mean temperature corrected is $\Delta T_{ML,C} = 7.27\ ºC$.

With the logarithmic mean temperature is possible to calculate the UA of the heat exchanger with the formula:

$$UA = \frac{P_{evap}}{\Delta T_{ML,C}} = \frac{861.60}{7.27} = 118.51\ kW/ºC$$

The UA value allows to calculate the NTU and this to calculate the efficiency. The UA value is what will be changed in order to try to understand the effect of the screen formed in the heat exchanger.

First it has to be calculated the initial conditions that will be common to all the scenarios.

$$\dot{m}_c = \frac{P_{con}}{\Delta T_{sew} * c_{pw}} = \frac{861.6}{5 * 4.19} = 41.12\ kg/s$$

$$C_{min} = min\left(c_{pw} * \dot{m}_h, c_{pw} * \dot{m}_c\right) = (4.19 * 34.44, 4.19 * 41.12) = 144.30$$

$$NTU = \frac{UA}{C_{min}} = \frac{118.51}{4.19 * 34.44} = 0.82$$

$$c = \frac{C_{min}}{C_{max}} = \frac{4.19 * 34.44}{4.19 * 41.12} = 0.84$$

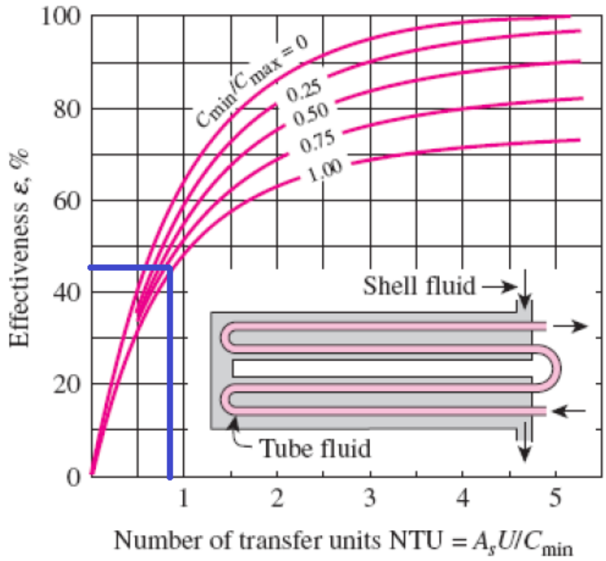


Figure 6.13: Shell and tube 2 passes efficiency table

It can be appreciated in the graph that the initial efficiency of the heat exchanger is around 0.46.

With this method it is possible to calculate the UA, NTU and the efficiency. The UA is the value that will change with the formation of the screen in different scenarios. The other values allow to calculate the effect of this change in the temperature entering the heat pump condenser or evaporator depending on the season.

It has been proposed 4 different scenarios of how the screen formation affects the performance of the heat exchanger:

- Scenario 1: no deterioration and normal performance of the heat exchanger.
- Scenario 2: decrease of 5% of the UA value each month, cleaning the heat exchanger in each change of season and at the end of the year.
- Scenario 3: decrease of 10% of the UA value each month, cleaning the heat exchanger in each change of season and at the end of the year.
- Scenario 4: decrease of 15% of the UA value each month, cleaning the heat exchanger in each change of season and at the end of the year.

In the next tables are shown scenarios 2, 3 and 4. In scenario 1 the values are the ones shown previously, making unnecessary its representation.

Scenario 2:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	302.97	287.83	273.43	118.50	112.58	106.95	101.60	96.52	318.92	302.97	287.83
NTU	3.24	3.08	2.92	2.78	0.82	0.78	0.74	0.70	0.67	3.24	3.08	2.92
ε	0.75	0.72	0.71	0.70	0.46	0.43	0.42	0.41	0.40	0.75	0.72	0.71
Tin HP	12.00	11.79	11.73	11.66	26.00	26.37	26.52	26.67	26.82	12.00	11.79	11.73

Table 6.2: 5% UA decrease per month cleaned at the start of the season

Scenario 3:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	287.03	258.33	232.49	118.50	106.65	95.99	86.39	77.75	318.92	287.03	258.33
NTU	3.24	2.92	2.62	2.36	0.82	0.74	0.67	0.60	0.54	3.24	2.92	2.62
ε	0.75	0.71	0.69	0.68	0.46	0.42	0.40	0.37	0.35	0.75	0.71	0.69
Tin HP	12.00	11.73	11.60	11.53	26.00	26.53	26.83	27.14	27.44	12.00	11.73	11.60

Table 6.3: 10% UA decrease per month cleaned at the start of the season

Scenario 4:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	271.08	230.42	195.86	118.50	100.73	85.62	72.77	61.86	318.92	271.08	230.42
NTU	3.24	2.75	2.34	1.99	0.82	0.70	0.59	0.50	0.43	3.24	2.75	2.34
ε	0.75	0.70	0.68	0.65	0.46	0.41	0.37	0.34	0.30	0.75	0.70	0.68
Tin HP	12.00	11.66	11.53	11.33	26.00	26.69	27.16	27.63	28.07	12.00	11.66	11.53

Table 6.4: 15% UA decrease per month cleaned at the start of the season

As expected, the UA decrease causes a temperature decrease in the heating season and an increase of temperature in the cooling season. These changes affect the behavior of the heat pump varying the COP and EER depending on the season, and consequently changing the electric consumption calculated in the previous chapter.

It has been calculated the electric consumption of the heat pump in each of the three scenarios:

Scenario 2:

Months	Tin HP (ºC)	COP	EER	Electric Consumption (kWh_{ele})
Jan	12.00	3.603	-	75 860.46
Feb	11.79	3.590	-	57 418.40
Mar	11.73	3.586	-	40 391.78
Apr	11.66	3.581	-	12 024.09
May	26.00	-	6.671	1 947.65
Jun	26.37	-	6.583	7 447.41
Jul	26.52	-	6.548	11 840.12
Aug	26.67	-	6.513	10 544.42
Sep	26.82	-	6.478	2 441.49
Oct	12.00	3.603	-	15 730.95
Nov	11.79	3.590	-	45 645.51
Dec	11.73	3.586	-	67 580.26
			TOTAL	348 872.54

Table 6.5: Electric consumption scenario 2

Scenario 3:

Months	Tin HP (ºC)	COP	EER	Electric Consumption (kWh_{ele})
Jan	12.00	3.603	-	75 860.46
Feb	11.73	3.586	-	57 487.78
Mar	11.60	3.577	-	40 490.11
Apr	11.53	3.573	-	12 053.49
May	26.00	-	6.671	1 947.65
Jun	26.53	-	6.546	7 489.26
Jul	26.83	-	6.474	11 974.42
Aug	27.14	-	6.404	10 724.44
Sep	27.44	-	6.334	2 496.95
Oct	12.00	3.603	-	15 730.95
Nov	11.73	3.586	-	45 700.66
Dec	11.60	3.577	-	67 744.78
			TOTAL	349 700.95

Table 6.6: Electric consumption scenario 3

Scenario 4:

Months	Tin HP (ºC)	COP	EER	Electric Consumption (kWh_{ele})
Jan	12.00	3.603	-	75 860.46
Feb	11.66	3.581	-	57 557.56
Mar	11.53	3.573	-	40 539.70
Apr	11.33	3.560	-	12 098.23
May	26.00	-	6.671	1 947.65
Jun	26.69	-	6.507	7 533.99
Jul	27.16	-	6.398	12 118.04
Aug	27.63	-	6.292	10 915.23
Sep	28.07	-	6.191	2 554.73
Oct	12.00	3.603	-	15 730.95
Nov	11.66	3.581	-	45 756.13
Dec	11.53	3.573	-	67 827.75
			TOTAL	350 440.42

Table 6.7: Electric consumption scenario 4

It can be appreciated how the electric consumption rises as the screen formation increases. Although the differences are not that high, from scenario 1 (no screen formation) to scenario 4 (15% of UA decrease) the yearly electric consumption increases in more than 3 MWh. In any case it is shown how the temperature affects directly the electric consumption of the heat pump.

6.3.2 *Sewage water temperature*

As it has been said previously Thermowatt provided wastewater temperatures of different years. To see how the sewage water temperature affects the performance of the system two years ago temperature averages have been considered.

In this case the average for heating season was 17ºC, and 22ºC for the cooling season.

It has been considered that the heat exchanger behaves as calculated before, maintaining the efficiency and the flows in both sides, considering that the change in the sewage temperature affects the temperature of the water entering the heat exchanger.

For the heating period the change of temperature to 17ºC makes the temperature change as it follows:

$$\varepsilon = \frac{28.23 * (T_{co} - 7)}{23..5 * (17 - 7)} = 0.75$$

$$T_{co} = 13.24\ ºC$$

For the cooling period the change of temperature to 22ºC makes the temperature change as it follows:

$$\varepsilon = \frac{32 - T_{ho}}{32 - 22} = 0.46$$

$$T_{co} = 27.4\ ºC$$

With these 2 temperatures, the electric consumption of the heat pump has been recalculated. It has been considered the scenario 1.

The results are shown in the next table:

Months	Tin HP (ºC)	COP	EER	Electric Consumption (kWh_{ele})
Jan	13.24	3.681	-	74 267.85
Feb	13.24	3.681	-	56 006.18
Mar	13.24	3.681	-	39 350.78
Apr	13.24	3.681	-	11 700.00
May	27.40	-	6.343	2 048.33
Jun	27.40	-	6.343	7 728.53
Jul	27.40	-	6.343	12 221.93
Aug	27.40	-	6.343	10 826.46
Sep	27.40	-	6.343	2 493.40
Oct	13.24	3.681	-	15 400.69
Nov	13.24	3.681	-	44 522.84
Dec	13.24	3.681	-	65 838.55
			TOTAL	342 405.54

Table 6.8: 2nd temperature model electric consumption scenario 1

Compared to the previous temperatures considered in the first scenario, it can be observed a decrease of more than 5 MWh. This is due to the fact that the heating needs are higher than the cooling needs, so an increase in the sewage water temperature in both season is more beneficial due to its incidence in the heating season.

The other 3 scenarios have been also recalculated.

Scenario 2:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	302.97	287.83	273.43	118.50	112.58	106.95	101.60	96.52	318.92	302.97	287.83
NTU	3.24	3.08	2.92	2.78	0.82	0.78	0.74	0.70	0.67	3.24	3.08	2.92
ε	0.75	0.72	0.71	0.70	0.46	0.43	0.42	0.41	0.40	0.75	0.72	0.71
Tint HP	13.24	12.99	12.91	12.83	27.40	27.67	27.78	27.90	28.01	13.24	12.99	12.91

Table 6.9: 5% UA decrease per month cleaned at the start of the season

Scenario 3:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	287.03	258.33	232.49	118.50	106.65	95.99	86.39	77.75	318.92	287.03	258.33
NTU	3.24	2.92	2.62	2.36	0.82	0.74	0.67	0.60	0.54	3.24	2.92	2.62
ε	0.75	0.71	0.69	0.68	0.46	0.42	0.40	0.37	0.35	0.75	0.71	0.69
Tint HP	13.24	12.91	12.74	12.66	27.40	27.79	28.02	28.26	28.49	13.24	12.91	12.74

Table 6.10: 10% UA decrease per month cleaned at the start of the season

Scenario 4:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	271.08	230.42	195.86	118.50	100.73	85.62	72.77	61.86	318.92	271.08	230.42
NTU	3.24	2.75	2.34	1.99	0.82	0.70	0.59	0.50	0.43	3.24	2.75	2.34
ε	0.75	0.70	0.68	0.65	0.46	0.41	0.37	0.34	0.30	0.75	0.70	0.68
Tint HP	13.24	12.83	12.66	12.41	27.40	27.92	28.28	28.64	28.98	13.24	12.83	12.66

Table 6.11: 15% UA decrease per month cleaned at the start of the season

The electric consumption of each scenario is shown in the next table:

Months	Scenario 2 (kWh_{ele})	Scenario 3 (kWh_{ele})	Scenario 3 (kWh_{ele})
Jan	74 267.85	74 267.85	74 267.85
Feb	56 234.77	56 313.10	56 391.99
Mar	39 566.43	39 677.69	39 733.92
Apr	11 780.59	11 813.91	11 864.78
May	2 048.33	2 048.33	2 048.33
Jun	7 803.97	7 837.68	7 873.66
Jul	12 391.78	12 499.76	12 614.93
Aug	11 022.12	11 166.58	11 319.08
Sep	2 548.94	2 593.37	2 639.40
Oct	15 400.69	15 400.69	15 400.69
Nov	44 704.56	44 766.83	44 829.55
Dec	66 199.35	66 385.50	66 479.57
TOTAL	343 969.38	344 771.28	345 463.76

Table 6.12: 2nd temperature model Electric consumption scenarios 2,3 and 4

As in the previous temperature case, the difference between scenario 1 and scenario 4 is 3 MWh in the total electric consumption.

Changing the average temperatures from 15-19ºC to 17-22ºC causes a decrease of approximately 5 MWh comparing the same scenarios. So, the wastewater temperature is a factor more relevant than the loss of efficiency in the heat exchanger.

For this reason, one more case has been considered regarding the change in the sewage temperature. In this last case it has been considered a variable temperature along the year and the seasons considering a minimum temperature of 15ºC and a maximum of 22ºC, which are the maximum and the minimum of both years. The transition through heating and cooling season is smoother.

In the following table are shown the temperatures selected for each month as well as the temperature entering the heat pump, calculated as in the previous cases, the COP and EER and finally the electric consumption. The results are for the scenario 1, without any influence of the solid depositions in the heat exchanger.

Months	Sewage T (ºC)	Tin HP (ºC)	COP	EER	Electric Consumption (kWh_{ele})
Jan	15	11.99	3.603	-	75 867.65
Feb	16	12.62	3.643	-	56 591.70
Mar	17	13.24	3.681	-	39 348.62
Apr	18	13.87	3.718	-	11 582.81
May	19	26.02	-	6.666	1 949.05
Jun	20	26.48	-	6.557	7 476.76
Jul	21	26.94	-	6.449	12 021.20
Aug	22	27.40	-	6.343	10 826.46
Sep	20	26.48	-	6.557	2 412.17
Oct	18	13.87	3.718	-	15 246.44
Nov	16	12.62	3.643	-	44 988.31
Dec	15	11.99	3.603	-	67 256.78
				TOTAL	345 567.94

Table 6.13: 3rd temperature model electric consumption scenario 1

The final value is in between the 2 cases presented before.

The other three scenarios have been studied in this last case as well.

The results are:

Scenario 2:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	302.97	287.83	273.43	118.50	112.58	106.95	101.60	96.52	318.92	302.97	287.83
NTU	3.24	3.08	2.92	2.78	0.82	0.78	0.74	0.70	0.67	3.24	3.08	2.92
ε	0.75	0.72	0.71	0.70	0.46	0.43	0.42	0.41	0.40	0.75	0.72	0.71
Tint HP	12.00	12.39	12.91	13.41	26.00	26.80	27.36	27.90	27.21	12.00	12.39	11.73

Table 6.14: 5% UA decrease per month cleaned at the start of the season

Scenario 3:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	287.03	258.33	232.49	118.50	106.65	95.99	86.39	77.75	318.92	287.03	258.33
NTU	3.24	2.92	2.62	2.36	0.82	0.74	0.67	0.60	0.54	3.24	2.92	2.62
ε	0.75	0.71	0.69	0.68	0.46	0.42	0.40	0.37	0.35	0.75	0.71	0.69
Tint HP	12.00	12.32	12.74	13.23	26.00	26.95	27.63	28.26	27.79	12.00	12.32	11.60

Table 6.15: 10% UA decrease per month cleaned at the start of the season

Scenario 4:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UA	318.92	271.08	230.42	195.86	118.50	100.73	85.62	72.77	61.86	318.92	271.08	230.42
NTU	3.24	2.75	2.34	1.99	0.82	0.70	0.59	0.50	0.43	3.24	2.75	2.34
ε	0.75	0.70	0.68	0.65	0.46	0.41	0.37	0.34	0.30	0.75	0.70	0.68
Tint HP	12.00	12.24	12.66	12.95	26.00	27.10	27.91	28.64	28.38	12.00	12.24	11.53

Table 6.16: 15% UA decrease per month cleaned at the start of the season

It is interesting to see that in this last case the trend followed by the temperature entering the heat pump is not the same in the heating period than in other two cases. In this case the temperature entering the heat pump rises, while in the other cases decreases. This is because of the increase of the sewage water temperature. Other fact that can be noticed is that as the percentage of the UA decrease is higher, the increase in the heat pump entering water is lower, but still increasing. This means that the sewage water temperature has a bigger influence than the screen formed in the heat exchanger.

In the other hand in the cooling period the trend is the same, the temperature rises as the decrease in the UA is bigger.

The electric consumption in each scenario is shown in the next table:

Months	Scenario 2 (kWh_{ele})	Scenario 3 (kWh_{ele})	Scenario 4 (kWh_{ele})
Jan	75 860.46	75 860.46	75 860.46
Feb	56 811.42	56 885.60	56 960.26
Mar	39 566.43	39 677.69	39 733.92
Apr	11 667.66	11 702.55	11 755.92
May	1 947.65	1 947.65	1 947.65
Jun	7 564.41	7 603.64	7 645.55
Jul	12 205.10	12 322.13	12 447.07
Aug	11 022.12	11 166.58	11 319.08
Sep	2 476.79	2 528.68	2 582.65
Oct	15 730.95	15 730.95	15 730.95
Nov	45 162.98	45 221.95	45 281.30
Dec	67 580.26	67 744.78	67 827.75
TOTAL	347 596.23	348 392.67	349 092.56

Table 6.17: 3rd temperature model Electric consumption scenarios 2,3 and 4

Although the heat pump entering water temperature had a different behavior than the other 2 cases, in terms of electric consumption of the heat pump, the results are the same. The difference between scenario 1 and scenario 4 is about 3 MWh.

6.3.3 *Conclusion*

Three temperature models have been studied and in each of them four scenarios have been considered giving 12 different results of the electric consumption of the heat pump. In order to compare the results in future chapters and to have a clearer idea of the results obtained, one of the cases has to be selected.

Regarding the temperature the last case with a smooth transition between the seasons seems the most realistic case of the three, due to the fact that the temperatures during a season does not remain constant. So, the last case is chosen.

Regarding the heat exchanger degradation, Thermowatt ensures that the heat exchanger has a self-cleaning system apart from the screening station. Despite this, a 100% cleaning it is hard to imagine when talking about sewage water. For this reason, the selected scenario in the last temperature model is the 2nd one, that considers a 5% monthly UA reduction, and a complete cleaning at the beginning of the season and the year.

The results of this case are summarized in the next table, and consumption per square meter has been added considering the floor area of the 3 buildings (17 895 m2) :

Months	Sewage T (ºC)	Tin HP (ºC)	COP	EER	Electric Consumption (kWh_{ele})	Electric Consumption (kWh_{ele}/m2)
Jan	15	12.00	3.603	-	75 860.46	4.24
Feb	16	12.39	3.629	-	56 811.42	3.17
Mar	17	12.91	3.661	-	39 566.43	2.21
Apr	18	13.41	3.691	-	11 667.66	0.65
May	19	26.00	-	6.671	1 947.65	0.11
Jun	20	26.80	-	6.481	7 564.41	0.42
Jul	21	27.36	-	6.352	12 205.10	0.68
Aug	22	27.90	-	6.231	11 022.12	0.62
Sep	20	27.21	-	6.386	2 476.79	0.14
Oct	18	12.00	3.603	-	15 730.95	0.88
Nov	16	12.39	3.629	-	45 162.98	2.52
Dec	15	11.73	3.586	-	67 580.26	3.78
				TOTAL	347 596.23	19.42

Table 6.18: 3rd temperature model Electric consumption scenario 2

6.4 Distribution subsystem

6.4.1 *Distribution subsystem sizing*

As it has been said the distribution system of the district system is a very important. Is the one responsible of the transportation of the energy from the heat pump to the buildings.

The pipes are buried under the ground which is not heated, so the thermal losses can be really important if the pipes are not properly insulated.

In the figure below, it is possible to see the configuration of the distribution subsystem.

Figure 6.14: Distribution subsystem layout

In order to size the pipes correctly is important to know how much water will passes through each of them. They have been divided in four parts:

- HP-0: has a length of 32 meters and through it passes the flow of the three buildings.
- 0-MO: has a length of 130 meters and through it passes the flow for the Mayor's Office and for the Government Window.
- MO-GW: has a length of 70 meters and through it passes the flow for the Government Window.
- 0-NM: has a length of 120 meter and through it passes the flow for New Market Hall.

The heat pump is able to provide both, heating and cooling needs, for this reason is only necessary one line of pipes for both needs. The line it has been sized attending the highest flow. For heating in nominal conditions, it is needed a flow of 19.09 kg/s and for cooling in the same conditions 35.32 kg/s. Thus, the pipeline it has been sized for a flow of 35.32 kg/s.

It has been used the maximum power of the three buildings and a weighted average with the maximum power of each building to determine the flow needed by each building.

The maximum power of each building and the total are:

	MAX heating (kW)	Date	MAX cooling (kW)	Date
Total	2 261.04	Jan 15th	675.71	Jul 23rd
NM	1 187.32	Jan 15th	400.21	Jul 23rd
GW	353.91	Jan 15th	123.20	Jul 23rd
MO	757.84	Jan 15th	239.01	Jul 23rd

Table 6.19: Buildings maximum heating and cooling power

It has been used the maximum cooling power because is the one that requires a higher flow.

The flow required for each building can be seen below:

New Market Hall:

$$\dot{m}_{NM} = \frac{35.32 * 400.21}{675.71} = 20.91\ kg/s$$

Government Window:

$$\dot{m}_{GW} = \frac{35.32 * 123.20}{675.71} = 6.44\ kg/s$$

Mayor's Office:

$$\dot{m}_{MO} = \frac{35.32 * 239.01}{675.71} = 12.49\ kg/s$$

With these results it is possible to size the different sections of the pipeline. It can be calculated the flow through each section:

- HP-0: 39.84 kg/s.
- 0-MO: 18.93 kg/s.
- MO-GW: 6.44 kg/s.
- 0-NM: 20.91 kg/s.

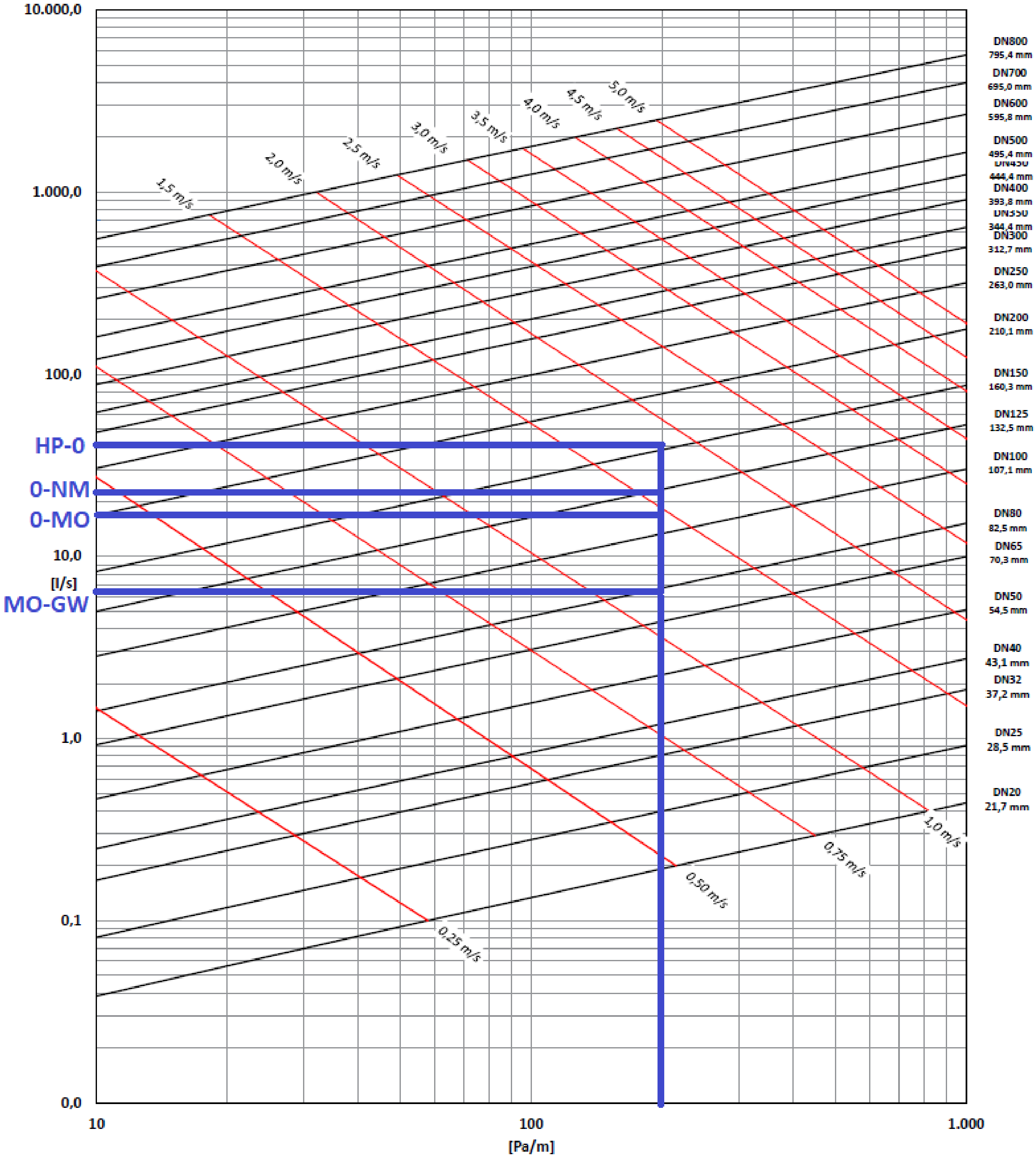
To dimension the pipes, it is necessary first to select the model of pipe according to the necessities. In this case the pipes should have a good insulation, to minimize the thermal losses, and a good resistance to deterioration because they will be outside the building.

The type of pipe selected has been a pre-insulated single steel pipe from the company SET (17). The pipes are insulated with polyurethane foam (PUR) and covered with PE casing pipe. The polyurethane material (PUR) has an excellent insulation value, high pressure resistance and is a long-lasting insulation.

Figure 6.15: SET pre-insulated single steel pipe

It has been selected due to its thermal performance (low U-value), possible diameters (20-800mm) and working temperature (up to 160ºC).

Once selected the type of pipe it is possible to size the different sections. With that purpose it has been used the pressure drop chart provided by the company. The maximum pressure drop has been considered 200 Pa/m and the maximum velocity 2.0 m/s.



Graph 6.4: Pressure loss graph for steel pipe

The graph shows the pipe diameter selected for each section of the distribution subsystem.

- MO-GW: DN 80 pressure drop 200 Pa/m.
- 0-MO: DN 125; pressure drop 100 Pa/m.
- 0-NM: DN 125; pressure drop 200 Pa/m.
- HP-0: DN 150; pressure drop 200 Pa/m.

In the cooling mode the water pass through the same pipes, but the flow is different, so the pressure drop is reduced.

The flow required for each building in the cooling mode is calculated in the same way as before:

New Market Hall:

$$\dot{m}_{NM} = \frac{19.09 * 1187.32}{2\ 261.04} = 10.02\ kg/s$$

Government Window:

$$\dot{m}_{GW} = \frac{19.09 *\ 353.91}{2\ 261.04} = 2.99\ kg/s$$

Mayor's Office:

$$\dot{m}_{MO} = \frac{19.09 * 757.84}{2\ 261.04} = 6.40\ kg/s$$

Summing the flows to determine what passes through each section, and using the same graph to determine the pressure drops:

- MO-GW: DN 80; 2.99kg/s; pressure drop 40 Pa/m.
- 0-MO: DN 125; 9.39 kg/s; pressure drop 33 Pa/m.
- 0-NM: DN 125; 10.02 kg/s; pressure drop 40 Pa/m.
- HP-0: DN 150; 19.41kg/s; pressure drop 50 Pa/m.

6.4.2 *Thermal losses/gains*

The thermal of the distribution subsystem are important to be calculated in order to know at what temperature the water will reach each building. Thus, the return pipeline is not considered yet.

For these calculations it has been used again the software TRNSYS. The software needs the interior diameter and length of each pipe section, the thermal transmittance of the pipe per square meter the flow the interior temperature and the temperature of the ground. The data have been obtained through the SET datasheets and the ground temperature have been calculated with TRNSYS considering a depth of 5 meters. Also, it has been considered an average ground temperature for each period.

It is important to separate between heating and cooling period and to characterize correctly each section of the pipeline.

In the heating period the pipe conditions to introduce in the software are:

Section	DN (mm)	Dint (mm)	ψ (W/mK)	U-value (W/m2K)	Flow (kg/s)	Length (m)	T_{in} (ºC)	T_{ground} (ºC)
HP-0	150	160.3	0.336	0.668	19.41	32	60	10.61
0-NM	125	132.5	0.287	0.689	10.02	120	$T_{out;HP-0}$	10.61
0-MO	125	132.2	0.287	0.689	9.39	130	$T_{out;HP-0}$	10.61
MO-GW	80	82.5	0.238	0.918	2.99	70	$T_{out;0-MO}$	10.61

Table 6.20: Pipe forward sections conditions in heating period

After entering the data, the results for each section of the pipeline in cooling season are:

	HP-0	0-NM	0-MO	MO-GW
Temperature (ºC)	59.99	59.95	59.95	59.88

Hear Power losses (kW)	0.53	1.70	1.84	0.82

Table 6.21: Pipe forward sections TRNSYS results in heating period

For cooling period calculations have been carry out with the same procedure:

Section	DN (mm)	Dint (mm)	ψ (W/mK)	U-value (W/m2K)	Flow (kg/s)	Length (m)	T_{in} (ºC)	T_{ground} (ºC)
HP-0	150	160.3	0.336	0.668	39.81	32	12	10.05
0-NM	125	132.5	0.287	0.689	20.91	120	$T_{out;HP-0}$	10.05
0-MO	125	132.2	0.287	0.689	18.93	130	$T_{out;HP-0}$	10.05
MO-GW	80	82.5	0.238	0.918	6.44	70	$T_{out;0-MO}$	10.05

Table 6.22: Pipe forward sections conditions in cooling period

And the results given by TRNSYS are:

	HP-0	0-NM	0-MO	MO-GW
Temperature (ºC)	7.000	6.999	6.999	6.997
Hear Power losses (kW)	0.03	0.11	0.11	0.05

Table 6.23: Pipe forward sections TRNSYS results in cooling period

It is interesting to observe that in summer the normal thing would be to have heat power gains instead of losses, but as the ground temperature is lower than the temperature of the water in the pipes the heat transfer happens from the pipes to the ground. In any case the losses are so low that its incidence can be neglected and can be seen the low variation in the temperature.

With these analyses it has been possible to determine the entering temperature to each of the buildings substations.

As it can be observed the temperatures do not vary a lot from the ones coming out of the heat pump, especially in the cooling case, where they do not vary at all. The reason for this is the high flow rate going through the pipes, which is even higher in the cooling case plus a lower temperature difference between the working and ground temperature.

In order to now the working temperature of the buildings substations it has been calculated the conditions of the return pipeline. With it will be possible to know the total thermal losses due to the distribution subsystem.

For calculating the return pipes have been followed the same path than previously, using TRNSYS and dividing heating and cooling season.

For heating season:

Section	DN (mm)	Dint (mm)	ψ (W/mK)	U-value (W/m2K)	Flow (kg/s)	Length (m)	T_{out} (ºC)	T_{ground} (ºC)
0-HP	150	160.3	0.336	0.668	19.41	32	T_{HP}	10.61
NM-0	125	132.5	0.287	0.689	10.02	120	$T_{in;\ 0-HP}$	10.61
MO-0	125	132.2	0.287	0.689	9.39	130	$T_{in;\ 0-HP}$	10.61
GW-MO	80	82.5	0.238	0.918	2.99	70	$T_{in;\ MO-0}$	10.61

Table 6.24: Pipe return sections conditions in heating period

The results allow the calculation of the outlet temperature of the building substations and the heat power losses of the return sections of the pipeline.

	0	NM	MO	GW
Temperature (ºC)	50.00	50.03	50.04	50.09

Hear Power losses (kW)	0.40	1.36	1.47	0.66

Table 6.25: Pipe return sections TRNSYS results in heating period

In the cooling season:

Section	DN (mm)	Dint (mm)	ψ (W/mK)	U-value (W/m2K)	Flow (kg/s)	Length (m)	T_{in} (ºC)	T_{ground} (ºC)
HP-0	150	160.3	0.336	0.668	39.81	32	T_{HP}	10.05
0-NM	125	132.5	0.287	0.689	20.91	120	$T_{in;\ 0\text{-}HP}$	10.05
0-MO	125	132.2	0.287	0.689	18.93	130	$T_{in;\ 0\text{-}HP}$	10.05
MO-GW	80	82.5	0.238	0.918	6.44	70	$T_{in;\ MO\text{-}0}$	10.05

Table 6.26: Pipe return sections conditions in cooling period

In this case the results are:

	HP-0	0-NM	0-MO	MO-GW
Temperature (ºC)	12	12	12	12
Hear Power losses (kW)	0.02	0.07	0.07	0.03

Table 6.27: Pipe return sections TRNSYS results in cooling period

With all the results, now it is possible to determine the working temperature range of each building substation, in both seasons heating and cooling.

Building	Working temperature range heating (ºC)	Working temperature range cooling (ºC)
Mayor's Office	[59.95-50.04]	[6.999-12.00]
Government Window	[59.88-50.09]	[6.997-12.00]
New Market Hall	[59.95-50.03]	[6.999-12.00]

Table 6.28: Building's energy substations working temperatures

It has also been determined the total distribution subsystem thermal losses (or gains). For it, the total heat power losses and gains have been summed and multiplied by the operating hours of each month previously calculated.

The results can be seen in the following table:

Month	Heating energy losses (kWh_{th})	Cooling energy gains (kWh_{th})
Jan	3 460.72	-
Feb	2 609.77	-
Mar	1 833.66	-
Apr	545.19	-
May	-	3.13
Jun	-	11.82
Jul	-	18.69
Aug	-	16.55
Sep	-	3.81
Oct	717.64	-
Nov	2 074.67	-
Dec	3 067.94	-
TOTAL	14 391.38	54.19

Table 6.29: distribution subsystem thermal losses and gains

The thermal losses are summed to the building energy needs. They represent 1.2% of the thermal needs. As it has been explained, this is due to the pipes insulation which minimize the thermal losses

6.4.3 *Electric consumption*

The other important point to consider in the distribution subsystem is the electric power needed for its correct functioning. In this case it is necessary to consider the different pressure drops along the system.

In the scheme below are shown the main elements that have to be considered:

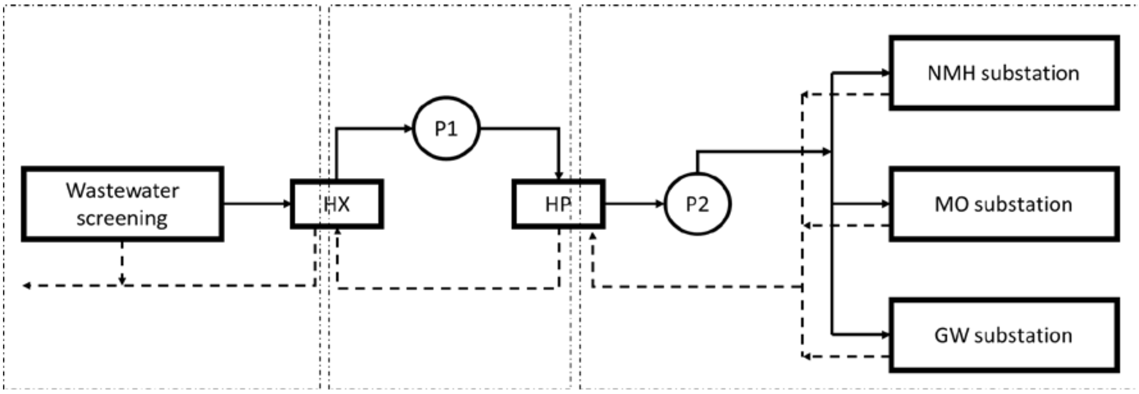


Figure 6.16: Distribution subsystem scheme

As it can be seen the system can be divided in 3 parts. In the first part are considered the wastewater screening and the heat exchanger swage water part. The second part is composed by the heat pump heat exchanger part, and the sewage part of the heat pump. And the third part is formed by the heat pump building part, the three buildings substations and the pipes going from the heat pump to each substation, plus another pump (P2).

Again, the functioning of the system has to be divided into heating and cooling season because the conditions are different.

6.4.3.1 Heating period

For the heating period and the buildings part it has to be considered the buildings substations, the forward and returns pipes and the heat pump condenser.

The buildings substations have been considered according the Euroheat and Power guidelines, which recommend a pressure differential of 100 kPa.

The heat pump condenser pressure drop is given in the datasheet and it is 15 kPa.

The pipes pressure drop can be calculated with the data taken from the pressure chart of the pipes and multiplied by the length:

- MO-GW: 40 Pa/m*70m = 2.8 kPa
- 0-MO: 33 Pa/m*130 = 4.29 kPa
- 0-NM: 40 Pa/m*120 = 4.80 kPa
- HP-0: 50 Pa/m*30 = 1.5 kPa.

In order to calculate the electric power needed ($Q_{elec,3}$) the pressure drop must be multiplied by the mass flow rate.

A security coefficient is applied due to the different elements that have not been considered such as different pipe geometries or changes in the path of the pipeline. This security factor is considered to be 2.

$$Q_{elec,3} = [(15 + 1.5 * 2) * 19.41 * 10^{-3} + (100 + 4.8 * 2) * 10.02 * 10^{-3} + (100 + 4.29 * 2) * 9.39 * 10^{-3} + (100 + 2.8 * 2) * 2.99 * 10^{-3}] * 2 = 5.56\ kW$$

It can be roughly estimated a 70% pump efficiency for the heating conditions, considering that the pump would be sized for the cooling conditions. Then the building part pump (P2 in the scheme) power will have to be at least 7.94 kW in winter.

In the second part are only consider the heat pump evaporator and the heat exchanger. The pipes are neglected due to their length.

The heat pump evaporator pressure drop is given in the datasheet, and it is 21.3 kPa.

The heat exchanger pressure drop is assumed to be 60 kPa.

The electric power needed for part 2 is:

$$Q_{elec,2} = (21.3 + 60) * 28.23 * 10^{-3} = 2.30\ kW$$

Considering the same estimated efficiency for this case (70%): 3.29 kW.

For the wastewater screening part, the supplier provides a value of 5.08 kW in the heating period.

So, the total electric power needed by the distribution subsystem in the heating mode is 16.31 kW.

6.4.3.2 Cooling period

For the cooling period the procedure to follow is the same as in the heating period, but changing some values, specially flows and pipes pressure drop.

For the building part the buildings substations have the same pressure differential 100 kPa.

The heat pump evaporator pressure drop is given in the datasheet and it is 32 kPa.

The pipes pressure drop can be calculated with the data taken from the pressure chart of the pipes and multiplied by the length:

- MO-GW: 200 Pa/m*70m = 14 kPa
- 0-MO: 100 Pa/m*130 = 7 kPa
- 0-NM: 200 Pa/m*120 = 24 kPa
- HP-0: 200 Pa/m*30 = 6 kPa.

The electric power needed is calculated as for the heating period

$$Q_{elec,3} = [(32 + 6 * 2) * 39.81 * 10^{-3} + (100 + 24 * 2) * 20.91 * 10^{-3} + (100 + 7 * 2) * 18.93 * 10^{-3} + (100 + 14 * 2) * 6.44 * 10^{-3}] * 2 = 15.66\ kW$$

For the cooling conditions the efficiency estimated is higher, because are the most restricted conditions. So, 75% pump efficiency can be considered for the cooling conditions. In the case of the cooling period the building part heat pump need a power of 20.88 kW.

As in the heating period, in the second part are only consider the heat pump evaporator and the heat exchanger. The pipes are neglected due to their length.

The heat pump condenser pressure drop is given in the datasheet, and it is 28.3 kPa.

The heat exchanger pressure drop is assumed to be 60 kPa as for the heating period.

The electric power needed for part 2 is:

$$Q_{elec,2} = (28.3 + 60) * 34.44 * 10^{-3} = 3.04\ kW$$

Considering the same estimated efficiency for this case (75%): 4.05 kW.

For the wastewater screening part, the supplier provides a value of 8.2 kW in the heating period.

The total electric power needed by the distribution subsystem in the heating mode is 31.94 kW.

To calculate the total electric consumption of the distribution subsystem during the year it has to be multiplied the electric power needed in each period by their operating hours.

The results are shown in the next table:

	Heating operating hours	Cooling operating hours	Distr. Subs electric energy (kWh_{ele})
Jan	346.77	-	5 655.75
Feb	261.50	-	4 265.06
Mar	183.73	-	2 996.70
Apr	54.63	-	890.99
May	-	16.48	526.45
Jun	-	62.19	1 986.35
Jul	-	98.35	3 141.23
Aug	-	87.12	2 782.57
Sep	-	20.06	640.84
Oct	71.91	-	1 172.82
Nov	207.88	-	3 390.57
Dec	307.41	-	5 013.83
TOTAL	1 442.02	285.22	32 463.17

Table 6.30: Distribution subsystem electric energy consumption

The total electric consumption of the distribution subsystem along the year is more than 32 MWh.

This means that the distribution subsystem implies around a 9% of the total electric consumption of the district energy system.

6.5 District energy system consumption

After the calculations, the electric consumption of the district energy system for space heating and cooling can be estimated. Summing the values previously calculated the results for the year are shown in the next table:

Month	Total electric consumption (kWh_{ele})	Total electric consumption (kWh_{ele}/m2)
Jan	81 516.21	4.56
Feb	61 076.48	3.41
Mar	42 563.13	2.38
Apr	12 558.65	0.70
May	2 474.10	0.14
Jun	9 550.77	0.53
Jul	15 346.33	0.86
Aug	13 804.68	0.77
Sep	3 117.63	0.17
Oct	16 903.77	0.94
Nov	48 553.55	2.71
Dec	72 594.09	4.06
TOTAL	380 059.40	21.24

Table 6.31: District energy system electric consumption

A yearly total consumption of more than 380 MWh, which is a considerable amount of energy, but this is due to the dimensions of the district energy system, considering the energy per square meter, 21.24 kWh/m2 is a really low quantity. And here it can be observed the benefits of the proposed system based in sewage water heat exchanger and heat pump.

Finally, the cost of the energy has been calculated, considering 0.16€ for each electric kilowatt hour.

Month	Total cost (€)	Total cost (€/m2)
Jan	13 042.59	0.73
Feb	9 772.24	0.55
Mar	6 810.10	0.38
Apr	2 009.38	0.11
May	395.86	0.02
Jun	1 528.12	0.09
Jul	2 455.41	0.14
Aug	2 208.75	0.12
Sep	498.82	0.03
Oct	2 704.60	0.15
Nov	7 768.57	0.43
Dec	11 615.05	0.65
TOTAL	60 809.50	3.40

Table 6.32: District energy system yearly cost

As it can be seen in the table the yearly cost of the proposed district energy system is above 60 000€.

7 Comparative analysis

In order to have an overview of the benefits of the implementation of the proposed system, a comparative analysis have been carried out with other generations systems widely used nowadays, an air source heat pump for heating and cooling, and a condensing boiler for heating and a chiller for cooling. In both cases the systems have been applied individually to each building, in order to understand as well the benefits of the district system.

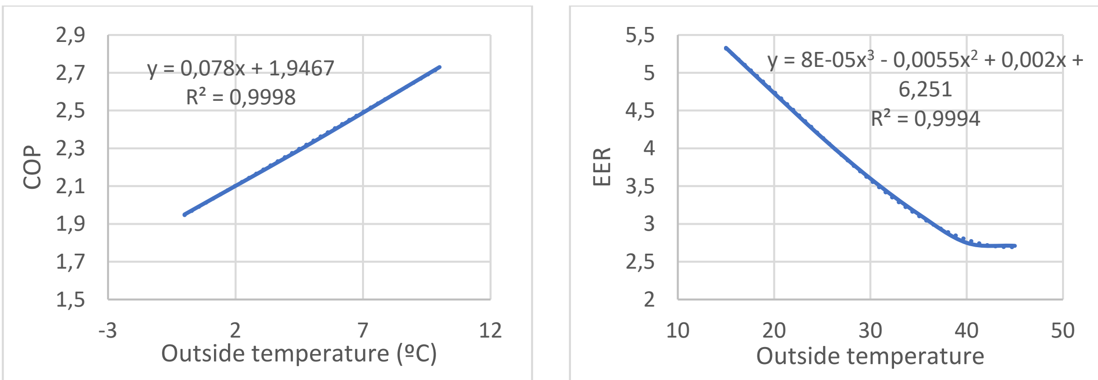
7.1 Air source heat pump

The air source heat pump as, indicated in its name, use as source or as sink depending on the season the external air. The inside processes are as the ones described in the introduction of this thesis.

For this comparison, it has been selected the model NRB-H of AERMEC (18), with enough power to provide the needs of each of the buildings.

Figure 7.1: AERMEC NRB-H

The data provided by the supplier allow the calculation of the COP and EER curves.



Graph 7.1: AERMEC NRB-H COP and EER variation with outside temperature

With these curves it is possible to determine the heat pump electric consumption of the three buildings:

Months	Tenv (ºC)	COP	EER	HP electric consumption (kWh_{ele})	HP electric consumption (kWh_{ele}/m2)
Jan	- 1.77	1.81	-	151 157.76	8.45
Feb	1.02	2.03	-	101 729.11	5.68
Mar	5.61	2.38	-	60 750.22	3.39
Apr	11.05	2.81	-	15 334.21	0.86
May	15.95	-	5.21	2 494.96	0.14
Jun	18.80	-	4.88	10 053.76	0.56
Jul	20.91	-	4.62	16 782.13	0.94
Aug	20.32	-	4.69	14 637.35	0.82
Sep	16.22	-	5.18	3 054.88	0.17
Oct	11.03	2.81	-	20 191.89	1.13
Nov	4.65	2.31	-	70 950.89	3.96
Dec	0.33	1.97	-	122 873.18	6.87
			TOTAL	590 010.35	32.97

Table 7.1: ASHP annual electric consumption

To this value it has to be summed the distribution subsystem energy plus the control subsystem that in this case, as it is considered separately each building, the estimation is lower than the district system. It has been considered a 5% of the energy. The total values are shown in the next table.

Months	Total electric consumption (kWh_{ele})	Total electric consumption (kWh_{ele}/m2)
Jan	158 715.65	8.87
Feb	106 815.57	5.97
Mar	63 787.73	3.56
Apr	16 100.92	0.90
May	2 619.71	0.15
Jun	10 556.45	0.59
Jul	17 621.24	0.98
Aug	15 369.22	0.86
Sep	3 207.63	0.18
Oct	21 201.48	1.18
Nov	74 498.44	4.16
Dec	129 016.84	7.21
TOTAL	619 510.86	34.62

Table 7.2: Energy system electric consumption

The yearly cost of this system considering again 0.16 €/kWh_{ele} is:

Months	Total cost (€)	Total cost (€/m2)
Jan	25 394.50	1.42
Feb	17 090.49	0.96
Mar	10 206.04	0.57
Apr	2 576.15	0.14
May	419.15	0.02
Jun	1 689.03	0.09
Jul	2 819.40	0.16
Aug	2 459.08	0.14
Sep	513.22	0.03
Oct	3 392.24	0.19
Nov	11 919.75	0.67
Dec	20 642.69	1.15
TOTAL	99 121.74	5.54

Table 7.3: ASHP energy system annual cost

7.2 Condensing boiler + air/water chiller

Boilers are pressure vessels designed to transfer the heat produced by combustion to a fluid. It is a widely spread generation system because its efficiency and flexibility but is not considered a renewable source of energy due to the gases produced in the combustion.

To simplify the calculations, it has been considered a condensing boiler with an efficiency of 85%. The chiller is considered the same as the previous case (NRB-H).

The results are shown in the next table:

Months	Generated thermal energy (kWh_{th})	Chiller electric consumption (kWh_{ele})
Jan	321 594.80	-
Feb	242 518.09	-
Mar	170 396.85	-
Apr	50 663.35	-
May	-	2 494.96
Jun	-	10 053.76
Jul	-	16 782.13
Aug	-	14 637.35
Sep	-	3 054.88
Oct	66 688.12	-
Nov	192 792.91	-
Dec	285 094.22	-
TOTAL	1 337 347.85	47 023.08

Table 7.4: CB+Chiller energy consumption

In this case to calculate the yearly cost of the system is calculate in a different way, as the result are part in thermal kilowatts and part in electric kilowatts.

The cost of an electric kilowatt is 0.16 €/kWh, while the cost of a thermal kilowatt is 0.07 €/kWh (low heating value).

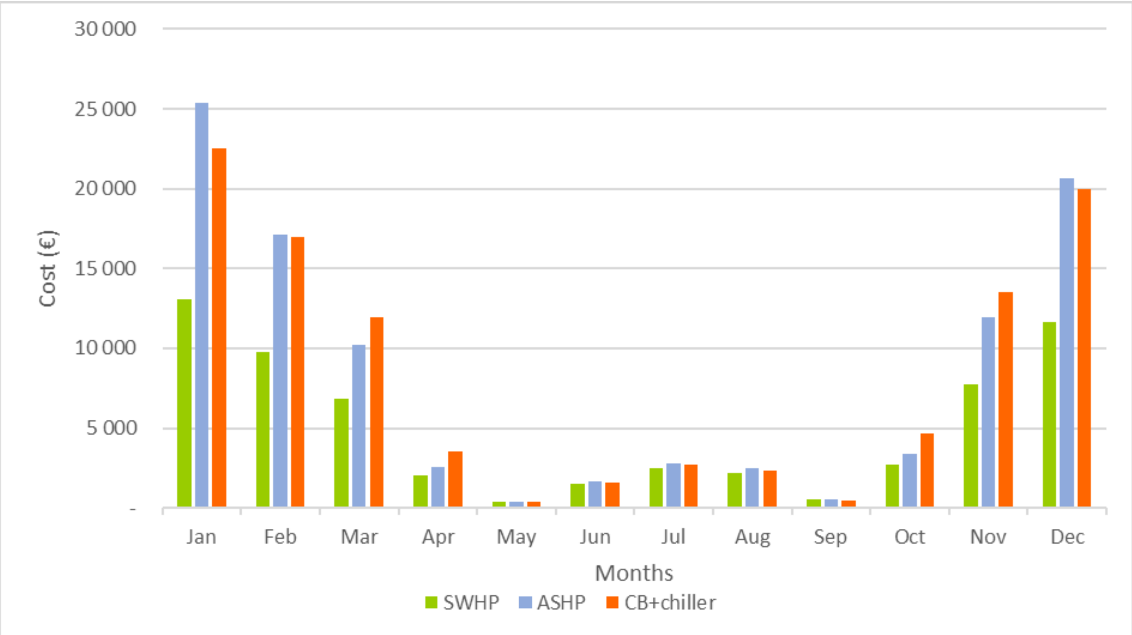
Months	Cost (€)	Cost (€/m2)
Jan	22 511.64	1.26
Feb	16 976.27	0.95
Mar	11 927.78	0.67
Apr	3 546.43	0.20
May	399.19	0.02
Jun	1 608.60	0.09
Jul	2 685.14	0.15
Aug	2 341.98	0.13
Sep	488.78	0.03
Oct	4 668.17	0.26
Nov	13 495.50	0.75
Dec	19 956.60	1.12
TOTAL	101 138.04	5.65

Table 7.5: CB+Chiller annual cost

7.3 Energy systems comparison

After calculating the costs of the yearly functioning of the different systems it possible to compare them.

To do so the results are shown graphically, in first place monthly:



Graph 7.2: Monthly cost comparison between the different energy systems

In second place the total costs:

Graph 7.3: Total cost comparison between the different energy systems

In the graphs can be observed that the proposed solution in this thesis, district energy system based on a sewage water heat pump has clearly the lower costs, a 39% less than the air source heat pump and a 40% less than the condensing boiler plus chiller. The reason of this are all the benefits explained along this thesis.

Entering more in detail and observing the monthly graph, the main differences respect the other systems are in the heating period, while in the cooling period the result are similar. The reason for this difference is the advantage of having an energy source that does not vary much along the year allowing to have a high efficiency in the more extreme months with temperatures below 0ºC.

8 Conclusions

The aim of this thesis was to evaluate the possibility to apply in three public building of the city of Budapest a district energy system based on a sewage water heat pump.

First it has been analyzed the weather of the city realizing that Budapest has a continental climate with large temperature differences with a predominance of cold temperatures. With a yearly temperature average of around 10ºC, minimums below -10ºC and maximums above 30ºC, it has been clear that the main concern to maintain the comfort values determined were the heating needs.

In second place, the three buildings that composed the system have been defined and modelled using the Type 56 of the TRNsys software, and thanks to information provided by Thermowatt.

The modelling of the buildings has allowed to know the energy needs of the three buildings through the energy balances, to compare them and to understand the difference between them, due to be constructed at different times when the priorities were different in each case. Being the New Market Hall the most important building in terms of energy needs close to 600 MWh/y and 52% of the heating needs of the whole system, as well as the most efficient in terms of kWh/m2.

At the end, the energy needs of the tree buildings is more than 1 136 MWh for heating and close to 225 MWh for cooling.

With the energy needs was possible to study the feasibility of the proposed district energy system.

For the modelling of the energy system have been used again data provided by Thermowatt, and also it has been necessary to make some assumptions due to the lack of information at certain times.

The main components (heat pump, heat exchanger and pipeline) of the energy system have been explained and it has been detailed the interaction between them through different schemes and drawings.

The heat pump was previously selected by Thermowatt, and it has been studied in this thesis its suitability for the purposes of the project. To do so, some assumptions and simplifications have been made. The first one was that the heat pump worked always in nominal conditions and that the excess or lack of energy were compensated by the high thermal inertia of the system. This assumption was necessary in order to keep constant some conditions and to study its interaction with the heat exchanger and consequently with the sewage water.

As it has been said one of the objectives of this thesis is to understand how the heat pump behaves with the sewage water and if it is enough to supply the energy to the district system. For it, the interaction of the heat pump and the heat exchanger is crucial. It has been determined the reaction of the heat pump with the water entering from the heat exchanger through the COP and the EER depending on the season, and with them it was possible to calculate its electric consumption in heating and cooling seasons.

The heat exchanger characteristics has been defined according to the nominal heat pump conditions and using the logarithmic mean temperature and NTU methods. These two methods were necessary to introduce changes in the heat exchanger temperature and to observe the heat pump behavior.

Twelve different situations have been analyzed by changing the heat exchanger efficiency simulating its possible degradation due to solid particle deposition caused by the sewage water, and by considering different models of sewage water temperature. The changes have affected the heat pump electric consumption getting values ranging from 342 MWh to 350 MWh. At the end in order to make comparisons with other systems it has been selected the scenario with low heat exchanger efficiency degradation and a sewage water temperature model with smooth transition between months, being in this case the electric consumption of 347 MWh.

The distribution subsystem has also been modelled defining the type of pipes their length and diameter and the flow needed in each building. With TRNSYS it has been possible to determine the electric consumption and the thermal losses and gains of the distribution subsystem. The results showed that the electrical consumption due to the pressure drops and heat pumps efficiency are much more important than the thermal losses. The electrical consumption corresponds to a 9% of the total electric energy consumption of the system, while the thermal losses cause in the worst case a variation of 0.12ºC. This is due to the proper insulation of the pipes and to the high flow rate in the system causing that the temperature differential was really low.

Summing the electric consumption of the heat pump and the distribution subsystem the energy cost of the district system amounts to more than 60 000€.

To other generation system have been considered in order to compare the results of the proposed system. Those systems have been air source heat pumps, and condensing boilers used for heating and air-water chillers used for cooling.

The results of the comparison showed that the proposed solution consisting in a sewage water heat pump is more economic in terms of annual energy consumption by a 39% than the air source heat pumps and by a 40% than the condensing boiler plus chiller.

In conclusion according to this thesis work results and considering the limitations due to assumptions made the district energy system based on sewage water heat pump and heat exchanger can be a reliable solution respectful with the environment under the adequate circumstances.

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