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T5

Design and implementation of water-water heat pump

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1 Introduction

Domestic climatization is one of the main contributors to greenhouse gases emission. This sector accounts for about 50% of PM_{10} emissions and almost 20% of climate-changing emissions (1). Therefore, nowadays, more and more renewable solutions are under development. Investing in this sector could prove both economic advantageous and ethic responsible.

The available solutions to achieve these environmental goals are multiple, ranging from the optimization of traditional systems to the creation of innovative technologies able to exploit natural renewable sources. Obviously, these developments must align with the economic possibilities of residents, creating a strong bonding between technological innovation and economic savings.

This project aims to develop a new water-to-water heat pump, named T5, with a nominal thermal power of 5 kW_t. The primary targets for this technology are small apartments with autonomous heating systems, offering a unique and comprehensive solution for heating, cooling and domestic hot water.

T5 utilizes advanced technology to maximize efficiency and minimize environmental impact. By leveraging natural refrigerants, it operates within the latest regulatory standards and delivers superior performances compared to traditional systems. The unit's compact design ensures easy installation and compatibility with existing infrastructure, reducing the need for expensive modifications.

This project has been developed by TEON, an Italian company specialized in the development and production of innovative renewable heating and cooling solutions. Their products, natural heat generators (T), are efficient and eco-friendly alternatives to traditional boilers for both residential and industrial applications.

Upon completion of the design and testing processes, the T5 heat pump will be added to their catalogue and made available on the market.

The aim of this thesis is to present this new technology and its potential features, describing all the project phases and analysing the final results achieved by installing T5 heat pump. To ensure clarity, the thesis has been divided into three main sections:

- A technical overview of heat pump technology, describing the thermodynamic laws that govern the working principle of this technology

- An environmental and economic analysis of T5 heat pump, comprehending also a statistic analysis of Italian residential buildings
- A detailed technical presentation of the product designed, covering the design process, final performance results and solid model representation of the product.

2 General overview of heat pumps and refrigeration systems

"A heat pump is an installation that, operating continuously, extracts heat from a lower temperature source and makes it available (along with the thermal equivalent of the energy used to make this operation possible) for external use at a higher average temperature.” (2)

The name "heat pump" comes from the operation of raising the thermal level of available energy as heat, which is particularly useful when the thermal energy is delivered at a temperature higher than the external environment. This context is referred to as thermodynamic heating.

Heat pumps, along with refrigerators, belong to a category of machines that operates based on reverse thermodynamic cycles. In this chapter the main characteristics of this type of machines and their operational thermodynamic cycles are analysed.

Firstly, it is important to distinguish between heat pumps and refrigerators:

- Refrigerators continuously remove heat from a source at a lower temperature than the external environment, thereby maintaining the refrigerated system.
- Heat pumps transfer thermal energy from a lower temperature source to a higher temperature source.

Regarding their thermodynamic operational principle, there is no fundamental difference between a refrigerator and a heat pump. The difference lies solely in the intended useful effect produced.

Air, water or the earth, even at lower temperatures relative to the space being heated, can contain thermal energy provided by the Sun during the day. Heat pump systems can exploit this energy to generate a useful effect. Furthermore, artificial heat sources, such as waste heat flows from industrial processes, can also be utilized.

Theoretically, the total heat delivered by a heat pump is equal to the heat extracted from the source plus the energy used to power the system.

Nowadays, heat pumps are one of the most efficient ways to provide heating and cooling across many applications and fields, as they can harness renewable energy sources for their operation. This leads to a reduction in emission of gases that contribute to global warming, such as carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen oxides (NO_x).

Generally, in loco emissions are negligible, although it depends on the type of heat pump used. However, comprehensive global emission analysis requires to consider the source of external energy consumed by the system.

To better understand the operational principle of this type of machines, an overview of thermodynamic cycles is required. Subsequently a description of the different types of heat pumps is reported.

2.1 Thermodynamic cycles

In the field of technical physics, direct thermodynamic cycles are typically considered.
Direct thermodynamic cycles are defined as cycles able to produce useful work by absorbing heat from a hotter source. The absorbed heat must then be released to a colder environment, allowing the cycle to restart. A greater temperature difference between the hot source and the cold environment results in higher efficiency.
These cycles are the basis for combustion engines, jet engines and traditional thermal and thermoelectric power plants.

However, the operational principle of heat pumps and refrigerators is based on “reverse thermodynamic cycles”. In these cycles, no work is produced; rather , work is required to transfer heat from a colder source to a hotter environment.

In the following sections, the ideal reverse cycle is discussed, followed by an examination of the real reverse cycle on which the heat pump technology is based.

2.1.1 Ideal Reverse Cycle for Machines Producing External Useful Effects

The ideal cycle for generating useful external effects that cannot occur spontaneously is the Carnot cycle (Figure 2.1). In this cycle, the system absorbs a certain amount of energy in the form of heat from a source at a lower temperature and, through an expenditure of external work, transfers the heat to a "thermal reservoir" at a higher temperature. This process perfectly aligns with the second law of thermodynamics, which states that a certain amount of work or heat is required to enable the transfer of energy.

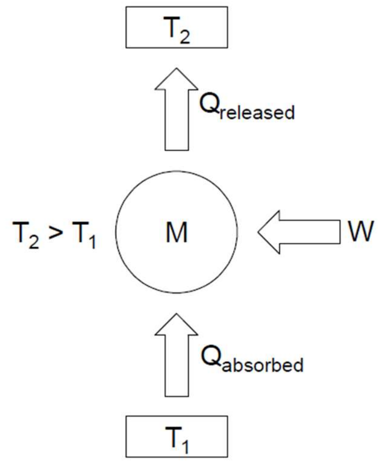


Figure 2.1: Carnot inverse cycle working principle

To analyse the reverse Carnot cycle more precisely, it can be represented as shown in Figure 2.2, considering a T-S diagram.

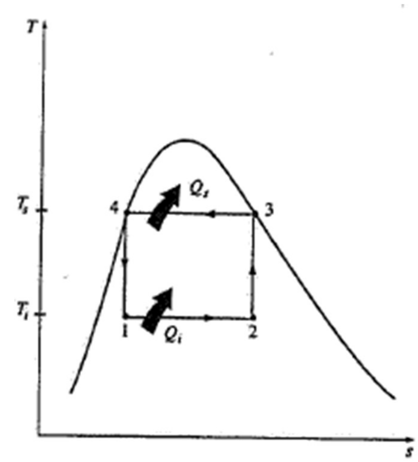


Figure 2.2: Inverse Carnot cycle represented in T-S diagram

It results evident that the cycle consists of four different transformations:

1. Isothermal Heat Absorption 1-2: The refrigerant then partially evaporates inside a heat exchanger (evaporator), absorbing a specific amount of heat from the outside at constant pressure p_1, given by: $Q_2 = h_2 - h_1$
2. Adiabatic Compression 2-3: The refrigerant is drawn by the compressor, which increases the pressure from p_1 to p_2, with a specific work expenditure given by: $|L_{2-3}| = h_3 - h_2$ increasing its temperature from T_1 to T_2.

3. Isothermal Heat Rejection 3-4: At constant pressure and temperature, p_2 and T_2 respectively, the fluid condenses inside a heat exchanger (condenser), releasing to the outside a specific amount of heat given by: $|Q_1| = h_3 - h_4$
4. Adiabatic Expansion 4-1: Starting from the saturated liquid state at point 4, the fluid expands isentropically from pressure p_2 to pressure p_1 through an expander (throttling valve), performing specific work given by: $L_{4-1} = h_4 - h_1$ lowering its temperature from T_2 to T_1.

All transformations occurring in the Carnot cycle are reversible because transformation 1 and 3 occur without friction and are adiabatic, meaning no heat is exchanged with the surroundings. Reversible adiabatic processes occur at constant entropy, so the Carnot cycle consists of two constant entropy processes and two constant temperature processes. However, since the idle condition for reversibility cannot be achieved in reality, the Carnot refrigeration cycle is purely theoretical. Nevertheless, it represents an important model for comparing real cycles in terms of their efficiency and the effects of maximum and minimum temperatures on their operation.

2.1.2 The Standard Reverse Cycle

The impossibility of realizing a reverse Carnot cycle in real systems is mainly due to two reasons:

- Compressing a mixture of liquid and vapor would require a compressor capable of handling both phases simultaneously.
- The difficulty of expanding the refrigerant in the presence of a high liquid phase content.

These problems can be overcome by fully vaporizing the refrigerant before compression and replacing the expansion, which is theoretically done by a turbine, with a throttling process using a valve or a capillary tube. The resulting cycle, called the standard reverse compression cycle, consists of four transformations and it is reported in Figure 2.3 using P-h and T-S diagrams.

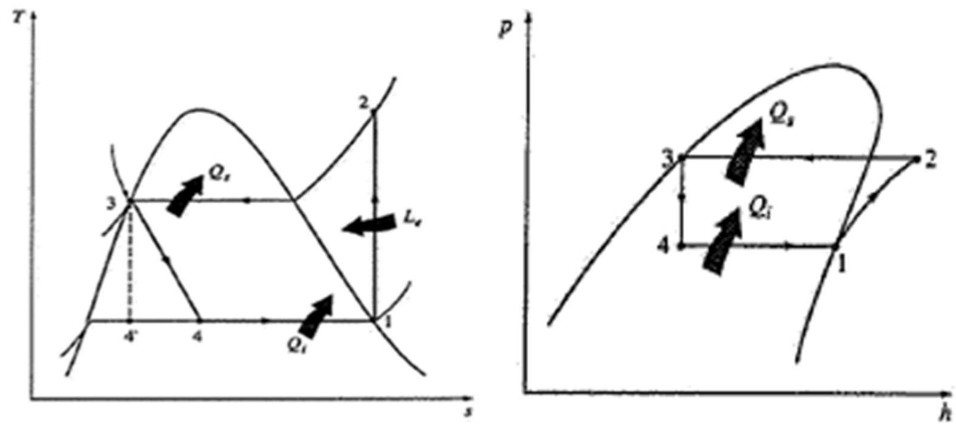


Figure 2.3: Reverse compression cycle represented in T-S and p-h diagrams

1. Isentropic compression 1-2: performed by a compressor
2. Isobaric heat rejection 2-3: performed by a condenser
3. Isenthalpic expansion 3-4: performed by an expansion valve
4. Isobaric heat absorption 4-1: performed by an evaporator

Further information on the main components of heat pump are provided in the next sections.

2.2 Performance metrics

The aim of this section is to present and discuss the main coefficients used to describe the performances of the heat pumps, allowing the comparison between different products.

2.2.1 Coefficient of Performance (COP)

The performance of heat pumps in terms of energy efficiency is evaluated using the Coefficient of Performance (COP). This metric is defined as the ratio between the useful heating power produced by the heat pump and the external power required to operate the cycle. Specifically:

$$COP = \frac{useful\ heat\ output}{required\ power\ input}$$

The COP indicates the efficiency of transferring heat energy from a lower temperature heat source to a higher temperature heat sink. It can be expressed in terms of power as:

$$COP = \frac{Q + L}{L}$$

where:

- Q is the heat extracted from the cold source
- L is the power input
- The sum between Q and L represents the useful heat delivered to the space to be heated

For vapor compression heat pumps, the input power corresponds to the electrical power required by the compressor.

For an ideal reversible heat pump (Carnot cycle), operating between a heat sink at temperature T_1 and a heat source at temperature T_2 (with $T_1 > T_2$), the COP would be:

$$COP = \frac{T_1}{T_1 - T_2}$$

Typical COPs for heat pumps range around 4, depending on the system and operating conditions. A higher COP indicates greater efficiency, which is influenced by:

- Lower temperature of the ambient in which heat is ejected
- Higher temperature of the heat source from which the same heat is absorbed.

The importance of COP lies in quantifying the temperature difference that the system can produce, i.e., the difference between the heat source temperature and the temperature at which the heat is released by the device.

2.2.2 Energy Efficiency Ratio (EER)

Similarly, when a heat pump is used for cooling purposes (refrigeration effect), the Energy Efficient Ratio (EER) instead of COP is used.

EER measures the electrical efficiency of a device in producing cooling effect:

$$EER = \frac{useful\ cooling\ output}{required\ power\ input}$$

In power terms, EER is defined as:

$$EER = \frac{Q}{L}$$

where:

- Q is the heat extracted from the hot source, which in this case is the space to be cooled.
- L is the electrical power input.

Similarly to COP, EER depends significantly on the temperature difference between the cooled space and the environment in which heat is dissipated. A smaller difference results in a higher EER value.

2.2.3 Seasonal Coefficient of Performance (SCOP) and Seasonal Energy Efficiency Ratio (SEER)

The Seasonal Coefficient of Performance (SCOP) and Seasonal Energy Efficiency Ratio (SEER) are required for the standard energy classification of heat pumps. The testing methodology is defined by the EU directive UNI EN 14825 (3).

These parameters are calculated yearly, considering three different climatic zones (warm, average and cold). They are strictly related to COP and EER, but account for additional factors such as:

- The ratio between ejected and absorbed thermal energy
- The season of utilization
- Standard external temperatures that can be reached in the season of utilization, depending on the climatic zone
- The operating hours of the heat pump.

2.3 Classification of Heat Pumps

Heat pumps are classified considering several characteristics, such as the type of energy required for the operation, the heat source used and the fluid used within the heating system of the space to be heated or cooled.

Furthermore, the volatile fluid that flows in the circuit of the heat pump, named refrigerant, can be chosen between a wide range of substances. The choice of refrigerant can significantly influence the performance of the heat pump in terms of operative temperatures and pressures. Refrigerants will be discussed in the next sections.

2.3.1 Energetic classification

The first heat pump classification is related to the energy type, allowing for the identification of two categories of heat pumps. Two different types of energy are used to perform the cycle:

- Mechanical energy, derived from electric motors or internal combustion engines (vapor compression heat pumps)
- Thermal energy, derived from absorption cycles (absorption heat pumps)

- **Vapor Compression Heat Pumps**

Most heat pumps utilise mechanical energy, performing the so called “vapor compression cycle”, with the main components being: the compressor, the expansion valve and two heat exchangers, namely the evaporator and the condenser. The various components are connected within a closed circuit through the refrigerant circulates.

The operation of the refrigerant in the heat pump follows this path (Figure 2.4):

- In the evaporator, the refrigerant temperature is kept lower than that the heat source, facilitating the necessary thermal exchange for the refrigerant to evaporate.
- The vaporized refrigerant is then draw into the compressor, where it is compressed to a higher pressure and temperature.
- The refrigerant flows through the heat exchanger, which acts as the condenser, where it cools and releases useful heat to the system's water before condensing.
- Finally, the refrigerant exits the condenser and is expanded by a throttling valve, reducing its pressure and completing the cycle.

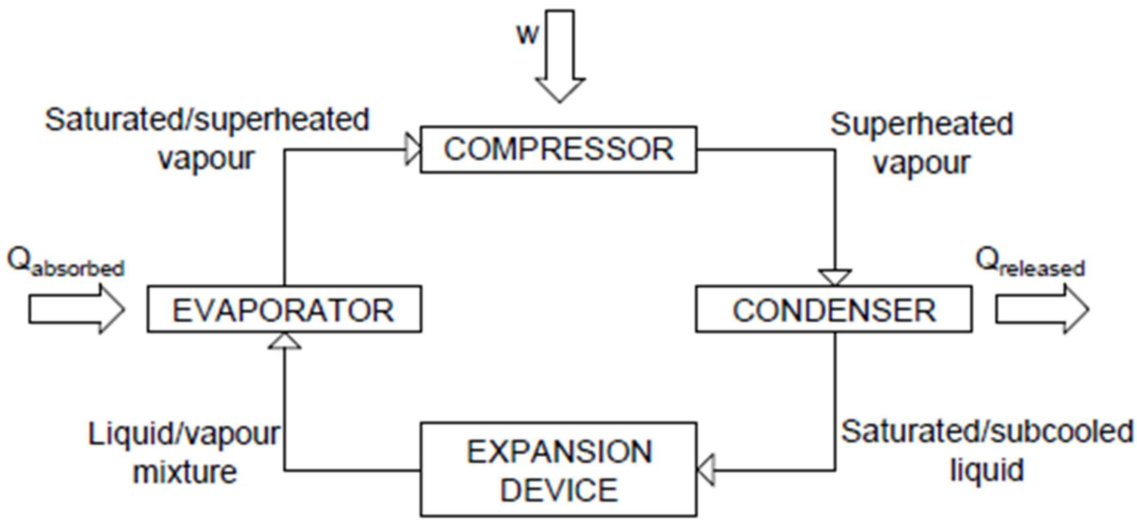


Figure 2.4: Vapour compression heat pump system

The compressor is usually powered by an electric motor or a combustion engine, each providing different advantages.

The electric motor allows the compressor to operate with minimal transformation losses, as the efficiency of converting electrical energy into mechanical energy generally exceeds 90%. Additionally, electricity can be produced by renewables, reducing the environmental impact of the machine. On the other hand, the operation of a system with an internal combustion engine allows the use of exhaust gas heat in addition to the heat generated at the condenser. However, the energy efficiency of converting thermal energy from the combustion engine into mechanical energy to ensure the rotation of the compressor is lower than that of an electric motor. Furthermore, the environmental impact is higher due to "in loco" emissions.

- **Absorption Heat Pumps**

Absorption heat pumps operation is based on the availability of thermal energy rather than mechanical one. They utilize the ability of liquids and salts to absorb vapor from the working fluid, which operates between the high and low-pressure zones. The most commonly used substances in these systems are:

- Water (working fluid) and lithium bromide (absorbent).
- Ammonia (working fluid) and water (absorbent).

In absorption systems, the compression is achieved thermally through the following components (Figure 2.5):

- A pump for the absorbent solution.
- A condenser where the vapor of the working fluid condenses.
- An evaporator where the working fluid evaporates.
- A generator that produces a denser absorbent solution.
- An absorber where heat is absorbed by the low-pressure solution.
- An expansion valve for expanding the working fluid from the high-pressure zone to the low-pressure zone.

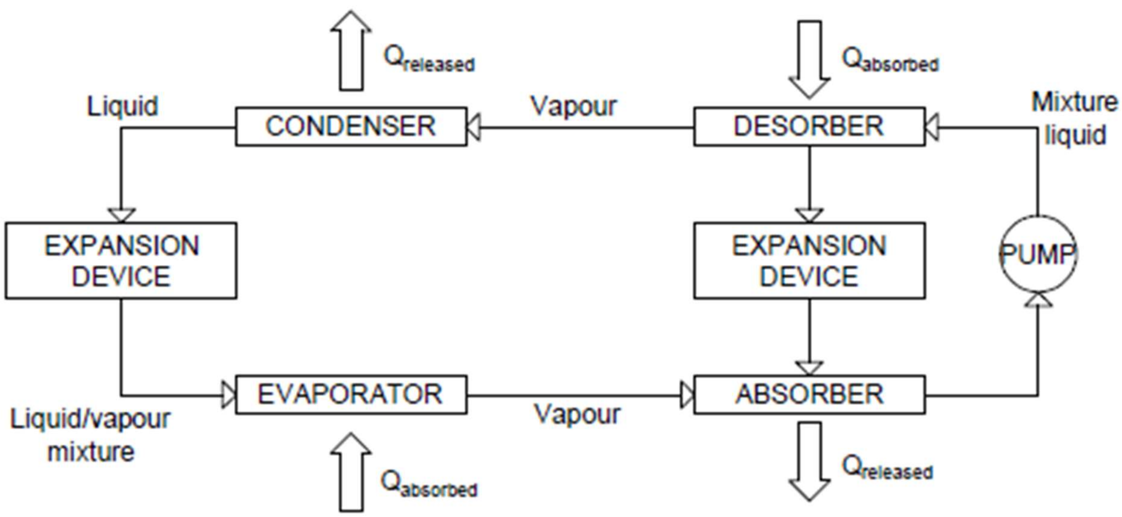


Figure 2.5: Absorption heat pump system

The absorption heat pump operates as follows: low-pressure vapor from the evaporator is conducted into the absorber, where it is absorbed by the absorbent solution. This exothermic process generates absorption heat, consequently increasing the liquid's temperature. Since the solution tends to lose its absorption capacity by absorbing vapor, it is conducted to the generator, where the working fluid vaporizes and separates from the absorbent solution. This process is made possible by the provision of high-temperature external heat, regenerating the solution to its desired initial concentration.

The vapor then condenses inside the condenser, releasing heat to the environment, while the absorbent solution returns to the absorber through the expansion valve and the refrigerant returns to the evaporator at a lower pressure through the throttling valve.

2.3.2 Classification of Compression Heat Pumps Based on the Heat Source

Compression heat pumps can be also classified considering both the external and the internal thermal source from which they exchange heat. The type of external (first term) and internal (second term) heat source determines six types of heat pumps:

- Air-to-Air
- Air-to-Water
- Water-to-Air
- Water-to-Water
- Ground-to-Air
- Ground-to-Water

Regarding the internal environment, which is heated or cooled, heat pumps are divided into two main categories:

- Air systems: thermal energy produced by the condenser is directly transferred through ducts and diffusers that exchange heat with indoor air. These systems are generally called splits.
- Water systems: heated or cooled water in a circuit transfer heat to various zones to be climatized, typically using fan coils or radiant panels.

For the external source, heat pumps are primarily categorized into three categories:

- **Air**

External air is an unlimited and always available energy source, characterized by variable temperatures. Daily thermal fluctuations and long-term seasonal variations must be considered in system design. The normalized temperature values for each geographical location, such as annual minimum and maximum temperatures and monthly average temperatures, are essential for design.

The UNI 5364 (4) standard associates a minimum design external temperature to major locations, and for others, climatic parameters can be calculated based on altitude and exposure relative to a reference city, according to UNI 10349 (5).

Due to the variations in external temperatures, D.P.R. 412/93 (6) divides the entire national territory into six climatic zones, each with a different heating system operating period. This division is made using "Degree Days" (DD), a parameter corresponding to the sum of the positive daily differences between the indoor temperature, conventionally set at 20°C, and the daily average external temperature over the heating season. Mathematically, degree days (DD) are expressed as:

$$DD = \Sigma\Sigma_{i=1}^{n}(T_0 - T_{e,i})$$

where:

- n is the number of days in the conventional heating period ($90 \leq n \leq 365$),
- T_0 is the conventional indoor temperature (20°C),
- $T_{e,i}$ is the daily average external temperature, and $T_{e,i} < T_0$.

This parameter gives immediate information about the climatic zone, the higher its value, the colder the local climate.

- **Water**

Heat pumps can utilize water as an external low-enthalpy heat source. The water used for the thermal process can be surface water (sea, lake, river) or groundwater. The investment costs are higher compared to air-source solutions due to the greater complexity of the system, which requires pumps, valves and possibly an artesian well and disposal system for exhausted water.

Groundwater is a highly suitable thermal source for heat pumps, maintaining constant temperatures year-round: typically 10–15°C under normal conditions and 15–25°C near thermal areas. The temperature of groundwater near the surface is close to the average external air temperature, increasing with depth, making annual thermal variations negligible at adequate depths.

Water-to-water heat pumps can be open-loop, directly utilizing groundwater, or closed-loop, using an intermediate heat transfer fluid as in traditional geothermal applications. Open-loop applications require one or more wells to draw and return water to the aquifer. The design of these wells depends on the site's geological properties and the flow rate needed for the heat pump.

In summary, the classification and functionality of heat pumps based on the type of heat source demonstrate the versatility and efficiency of these systems in various climatic and geographical conditions. Understanding the characteristics of each type helps in selecting the most appropriate system for specific heating and cooling needs.

- **Geothermal**

Geothermal energy is stored in the Earth's crust and can be extracted by heat pumps through borehole systems. Geothermal energy consists of two main components: heat from deeper layers of the Earth and heat from the external environment originating from the Sun.

External space heat only influences the shallowest layer of the Earth's crust and becomes negligible beyond 20 meters depth. Below this depth, ground temperature stabilizes around 13–15°C up to about 100 meters. At this point, the geothermal gradient, caused by heat from the Earth's core, sets in, increasing temperature by 30°C every 1000 meters.

The temperature of the subsurface is a crucial parameter for assessing the economic viability of a geothermal system because it determines the efficiency of the heat pump. A temperature close to 10°C indicates a thermal jump for operation in radiant floor heating at 35°C, resulting in a 25°C temperature differential. A temperature of 0°C would require a compression jump of 35°C.

Greater thermal jumps necessitate more compression work, leading to increased electrical energy demand from the heat pump. Open-loop systems, which extract groundwater, maintain constant temperatures at the geothermal evaporator, regardless of the heat pump's operating hours. While typically, closed-loop systems experience decreasing operating temperatures as hourly demand increases, generally lower than those achievable by open-loop systems. This is why the coefficient of performance (COP) of open-loop systems is generally higher than the ones of closed-loop systems.

Average temperature ranges found at our latitudes at different depths are as follows:

- From 3°C in winter to 17°C in summer within the first 2 meters from the ground surface.
- Constant 12°C at about 15 meters from the ground surface.

The graph in Figure 2.6 shows the variability of ground temperature throughout the seasons and indicates that temperature oscillations decrease with increasing depth from the ground surface.

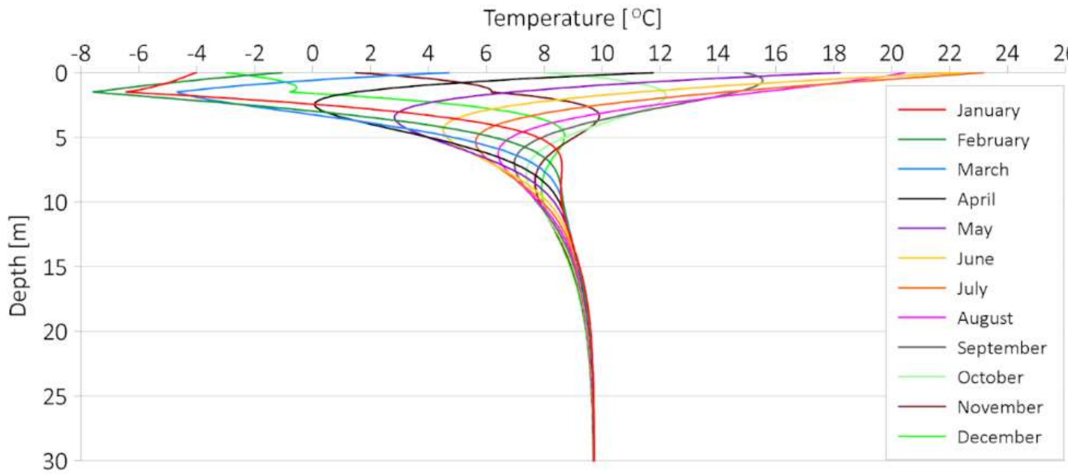


Figure 2.6: Monthly ground temperature

During winter operation, geothermal heat pumps extract energy from the subsurface, resulting in temperature reduction. Surface energy capture systems are positioned in a zone of ground influenced by outdoor air temperature, thus offering a narrower operational thermal margin compared to vertical systems. The technical disadvantage of these systems, related to lower evaporative temperatures, is offset by oversizing the horizontal collection network, as the increase in surface network results in minimal cost increments compared to vertical systems.

The circulating solution in the probes can reach temperatures below 0°C, causing ice crystal formation. To prevent fluid solidification, an antifreeze liquid is added to the solution. These mixtures, based on ethylene glycol or polypropylene glycol, lower the freezing temperature proportionally to the percentage in solution; typically, with a percentage close to 20%, freezing temperatures are around -10°C. The use of these solutions increases fluid viscosity and reduces heat exchange capacity as a drawback.

There are two types of geothermal systems based on the type of collectors used: horizontal and vertical, as shown in Figure 2.7.

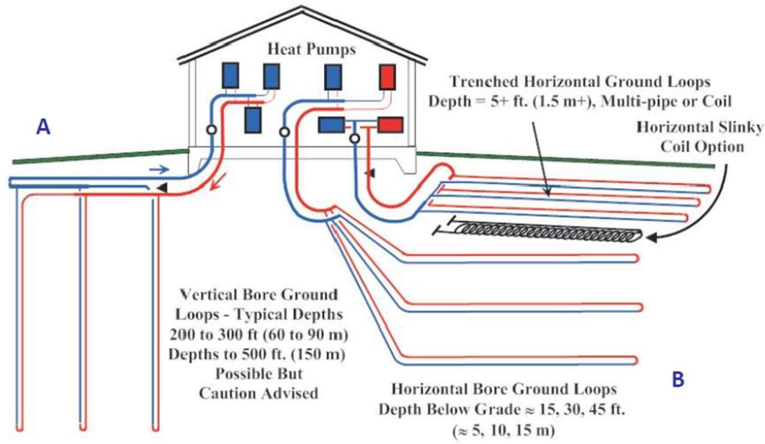


Figure 2.7: Horizontal and vertical ground heat exchanger systems

Unlike horizontal collectors, vertical collectors require a deep well or multiple shallower wells where pipes filled with glycol water exchange heat with deeper layers of the ground. This solution involves substantial costs but benefits from higher temperatures at greater depths and less influence from climatic variations. Additionally, with specific terminals, there is a possibility of free summer cooling.

Understanding geothermal energy sources and their utilization through various types of heat pump systems underscores their efficiency and adaptability across different climatic and geological conditions. Choosing between horizontal and vertical systems depends on factors like installation costs, ground conditions, and desired thermal performance, ultimately impacting system effectiveness and economic viability.

2.4 Refrigerant

Refrigerants, as previously explained, are the fluids circulating in the heat pump circuit. Their physical properties allow them to absorb heat at low temperature and pressure and then release it at high temperature and pressure, through cycles of expansion and compression. Typically, the heat transfer corresponds to a state transition between liquid and vapour, allowing the utilisation of latent heat.

Refrigerant are classified into three main categories:

- Organic Fluids
- Hydrocarbons
- Halogenated Hydrocarbons:
    - Chlorofluorocarbons (CFC)
    - Hydrofluorocarbons (HFC)
    - Hydrochlorofluorocarbons (HCFC)
    - Perfluorocarbons (PFC)

There is no perfect refrigerant, as each fluid performs better under different specific conditions. Therefore, it is essential to analyse the application to choose the most suitable option for the intended purpose. Further considerations when selecting refrigerant relate to environmental impact, safety and economic criteria.

A list of the main thermodynamic properties and their explanations is here reported:

- Compression energy: should be minimized to reduce electricity consumption.
- Cooling capacity: should be optimised to reduce the refrigerant charge.
- Heat transfer coefficients: should be high to minimise the dimensions of heat exchangers.
- Freezing point: should be as low as possible to enable heat absorption from colder sources.
- Critical point: should be as high as possible to transfer heat at the highest possible temperature

Regarding safety, the key considerations involve flammability and toxicity. In the Table 2.1 reports the safety classification of various refrigerant.

Class	Characteristics
A	Low toxicity (< 400 ppm; exposure for more than 30 minutes can lead to health hazards)
B	High toxicity (> 400 ppm; death hazard)
1	Flame doesn't propagate in air at 21°C and 101 kPa
2	Low flammability (> 0.1 kg/m³ in air at 21°C and 101 kPa); Lower heat of combustion < 19 kJ/kg
2L	Low flammability (> 0.1 kg/m³ in air at 21°C and 101 kPa); Lower heat of combustion < 19 kJ/kg; Propagation velocity < 0.1 m/s
3	High flammability (> 0.1 kg/m³ in air at 21°C and 101 kPa); Lower heat of combustion ≥ 19 kJ/kg

Table 2.1: Toxicity - flammability refrigerant classification

Finally, considering the environmental impact of these fluids, two indices have been introduced:

- Ozone Depletion Potential (ODP), that represents the capacity to destroy ozone. The scale is referenced to R11 (CFC), which has an ODP of 1, while inert refrigerants have an ODP of 0.
- Global Warming Potential (GWP), expressed in kgCO2e, is an index useful for comparing gases based on their ability to absorb infrared thermal radiation by a unit mass of the substance over a specific time frame after it has been released into the atmosphere. The scale is based on CO_2 that has a GWP of 1.

The choice of refrigerants is also based on regulation, in particular regarding the fluorinated gases (F-gases). In the next sections, the ASHRAE nomenclature and regulatory considerations are discussed.

2.4.1 ASHRAE Classification for Refrigerants (7)

Pure Synthetic

- Denoted with acronyms in the form R – I – II – III – IV – V – VI, where:
  - I: C if cyclic derivatives
  - II: Number of double bonds minus 1
  - III: Number of carbon atoms minus 1
  - IV: Number of hydrogen atoms plus 1
  - V: Number of fluorine atoms
  - VI: A lowercase or capital letter, depending on the molecular structure (e.g., 'a' = asymmetric positional isomer)

Chlorofluorocarbons (CFC)

- Simple organic compounds consisting of chlorine, fluorine, and carbon. They are no longer used due to their harmful effect on the ozone layer, despite their excellent properties: chemical stability, non-toxicity, odour-free, non-flammability, low production costs and good thermodynamic properties.

Hydrochlorofluorocarbons (HCFC)

- Synthetic compounds composed of fluorine, chlorine, carbon and hydrogen. They are considered transition refrigerants used initially to replace CFCs. They have similar properties but are less damaging to the environment due to a shorter atmospheric lifetime.

Hydrofluorocarbons (HFC)

- Synthetic compounds composed of fluorine, chlorine and carbon. HFCs have completely replaced CFCs and HCFCs in climatization applications due to their zero impact on the ozone layer, although they do not have as good properties as the refrigerants they replaced.

Hydrofluoroolefins (HFO)

- Synthetic compounds composed of hydrogen, fluorine, and carbon, with at least one double bond in their structure. HFOs are used as next-generation refrigerants due to their zero-ozone depletion potential and significantly lower global warming potential (GWP) compared to HFCs. However, their chemical stability and other thermodynamic properties may vary depending on the specific type of HFO used.

Mixtures

- These result from combining two fluids of similar chemical nature that are inert with respect to each other. Mixtures are classified into three classes:
  - **Azeotropic**: Change phase at constant pressure and temperature, behaving as pure fluids with constant composition even in case of leakages.
  - **Zeotropic**: Exhibit a temperature variation, called glide, during phase change, potentially leading to a different composition of the mixture in case of leakages, affecting both safety and performance.

- **Almost Azeotropic**: Have a smaller glide that doesn't significantly affect safety and performance.

Natural Refrigerants

- Studied for their minimal environmental impact. Main natural refrigerants include:
  - **Water (R718)**: Numerous advantages related to cost and environmental impact, although not applicable for vapor compression plants due to thermal properties.
  - **Ammonia (R717)**: Enhanced properties like low specific volume, high evaporation heat and high heat transfer coefficient, but with disadvantages such as toxicity, flammability and potential damage to copper in hydraulic circuits.
  - **Hydrocarbons**: Flammable with quantity limits depending on the application but offer advantages like null environmental impact, optimal heat transport properties, low cost and compatibility with traditional materials.
  - **Carbon Dioxide (R744)**: Advantages include high heat transfer coefficient and energy content, low viscosity and small compression ratio, resulting in lower energy consumption. Limitations include high condensation temperature and high operating pressure requirements.
  - **R290 (Propane)**: A hydrocarbon refrigerant that offers excellent thermodynamic performance and minimal environmental impact due to its zero-ozone depletion potential and negligible global warming potential. It is highly flammable, with usage limitations based on the application, but is compatible with traditional materials and offers low cost and efficient heat transfer properties.
  - **R600a (Isobutane)**: Another hydrocarbon refrigerant known for its low environmental impact, with zero ozone depletion potential and very low global warming potential. Like R290, it is highly flammable and subject to quantity restrictions depending on the system. R600a is widely used in domestic refrigeration due to its energy efficiency, low cost, and good compatibility with common materials.

2.4.2 European Regulation Regarding F-Gas

F-gases are synthetic refrigerants widely used in refrigeration systems, developed especially in the 90s to replace other substances, such as CFC and HCFC, which posed ozone depletion risk. However, F-gases have a higher Global Warming Potential. As a result, the European Union has implemented regulations in order to reduce F-gas utilization and eventually phasing them out.

In Italy, the main regulation on refrigerants is the D.P.R. n. 146/2018 (8), effective from 24/01/2019, based on the UE regulation 517/2014 (9) on F-gases. UE on 20/02/2024 published a new regulation 2024/573 (10), effective from 11/03/2024, that imposes more strict constraints updating regulation 517/2014 (9).

These regulations impose restriction on:

- Containment, use, recovery and destruction of these gases
- Placing in the market of products and machines based on this type of refrigerants
- Quantitative limits regarding the refrigerant charge to be used.

Furthermore, following the regulations, maintenance and installation works need to be performed by specialized operators and a national telematic register of operators and companies is necessary.

2.5 Main heat pump components

The aim of this section is to introduce and discuss the main components required to perform an inverse thermodynamic cycle.

A list of these components is provided below, with a detailed description to follow:

- Compressor
- Lamination or thermostatic valve
- Evaporator
- Condenser

Furthermore, in case of a machine used to produced domestic hot water, a water storage tank is also necessary.

Other minor components won't be discussed here, but will be present in the next sections, analysing the heat pump designed during the draft of this thesis.

2.5.1 Compressor

The component that more represents the heating (or cooling) capacity of a heat pump is the compressor. It also represents the main source of energy consumption in heat pump operation. These characteristics make the compressor the first component to be selected when designing a machine of this type.

Various types of compressors exist, each with distinct technical characteristics, particularly in terms of performance, size and noise emissions. This allows for the selection of the appropriate compressor based on the specific application.

Considering heat pumps, generally compact solutions, with low noise emission levels are preferred. The most widely used types of compressors for heat pumps include:

- Reciprocating
- Scroll
- Screw
- Rotary
- Twin rotary

The following sections provide a detailed discussion of each technology.

Reciprocating compressors

Reciprocating (or piston) compressor is a technology based on crankshaft activated pistons to compress air (Figure 2.8). Two types of this machines are existing: mono-stage, in which air is compressed in a unique phase, and bi-stage, in which air is compressed into two separated stages, the first at intermediate pressure and the second one at high pressure, resulting in an enhanced efficiency.

Figure 2.8: Reciprocating compressor

General characteristics of reciprocating compressors are:

- Low initial cost
- High efficiencies and pressure levels considering bi-stage machines
- Low sensibility to aggressive environmental conditions
- Operability at lower power with respect to the nominal one without detrimental effects
- Non-continuous operation
- High noise and vibration emissions
- Off-periods for cooling down the machine are required
- High maintenance costs
- Short lifespan

Scroll Compressors

Scroll compressors, also known as spiral compressors or scroll pumps, are positive-displacement compressors (Figure 2.9). They consist of two spirals, one fixed and one movable. The gas is drawn into the scroll cycle and follows the spirals toward the centre, resulting in smaller chambers where the gas is compressed. This process is known as "internal" compression.

Scroll compressors can be either oil-lubricated or oil-free. Oil-free versions are ideal for applications requiring clean, dry air without oil contamination in the compression chamber. Scroll compressors are more efficient and emit less noise and vibration compared to reciprocating compressors.

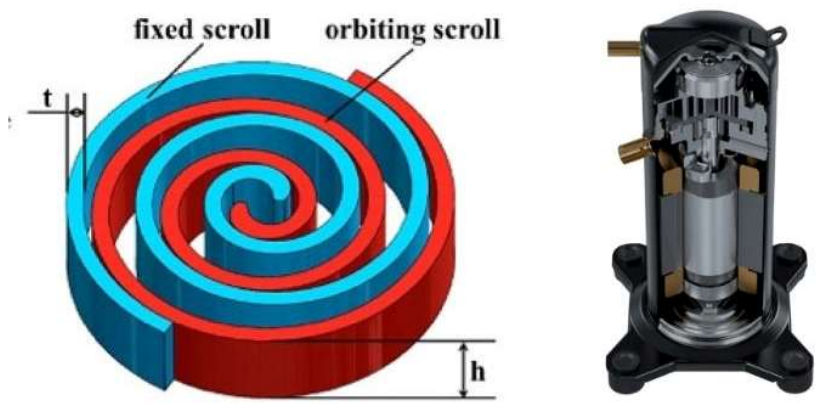


Figure 2.9: Scroll compressor

General characteristics of scroll technology are:

- Enhanced and optimized performances in low-capacity applications
- Compact dimensions
- Low maintenance costs
- Low noise and vibration emissions
- High initial costs
- Not suitable for application requiring regulation
- Sensibility to ambient contaminants such as dust and humidity, but their structural simplicity reduces the probability of faults

Screw compressors

Screw compressors have been used in refrigeration applications since 1950s, thanks to their reliability and efficiency. They are composed by two helicoidal rotors engaging tightly without touching each other, resulting in continuous pulsation-free compression.

In Figure 2.10: Screw compressor is represented a screw compressor.

Figure 2.10: Screw compressor

General characteristics of screw technology are listed below:

- Wide range of applications, their configuration allows an efficient compression of both smaller and larger air volumes
- High efficiency
- Low initial cost
- Continuous operation
- Low maintenance requirement due to the reduced number of rotating parts
- High sensibility to contaminants in the environment
- High noise and vibration emissions
- High maintenance requirements due to their structural complexity

Rotary Compressors

Rotary compressors feature a cylindrical chamber with two openings (intake and discharge) and an eccentrically positioned rotor (Figure 2.11). The eccentric rotation reduces the volume, thereby compressing the gas.

Figure 2.11: Rotary compressor

Main features of this technology are:

- Continuous operation
- Reliability
- Long lifespan
- Low noise and vibration emissions
- High initial cost
- Sensible to contaminants in the environment
- Needing of a specialized maintenance

Twin Rotary Compressors

Twin rotary compressors are similar to rotary compressors but have two rotors working in opposition (Figure 2.12). This configuration presents the same features of rotary compressors, although it enhances efficiency and allows better modulation of motor speed, though it comes at a higher cost.

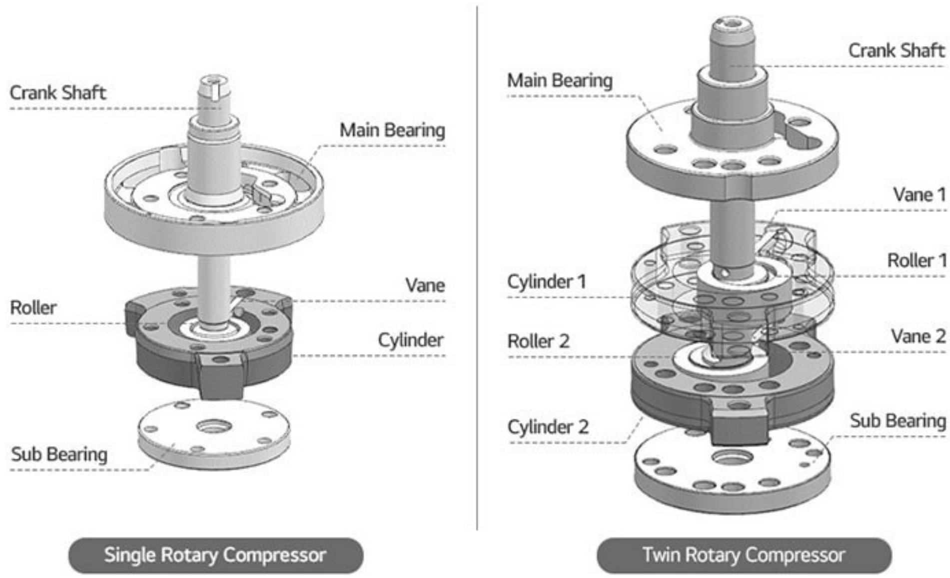


Figure 2.12: Comparison between Rotary and Twin rotary compressors (11)

2.5.2 Expansion valve

Expansion valves are crucial components in heat pumps and refrigeration systems. Their primary function is to regulate refrigerant flow and reduce the pressure from the condenser, allowing the refrigerant to expand and cool before entering the evaporator. These valves play a key role in maintaining the efficiency of the cooling or heating cycle.

Their ability to control refrigerant flow precisely, adapt to load changes and optimise system performance makes expansion valves essential in modern Heating, Ventilation and Air Conditioning (HVAC) systems and refrigeration technology.

The core principle behind expansion valves is the throttling process. The high-pressure liquid refrigerant from the condenser is forced through the valve, where it undergoes a rapid pressure drop. This expansion causes a portion of the liquid refrigerant to evaporate, resulting in a mixture of cold liquid and vapor that enters the evaporator. In the evaporator, the refrigerant absorbs heat from the surroundings (or the space to be cooled), thus achieving the desired cooling effect.

Below, different types of expansion valves are discussed based on their working principles and applications.

Thermostatic Expansion Valves (TXV)

Thermostatic Expansion Valves (Figure 2.13) are widely used due to their precision in controlling refrigerant flow. They consist of a sensing bulb, diaphragm and valve body. The sensing bulb, filled with a substance similar to the refrigerant, is placed at the evaporator outlet. Changes in temperature at this point cause the fluid in the bulb to expand or contract, moving the diaphragm and adjusting the valve opening accordingly.

Main features of this typology of expansion valves are:

- High accuracy in maintaining superheat
- Good response to load variations
- Enhances system efficiency

TXVs are mainly used in commercial and residential air conditioning systems.

Figure 2.13: Thermostatic Expansion Valve

Below, the operation principle of this technology is reported:

- The sensing bulb monitors the temperature of the refrigerant leaving the evaporator.
- As the temperature rises, the pressure in the bulb increases, pushing the diaphragm to open the valve and allow more refrigerant flow.
- Conversely, if the temperature drops, the bulb pressure decreases, causing the valve to close slightly and reduce the refrigerant flow.

Electronic Expansion Valves (EEV)

Electronic Expansion Valves (Figure 2.14) are controlled by an electronic controller that receives inputs from various sensors within the system. These valves use a stepper motor or solenoid to adjust the refrigerant flow with high precision, based on real-time data such as temperature and pressure.

General characteristics for EEVs are:

- Precise control over refrigerant flow
- Capable of complex control strategies
- Improved system performance and energy efficiency

Main application fields are:

- Advanced HVAC systems
- Variable Refrigerant Flow (VRF) systems

- High-efficiency heat pumps

Figure 2.14: Electronic Expansion Valve

The operation principle of EEVs is:

- Sensors provide real-time data to the electronic controller
- The controller processes the data and sends precise commands to the stepper motor or solenoid
- The motor adjusts the valve opening to regulate the refrigerant flow accurately

Automatic Expansion Valves (AXV)

Automatic Expansion Valves (Figure 2.15) regulate refrigerant flow based on evaporator pressure, maintaining a constant pressure regardless of load variations. They automatically adjust the valve opening in response to pressure changes in the evaporator.

Main advantages of this type of valves are:

- Simple operation and design
- Cost-effective
- Suitable for applications with stable loads

AXVs are generally used in smaller systems, such as small commercial refrigeration units and domestic refrigeration.

Figure 2.15: Automatic Expansion Valve

Below, the operation principle of this technology is reported:

- The valve maintains a constant evaporator pressure by adjusting the opening based on pressure changes.
- As the evaporator pressure rises, the valve closes to reduce refrigerant flow.
- When the pressure drops, the valve opens to increase the flow.

Capillary Tubes

Capillary tubes (Figure 2.16) are simple, fixed metering devices that reduce refrigerant pressure through a long, narrow tube. The pressure drop occurs due to the tube's length and small diameter, which restricts the flow of refrigerant.

Below are reported major advantages regarding this technology:

- Inexpensive
- No moving parts, making them highly reliable
- Simple to implement

Similarly to AXVs, capillary tubes are used in small applications, such as household refrigerators and small-scale heat pump systems.

Figure 2.16: Capillary tubes

Here is presented the operation principle of this type of expansion valve:

- The refrigerant flows through the narrow tube, experiencing a pressure drop due to the tube's resistance.
- The simple design results in a constant refrigerant flow rate, suitable for systems with steady operating condition.

2.5.3 Heat exchangers

Heat exchangers are devices designed to efficiently transfer heat from one medium to another. They play a crucial role in various industrial and domestic applications, including heating, cooling and refrigeration systems. Regarding heat pumps, two heat exchangers are required:

- Evaporator, which extracts heat from the hot source, and transfer this thermal energy to the refrigerant
- Condenser, which transfer the heat from the refrigerant to the environment to be heated.

Heat exchangers can be classified into several types based on their design and the nature of the heat transfer process:

- **Shell and Tube Heat Exchangers**: These consist of a series of tubes, one set carrying the hot fluid and the other the cold fluid. The tubes are housed within a cylindrical shell, allowing heat transfer through the tube walls. They are widely used in industrial applications due to their robust design and ability to handle high pressures and temperatures.
- **Plate Heat Exchangers**: Comprised of multiple thin, corrugated plates stacked together, plate heat exchangers provide a large surface area for heat transfer. The fluids flow through alternate channels formed by the plates. They are highly efficient and compact, making them suitable for applications requiring a small footprint, such as residential heating systems and HVAC applications.
- **Air-Cooled Heat Exchangers**: These use air to cool fluids, typically using a fan to force air over a finned tube bundle. Air-cooled heat exchangers are commonly used in applications where water is scarce or where direct cooling with air is more economical.
- **Double Pipe Heat Exchangers**: Consisting of one pipe inside another, double pipe heat exchangers allow heat transfer between two fluids. The inner pipe carries one fluid, while the outer pipe carries the other. This simple design is often used in small-scale applications or where space is limited.
- **Plate and Shell Heat Exchangers**: Combining the features of plate and shell and tube heat exchangers, these devices use a series of plates within a shell. They offer the benefits of both high efficiency and the ability to handle high pressures and temperatures, making them suitable for demanding applications in the chemical and petrochemical industries.

- **Finned Tube Heat Exchangers**: These have fins attached to the tubes to increase the surface area for heat transfer. Finned tube heat exchangers are commonly used in air conditioning, refrigeration, and automotive applications due to their enhanced heat transfer capabilities.
- **Regenerative Heat Exchangers**: Designed for applications requiring the periodic storage of heat, regenerative heat exchangers alternate between storing heat from a hot fluid and releasing it to a cold fluid. They are often used in energy recovery systems and industrial processes where heat recycling is essential.

Each type of heat exchanger has its advantages and specific use cases, depending on factors such as efficiency, capacity, size, cost, and the nature of the fluids involved. Selecting the appropriate type is crucial for optimizing the performance and cost-effectiveness of a thermal system.

The sizing process for heat exchangers is based on the thermal capacity of the machine. Considering a heat pump, to dimension the evaporator it is necessary to evaluate the requested cooling capacity, representing the heat to be extracted from the source. While to dimension the condenser the heating capacity (equal to the sum of cooling capacity and external energy required, i.e. absorbed by the compressor) must be considered, since it represents the heat released in the ambient to be heated.

If the same heat pump is used to produce both heating and cooling, an inversion in the cycle verse is required. In these systems, regarding the sizing of heat exchangers, generally two evaporators are considered, resulting in an oversizing of the condenser.

2.6 Advantages and limitations of heat pump systems

Heat pumps offer several advantages over traditional heating systems:

- **Cost-effectiveness**: Heat pumps can significantly reduce heating costs, often by up to 50% compared to traditional systems. Operating costs are also generally lower due to their efficient operation.
- **Energy efficiency**: Heat pumps deliver substantial energy savings, ranging from 40% to 60% for winter heating compared to conventional fossil fuel systems. This leads to a significant reduction in harmful emissions such as nitrogen oxides (NOx), sulphur dioxide (SO2) and greenhouse gases like carbon dioxide (CO2), thereby contributing to environmental protection.
- **Versatility and integration**: Heat pumps can provide both heating in winter and cooling in summer, as well as hot water production, all with a single integrated system. This eliminates the need to manage separate air and water systems, simplifying infrastructure and improving overall efficiency.
- **Use of renewable energy**: Heat pumps harness low-temperature thermal energy extracted from natural sources such as air, water, or soil. This allows them to utilize up to 75% renewable energy, significantly reducing the consumption of electric energy required for operation. Furthermore, combining heat pumps with technologies like solar panels or wind turbines can achieve nearly carbon-neutral energy balance.
- **Integration with other technologies**: Heat pumps seamlessly integrate with other traditional and renewable technologies, enabling more flexible and optimal energy solutions for various applications.
- **Suitable for retrofit and new installations**: Due to their high efficiency, characterized by high Coefficient of Performance (COP) values, heat pumps are ideal for retrofitting existing systems or installing in new buildings, both residential and industrial.
- **Government incentives**: Many countries, including Italy, offer governmental incentives and subsidies for purchasing and installing heat pumps. These incentives make it more cost-effective to adopt energy-efficient technologies.

However, heat pumps have some limitations:

- **Temperature dependency**: The performance data provided for heat pumps are typically based on standard operating conditions that do not account for temperature variations. The main limitation arises from the fact that the temperature of hot water produced by current technologies is relatively low, restricting their use for space heating. As the desired water temperature increases, the efficiency of the heat pump system decreases significantly.
- **Hot Water Sanitization**: Heat pumps face challenges when used for domestic hot water heating, particularly in preventing Legionella bacteria. The low water temperatures required for efficient heat pump operation are insufficient for ensuring the necessary hygienic treatment to eliminate Legionella. This often necessitates additional systems to raise water temperatures to around 70°C, thereby reducing the heat pump's Coefficient of Performance (COP) substantially.
- **Performance in cold conditions**: The efficiency of a heat pump is also influenced by the temperature of the cold source from which heat is extracted. As the temperature of the cold source decreases, the system's efficiency decreases because more work is required to compress the refrigerant to the desired temperature.

Obviously, all these disadvantages strongly depend on the characteristics of each specific heat pump, in particular regarding the refrigerant properties and the source underutilization. In fact, some particular refrigerants allow to reach high temperatures, comparable to combustion-based heating plants outputs, thus reducing Legionella’s issues and being compatible with traditional heating distribution systems.

In conclusion, heat pumps offer significant savings on energy costs and reduces emissions, supporting global goals for environmental and energy sustainability. Although their operational efficiency is strongly dependent on maintaining optimal temperature differentials between hot and cold sources, thus a strict control is required.

3 General overview of T5 project

As explained in the abstract, T5 is a new heat pump designed specifically to replace traditional combustion-based heating systems for domestic applications. More precisely, the aim of the project is to create a competitive alternative for apartments with autonomous heat systems.

The aim of this project is to create a technology able to produce in a single solution:

- Heating
- Cooling
- Domestic hot water (if coupled with water tank)

Therefore, two different versions of this machine have been designed: one with and one without the water tank. Technical details regarding the differences between these versions will be discussed later in this dissertation.

In this section, several analyses will be performed. The first will focus on statistical data regarding Italian residential building, to better understand the commercial target of this project and the actual condition in Italy.

Then, a comparison with products created by competitors will be performed, underlining the innovative features and superior performances offered by T5 technology.

Furthermore, an economic analysis will be reported, detailing both the costs required to install T5 system and the potential savings it can generate. Final result will be a cashflow analysis, necessary to understand the economic differences with respect to a traditional system.

Finally, an emission analysis will be performed, highlighting the minor environmental impact of this product with respect to combustion-based systems.

3.1 Heating and Cooling Systems in Italian Residential Buildings

This chapter explores the statistical data on Italian housing, focusing on apartments equipped with autonomous heating and cooling systems. It will explore the types of systems used, their geographic distribution and the implications of these statistics on energy consumption and policy planning.

According to ISTAT data (12), in Italy the 45% of apartments are equipped with autonomous heating systems, while the remaining 55% rely on centralized heating. Although cooling systems are less prevalent compared to heating ones, but their adoption is increasing due to hotter summers. About 40% of households have some form of air conditioning, with split-system air conditioners being the most common type.

Autonomous systems in Italian apartments can be categorized primarily into four types for heating: gas boilers, heat pumps, electric heaters/coolers, biomass and other systems. Each type has distinct characteristics and efficiency levels.

- Gas boilers: these are the most common type of heating system (60% ca), particularly in urban areas. They are efficient, relatively inexpensive and suitable for the Italian climate
- Heat pumps: increasingly popular due to their higher energy efficiency and lower environmental impact, heat pumps provide both heating and cooling purposes, making them versatile. Nowadays, they account for 25% but this percentage is rapidly increasing
- Electric heaters/coolers: less common due to higher running costs but still used in areas where gas supply is limited or in older buildings. They account for about 10%
- Biomass and other systems: this class includes biomass, solar thermal and other renewable-based plants. These systems are more common in rural areas and account for about 5% of the entire Italian housing

Regarding cooling systems, three main technologies are actually in use:

- Air conditioners: the most prevalent cooling systems, present in about 80% of Italian buildings that are equipped with air cooling systems. They are particularly widespread in the central and southern regions, where summers are hotter and longer.
- Evaporative coolers and fans: Around 14% of buildings use these systems. These are less effective in very humid conditions but are energy-efficient and cheaper to install and run.

- Integrated HVAC Systems: integrated heating, ventilation and air conditioning (HVAC) systems are found in approximately 6% of Italian housing, mostly in newly built or recently renovated buildings. These systems offer comprehensive climate control and are highly efficient.

From a marketing point of view, it is more useful to consider these data on a geographic base. In fact, the distribution of apartments with autonomous heating and cooling systems varies significantly across Italy, influenced by factors such as climate, urbanization and regional energy policies.

At the end of each section, a table reporting data based on recent investigations performed by the Italian National Institute of Statistics (ISTAT) (12) will be reported.

- **Northern Italy**

This region has the highest concentration of apartments with autonomous heating systems. Approximately 60% of apartments in this area are equipped with gas boilers due to the colder climate, which requires efficient and powerful heating solutions. However, the uptake of autonomous cooling systems is lower, with only around 20% of apartments having such systems, predominantly heat pumps and electric coolers.

Total number of apartments: 10 million	Autonomous heating: 6 million (60%)	Gas boilers: 4.8 million (80%)
		Heat pumps: 900’000 (15%)
		Electric heaters: 300’000 (5%)
	Autonomous cooling: 2 million (20%)	Heat pumps: 1 million (50%)
		Electric coolers: 1 million (50%)

Table 3.1: Statistical data regarding heating and cooling systems in Northern Italy

- **Central Italy**

In central Italy, around 45% of apartments have autonomous heating systems. The use of heat pumps is more common here compared to the north, accounting for about 30% of the autonomous systems due to the milder winters. For cooling, about 35% of apartments use autonomous systems, with a significant preference for heat pumps that offer both heating and cooling functionalities.

Total number of apartments: 7 million	Autonomous heating: 3.15 million (45%)	Gas boilers: 1.9 million (60%)
		Heat pumps: 900’000 (30%)
		Electric heaters: 300’000 (10%)
	Autonomous cooling: 2.45 million (35%)	Heat pumps: 1.75 million (70%)
		Electric coolers: 700’000 (30%)

Table 3.2: Statistical data regarding heating and cooling systems in Central Italy

- **Southern Italy and Islands**

Autonomous heating systems are less prevalent in the south with only about 25% of apartments having such systems. Electric heaters are more commonly used here, particularly in older buildings, because of the warmer climate which reduces the necessity for constant heating. Conversely, autonomous cooling systems are more prevalent due to the hotter climate, with approximately 40% of apartments equipped with such systems, primarily electric coolers and heat pumps.

Total number of apartments: 6 million	Autonomous heating: 1.5 million (25%)	Gas boilers: 750’000 (50%)
		Heat pumps: 300’000 (20%)
		Electric heaters: 450’000 (30%)
	Autonomous cooling: 2.4 million (40%)	Heat pumps: 1.5 million (63%)
		Electric coolers: 900’000 (37%)

Table 3.3: Statistical data regarding heating and cooling systems in Southern Italy and Islands

The predominance of gas boilers in the north reflects the need for robust heating solutions due to colder winters. However, the growing popularity of heat pumps in central and southern Italy indicates a shift towards more sustainable and energy-efficient technologies. This trend is supported by government incentives for energy-efficient home improvements and the increasing awareness of environmental issues among residents.

In addition, regional energy policies and infrastructure development play a crucial role in shaping these statistics. For instance, regions with better access to natural gas infrastructure tend to have higher rates of gas boiler installations. Conversely, areas with significant investments in renewable energy sources and electricity grids see more heat pumps and electric heaters/coolers.

The higher prevalence of cooling systems in the south highlights the climatic necessity for such installations, driven by hotter summers compared to the rest of Italy. The dual functionality of heat pumps for both heating and cooling is particularly advantageous, offering energy efficiency and cost savings over time.

3.2 Commercial alternatives

This paragraph is dedicated to a comparison between T5 heat pump and alternative technologies present in the market. Being a water-to-water heat pump, with such a modest rated power, there are only few other similar commercial products. In fact, the other producers prefer to design air-to-water or air-to-air heat pumps, creating cheaper products, although offering lower performances and less reliability.

Furthermore, the supply temperature provided to the heating distribution system by these types of heat pumps is generally lower than the one guaranteed by T5. This often requires the renovation of the distribution system, resulting in invasive and expensive retrofitting costs of the entire building, or the installation of split systems, not able to provide the same benefits as radiator systems.

The aim of this project is to create a real alternative to gas boilers, creating a technology able to guarantee the same reliability as traditional boilers. However, this objective results in higher installation costs. Nevertheless, as shown through a cashflow analysis, the payback period for the system is not excessive long, as will be demonstrated in the next paragraph.

Other renewable-based alternatives, such as solar thermal technologies, were also considered. However, these technologies present the same instability, due to their dependence on climatic conditions, much like air-based heat pumps. Therefore, they resulted to be feasible as part of hybrid systems coupled with combustion-based generators but are not capable of meeting thermal demands on their own.

Nevertheless, some comparable water-to-water heat pumps has been identified:

- NIBE F115-12
- IVT Greenline HE
- Alpha Innotec WZS

Table 3.4 provides a technical comparison between these technologies. All performance data are referred to evaporating temperature equal to 0°C and water supply temperature of 35°C, in order to make a more meaningful comparison between these heat pumps.

Regarding the features offered by these products, they all meet the same requirements as the T5, providing heating, cooling and domestic hot water. As T5, these competitors also offer different versions of these machines, each designed to meet varying demands.

Model	T5	NIBE F115-12 (13)	IVT Greenline HE C6/E6 (14)	Alpha Innotec WZS (15)
Rated thermal capacity [kW]	5,47	5,06	5,40	4,70
Rated cooling capacity [kW]	4,46	4,02	4,05	3,70
Rated electric power [kW]	1,01	1,04	1,35	1,00
Coefficient Of Performance	5,42	4,87	4,00	4,70
Dimensions [mm] (height/width/depth)	1800/600/600	1500/600/620	1800/600/645	1850/598/730
Refrigerant	R290	R407C	R407C	R410A
Global Warming Potential	3	1774	1774	2088
Domestic Hot Water volume [l]	160,00	Variable	185,00	178,00
Source flowrate [l/h]	1279,93	1044,00	1080,00	1050,00
Heating flowrate [l/h]	941,66	288,00	720,00	850,00

Table 3.4: Water-to-water commercial heat pumps comparison

As summarized in Table 3.4, the T5 results to guarantee better performances compared to the other models. Furthermore, it resulted to be also more eco-friendly since it uses a natural refrigerant (R290) with lower Global Warming Potential (GWP). This aspect is particularly significant given the EU's environmental goals, which are leading to strict regulations that could limit or eventually prohibit the use of pollutant refrigerants.

Considering product dimensions, all models are quite similar. Although T5 is slightly more compact, due to the lower water tank capacity. The tank has been specifically dimensioned to withstand specific requirements, as will be detailed in the section on the storage sizing.

3.3 Business plan and cashflow analysis

This section focuses on the economic analysis that led to the creation of a comprehensive cashflow analysis. Two distinguished analyses were performed, following the same steps: one for the case with domestic hot water tank and one for the case without storage.

This analysis can be divided into several steps and this section will follow the same procedure, explaining each phase while distinguishing between the two versions of the technology.

3.3.1 T5 coupled with water tank case

- **Source costs**

To better estimate the cost related to the sources of the heat pump, an analysis performed by E.Geo s.r.l., a company specialized in sizing and realization of low enthalpy geothermal plants, was considered. They estimated the cost for geothermal circuits based on the rated power of the plant and an interpolation was performed to obtain the specific result for a residential T5 system. The result of this interpolation showed that these installations cost about 580 €/kW.

Before continuing with this dissertation on the expected system costs, it is necessary to clarify the basic hypothesis. It was considered to install one T5 heat pump for each apartment, in a building containing 20 apartments. Considering T5's nominal thermal capacity (6,3 kW), it resulted to be a system with rated power equal to 126 kW.

Finally multiplying the price per kW of the installation, by the rated power of the entire system and dividing it by the number of apartments, the final result was obtained: the source circuit cost is about 3.650 € per apartment.

- **Consumption prevision**

The second phase corresponds to the analysis of average data regarding energy consumption for thermal needing, with the aim to predict annual costs. This section is itself divided into two parts: one referred to the traditional heating system and the second one to the T5 situation.

- Traditional boiler

Average national data provided by the Autorità di Regolazione per Energia Reti e Ambiente (ARERA) (16) were used to predict monthly gas consumption. It was assumed that the system would be installed in Turin, considering default energy market and average consumption class (1250 – 1500 Smc per year). By considering Lower Heating Value of methane equal to 9,6 kWh/Smc it was possible to calculate the amount of gas monthly consumed expressed in kWh.

Finally, the thermal demand of each apartment needed to be estimated, therefore, it was considered a standard efficiency for traditional boiler equal to 90,6%. This value was derived by D.M. 26.06.2009 art. 7 (17), which describes the standard efficiency values for boilers depending on their rated capacity.

Once the thermal demand was obtained, energy consumption for domestic hot water production and heating was separated. In particular, it was considered the amount of energy requested in September as the standard demand for domestic hot water production throughout the year, except for the summer months, when consumption is lower (entirely considered as DHW production). Finally, the following graph was obtained (Figure 3.1).

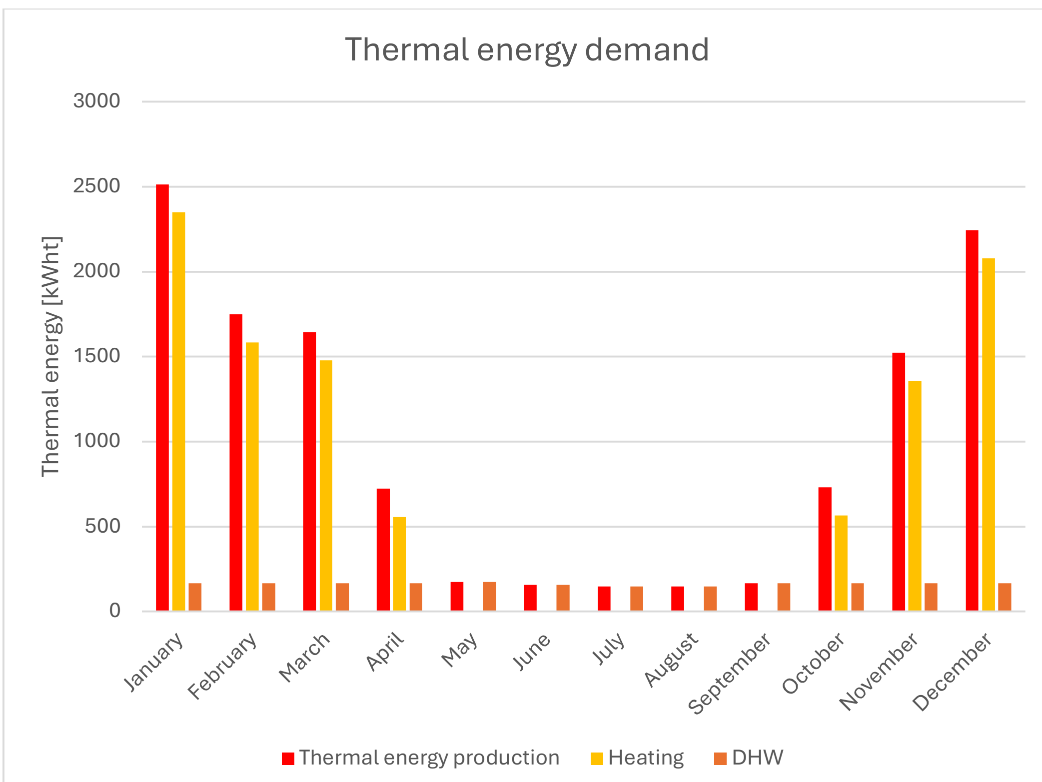


Figure 3.1: Thermal energy demand

- T5

To estimate T5 system's consumptions, the same average thermal demand as described in the previous section was considered.

Since heat pump performances strongly depend on different factors, such as heating supply and source temperatures, a detailed analysis on ambient condition, again assuming installation in Turin, was performed.

The external temperature was predicted month by month by means of UNI 10349 (5). Using these data, the supply temperature of heating system was evaluated by means of the climatic curve. Figure 3.2 reports data related to external temperatures and heating system supply temperatures, while the supply temperature for domestic hot water production was assumed to be constant at 55°C.

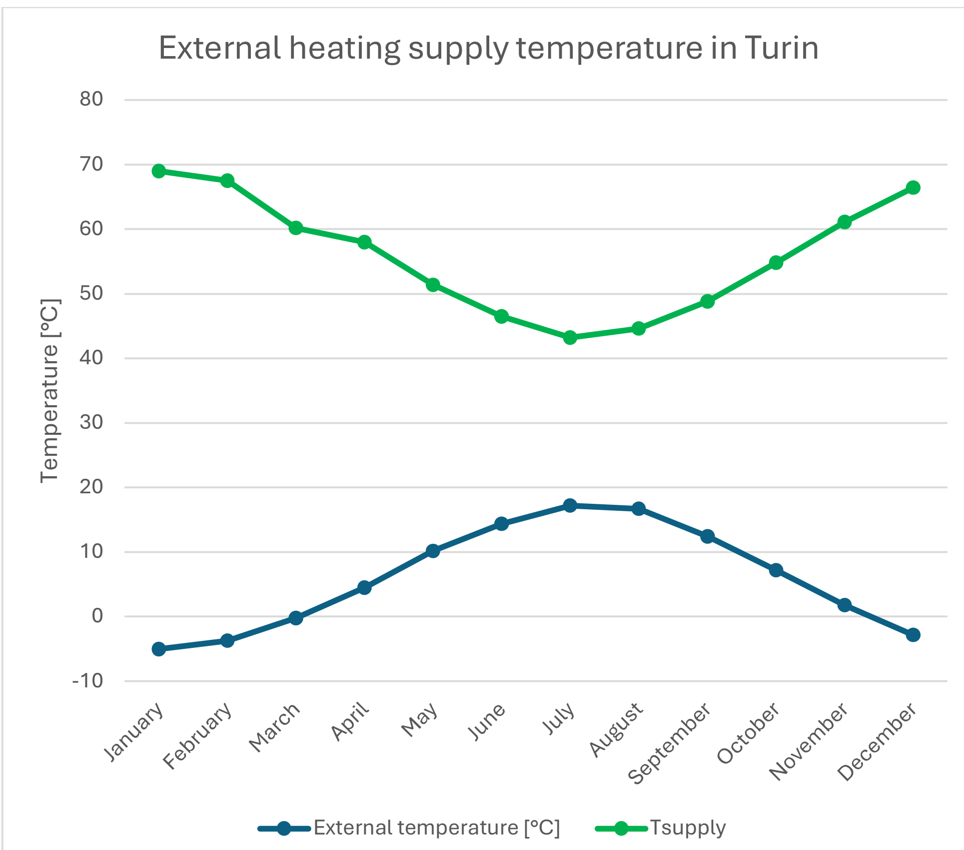


Figure 3.2: Temperature derived by climatic curve

Considering both heating demand and domestic hot water production, it was possible to evaluate the electric consumption of the heat pump. Results are reported in Figure 3.3.

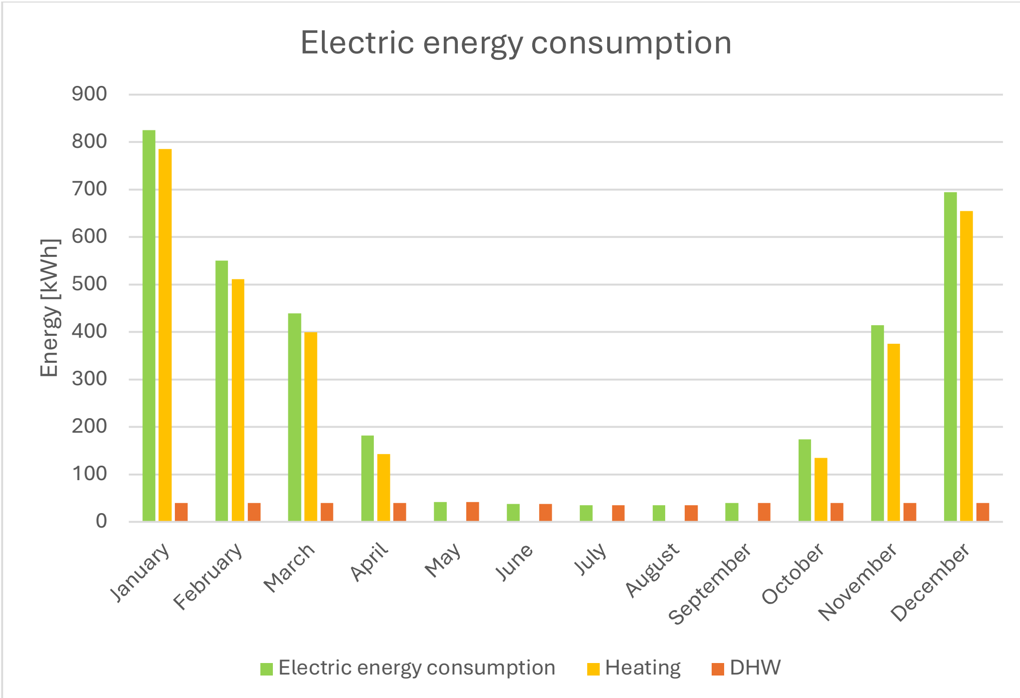


Figure 3.3: Electric energy consumption

At this point it was possible to estimate the annual expenditure for both the traditional boiler and the heat pump installed. It was considered a 10 years period (2024 - 2034), considering energy cost predictions provided by Veos SpA. These projections take in account the introduction of European Union Emissions Trading Scheme (EU ETS) in 2027, which imposes an overtax on energy sources contributing to greenhouse gases emissions.

Finally, Figure 3.4 and Figure 3.5 illustrate the annual expenditure for the two cases (boiler and heat pump) and the other reporting the annual saving from using T5.

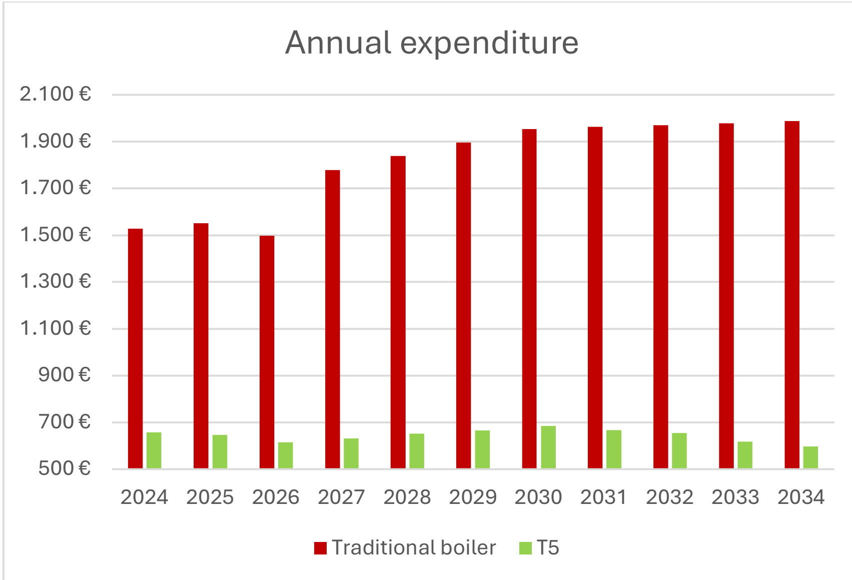


Figure 3.4: Annual expenditure in the two different cases

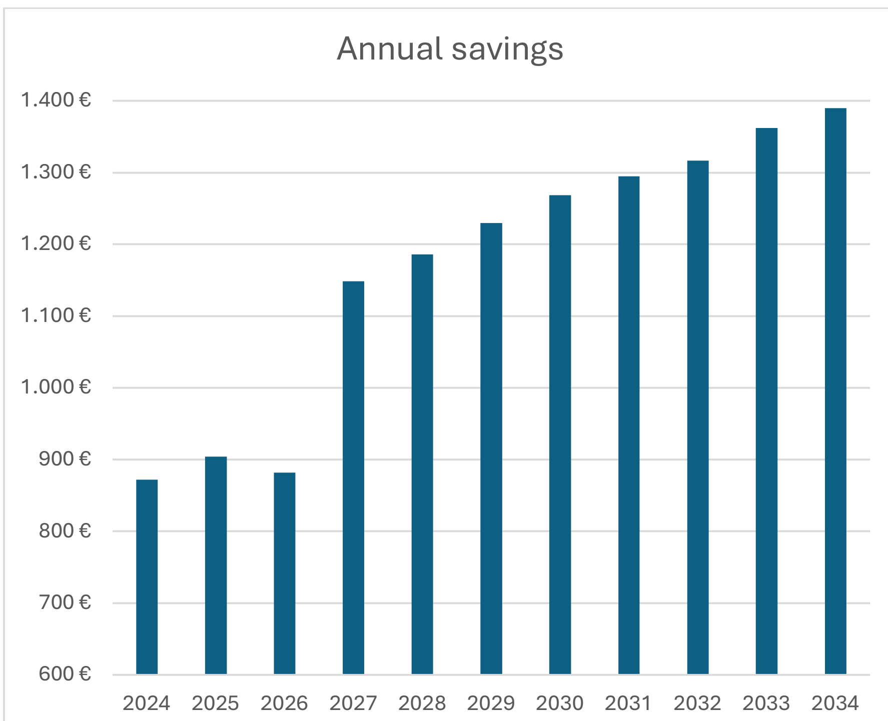


Figure 3.5: Annual savings installing T5

It is evident that deciding to install T5 leads to significant annual savings, always over 800 €, with an increasing trend due to EU ETS introduction, which will drive up gas price.

- **Annual ordinary maintenance expenditure**

To predict the annual expenditure for ordinary maintenance both for traditional boilers than for water-to-water heat pump systems, an analysis performed by Ennovia s.r.l. was considered.

Firstly, general system maintenance for the entire building, common to both traditional and heat pump systems, was considered. Since it is referred to the entire building, the prices that will be reported below need to be divided by the number of apartments (20). General maintenance includes:

- Periodic controls, considering filter cleaning, leakages controls, temperature and pressure measurements, etc., that needs to be performed every year and accounts for about 300 €
- Insulating restoration, once every 8 years and accounts for 200 €
- Pump substitution, every 4 years and accounts for 200 €
- Lubrication, to be performed annually, accounting for 40 €
- Limescale removal, annually performed and accounting for 40 €
- Regulation electric valves substitution, to be performed every 5 years and accounts for 300 €

Figure 3.6 presents the general maintenance costs for building heating systems

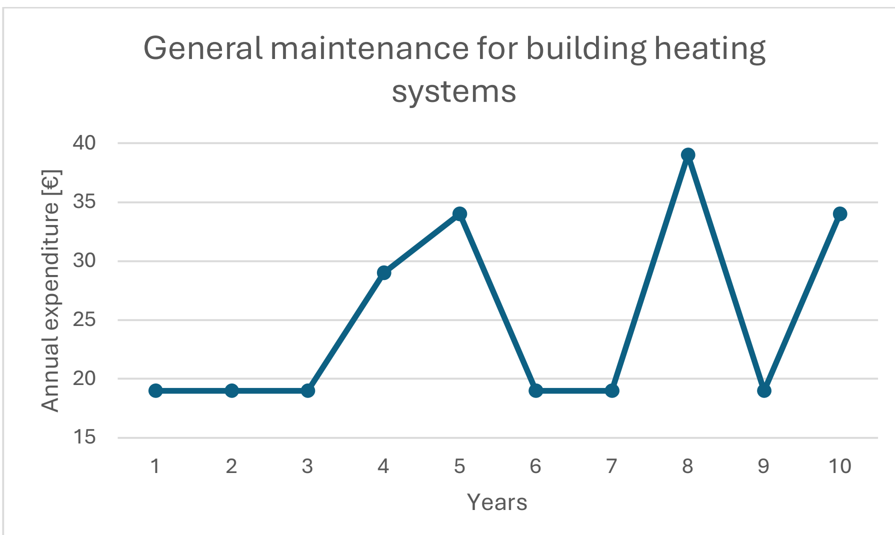


Figure 3.6: General ordinary maintenance for building heating systems

Then specific ordinary maintenance, which is different between traditional boilers and heat pumps, was considered.

Regarding traditional boilers, D.P.R. 74/2013 (18) states that a flue gas analysis must be performed during the starting of the boiler, immediately after installation, repeated after 4 years and then every 2 years. Furthermore, a general inspection, focusing on the operational status and especially efficiency of the boiler, must be performed every 4 years. Maintenance also includes the annual replacement of the polyphosphate dosing unit. Commercial analyses provided the following average costs:

- Flue gases analysis: 60 € (19)
- General control (including efficiency analysis): 100 € (19)
- Polyphosphate dosing unit replacement: 80 € (20)

Consequently, Figure 3.7 was obtained.

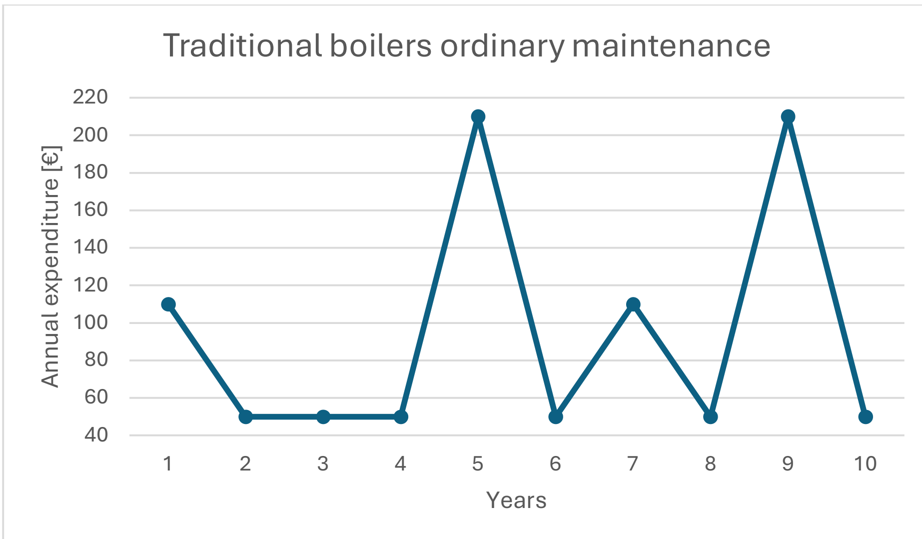


Figure 3.7: Ordinary maintenance for traditional boilers

For heat pumps, more frequent maintenance is required, although the cost must be divided among the number of apartments, since it regards especially well system maintenance. Here the list of operations required and their corresponding costs, considering the ones of Teon s.r.l. maintenance service:

- Water analysis (chemicals and flowrate) every 3 years: 700 €
- Renewal of discharge concession every 4 years: 1000 €
- Annual consumption reporting: 100 €
- Annual cleaning and sanitation: 200 €
- Pumps and metal parts cleaning every 2 years: 150 €

Always considering 20 apartments, Figure 3.8 was obtained.

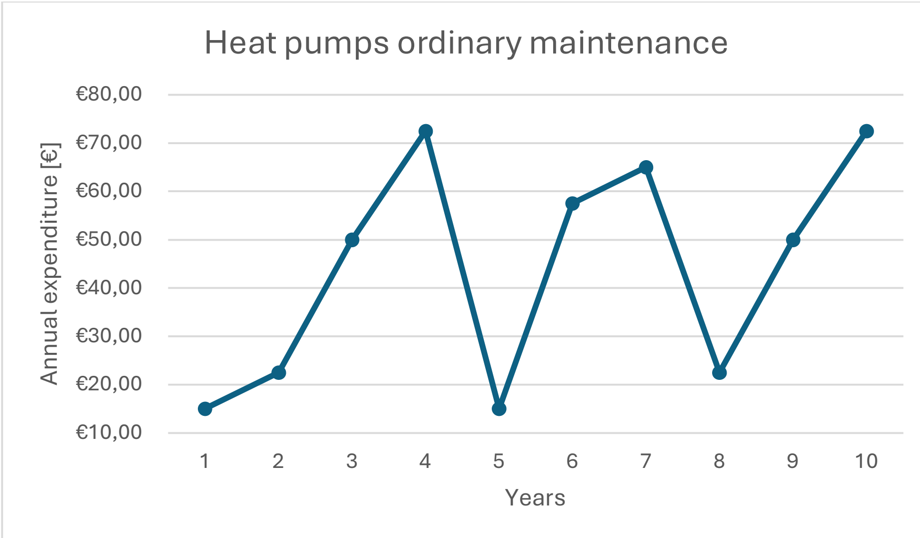


Figure 3.8: Ordinary maintenance for heat pumps

A final consideration for heat pumps involves additional costs using F-gas refrigerant, as stricter maintenance is required.

Finally, to better compare heat pumps and traditional boilers, the following graphs were plotted.

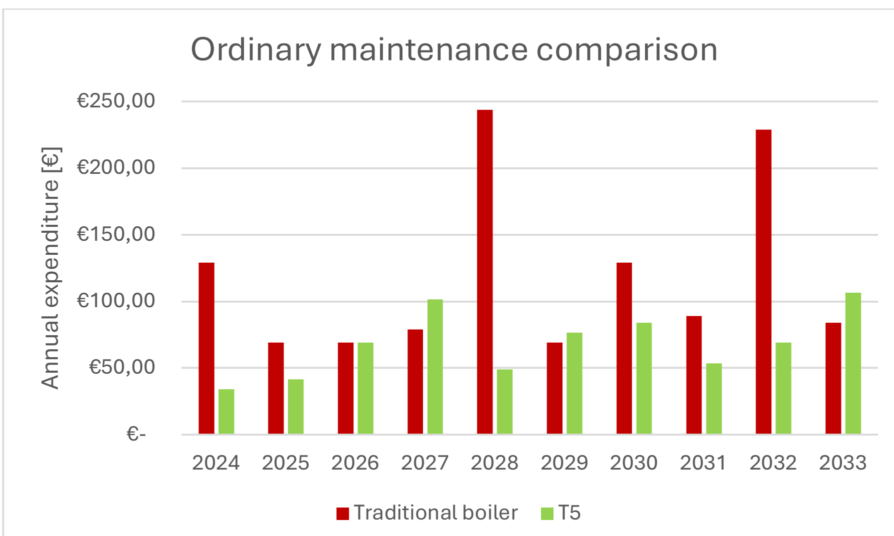


Figure 3.9: Annual expenditure in the two different cases

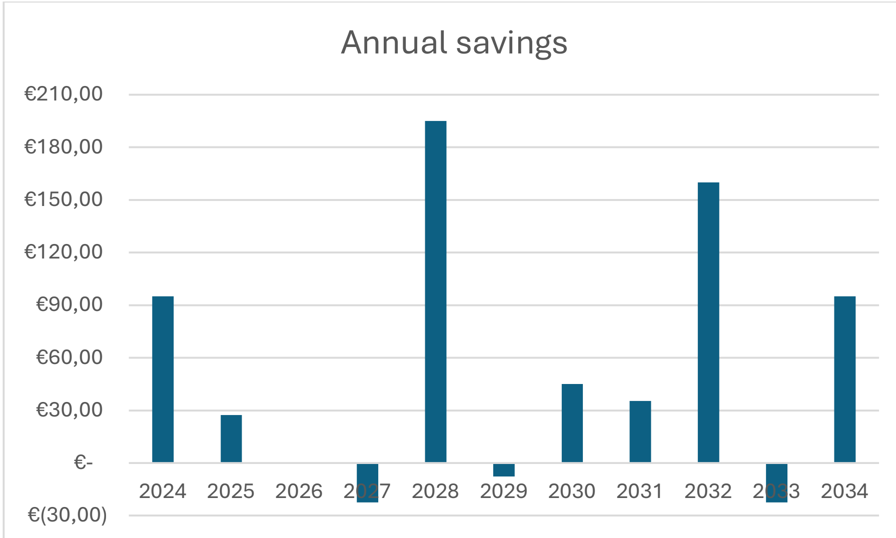


Figure 3.10: Expenditure comparison between traditional boilers and T5

Analysing these graphs, it is evident that not every year it results more convenient to install T5 technology, although considering overall expenditure, T5 still remains the cheaper solution.

- **Total annual expenditure comparison**

In this paragraph a quick summary of the previous analysis is reported, with the aim to simplify the economic considerations before performing the complete cashflow analysis.

Figure 3.11 and Figure 3.12 show a sum between maintenance and consumption expenditures.

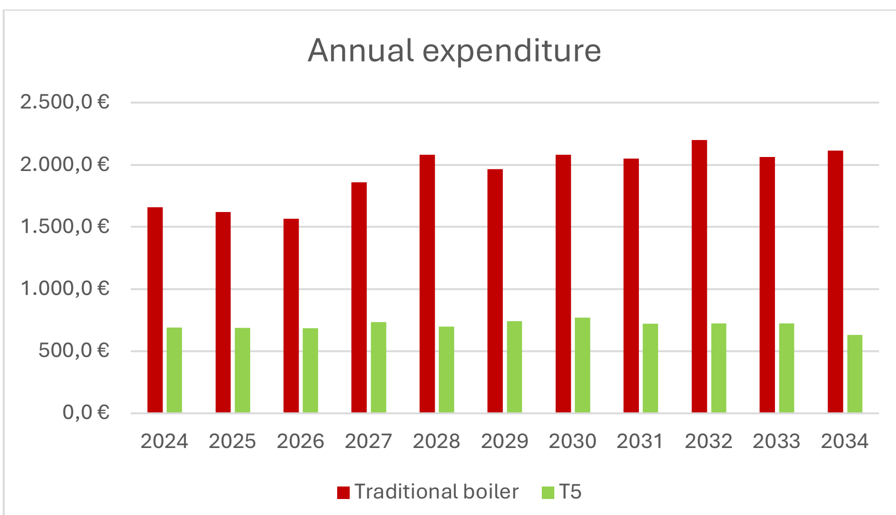


Figure 3.11: Annual global expenditure in the two different cases

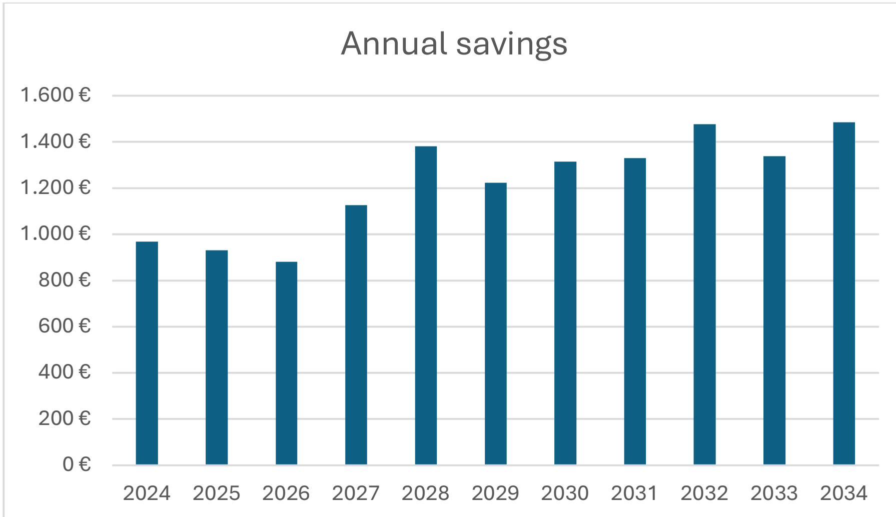


Figure 3.12: Annual global savings with the installation of T5 technology

It can be seen that T5 consistently proves to be the most cost-effective solution, allowing for considerable economic savings each year.

- **Incentives**

The most convenient Italian incentive resulted to be the Conto Termico 2.0 (21), which was applied in the cashflow analysis.

Conto Termico 2.0 promotes energy efficiency and the use of renewable energy sources in buildings. Introduced in 2016 as an enhancement of the original Conto Termico scheme, it aims to encourage both private individuals and public entities to adopt sustainable energy solutions. The program provides financial support for a wide range of interventions, including the installation of high-efficiency heating systems (such as heat pumps and biomass boilers), solar thermal panels, building insulation and the replacement of old windows and lighting systems with energy-efficient alternatives.

One of the key features of Conto Termico 2.0 is its simplicity and speed. Eligible applicants can receive up to 65% of the cost of their projects covered, with payments typically made within two months after the project completion. This financial support is non-refundable and is intended to make energy-saving projects more accessible and economically viable for homeowners, businesses and public administrations.

The program is managed by the Gestore dei Servizi Energetici (GSE), which oversees the application process and disbursement of funds. To apply, applicants must submit detailed documentation of their energy efficiency improvements through the GSE portal. The Conto Termico 2.0 is part of Italy's broader strategy to reduce greenhouse gas emissions, decrease energy consumption and achieve the country's environmental targets.

To calculate the financial incentive under this program, three parameters are required, whose meaning and value in our case are reported below:

- COP, already introduced in the sections above. It is equal to 4,7 for T5 technology
- Valorisation coefficient (Ci), which depends by the type of heat pump technology. In case of water-to-water heat pumps it is equal to 0,16
- Nominal thermal power, already discussed above. It is equal to 6,3 considering T5
- Utilization coefficient (Q_{uf}), that depends on the climatic zone considered

To calculate the predicted incentive (I_a), the following formula is used:

$$I_a = E_i * C_i \ [€]$$

Where Ei corresponds to the incentivized thermal energy produced and it is calculated as:

$$E_i = P_n * Q_{uf} * \left(1 - \frac{1}{COP}\right) \ [kWh_t]$$

Table 3.5 reports the results of this calculation, depending on the climatic zone.

COP	4,7	Utilization coefficients (Q_{uf})					
Ci	0,160						
Pn	6,3	600	850	1100	1400	1700	1800
Climatic zone		A	B	C	D	E	F
Total incentive (I_a)		952 €	1349 €	1746 €	2222 €	2698 €	2857 €

Table 3.5: Conto Termico 2.0 Calculation

Generally, the Conto Termico incentive is paid in two instalments over two years. However, if the incentive is lower than 5000 €, the total amount is paid in a single tranche, during the year of the investment.

It needs to be reminded that these results are only predictions. To discover the real amount for the incentive, GSE site needs to be used.

In our case, Turin was considered the project location, so climatic zone E is the one of interest.

- **Cashflow analysis**

The final section of this economic analysis is related to the cashflow analysis.

To perform this type of analysis, four data points were considered:

- Savings obtained by installing T5 compared to a traditional boiler, evaluated year by year in the previous sections
- T5 price, that was set by Teon s.r.l. corresponding to 4000 €
- Installation cost for the system, discussed above and equal to 3650 € ca.
- Incentives, as calculated in the Conto Termico 2.0 section, resulting to be equal to 2698 €

Figure 3.13 shows the result of the analysis.

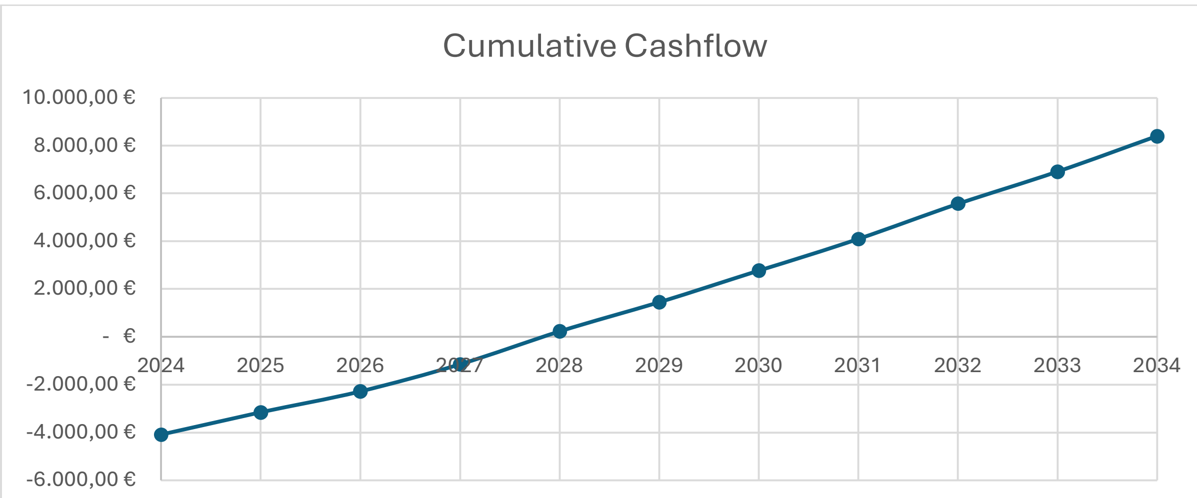


Figure 3.13: Cashflow analysis

The payback time, corresponding to the point in which the costs are equal to 0, was calculated to be equal to 3,8 years.

This result shows that, although the installation of this product may initially seem expensive, especially in comparison with traditional gas boiler systems, it guarantees significant economic savings, with more than 8.000€ saved over 10 years.

3.3.2 T5 without water tank case

Since the procedure is similar to the one discussed before, this section will be shorter, enlightening only the differences with respect to the previous case.

In particular, source and maintenance costs, as well as the incentive discussion, are the same as the previous case, therefore they won't be repeated.

- **Consumption prevision**

The same procedure and considerations were applied as in previous case, although the results differ since the production of domestic hot water was excluded from the calculations. The same ARERA data (16) and procedure to calculate electricity consumption with climatic curve were considered. Figure 3.14, Figure 3.15 and Figure 3.16 are reported without further explanation.

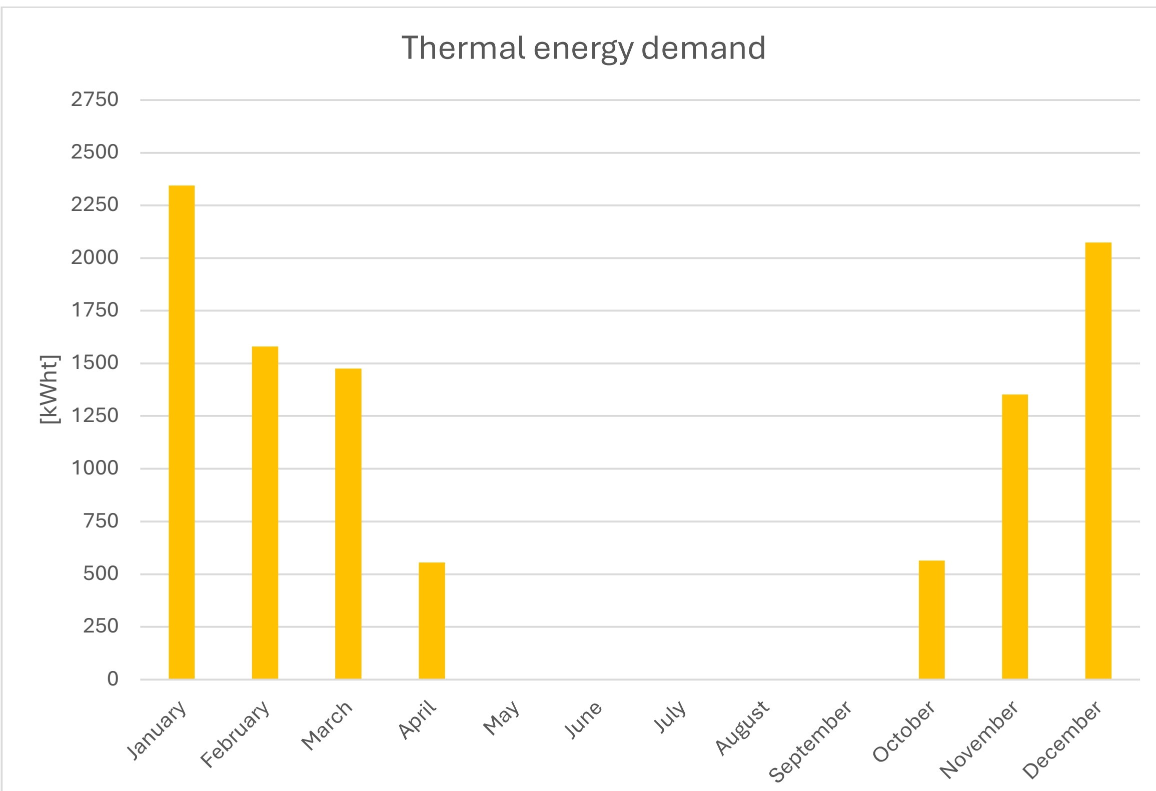


Figure 3.14: Heating demand

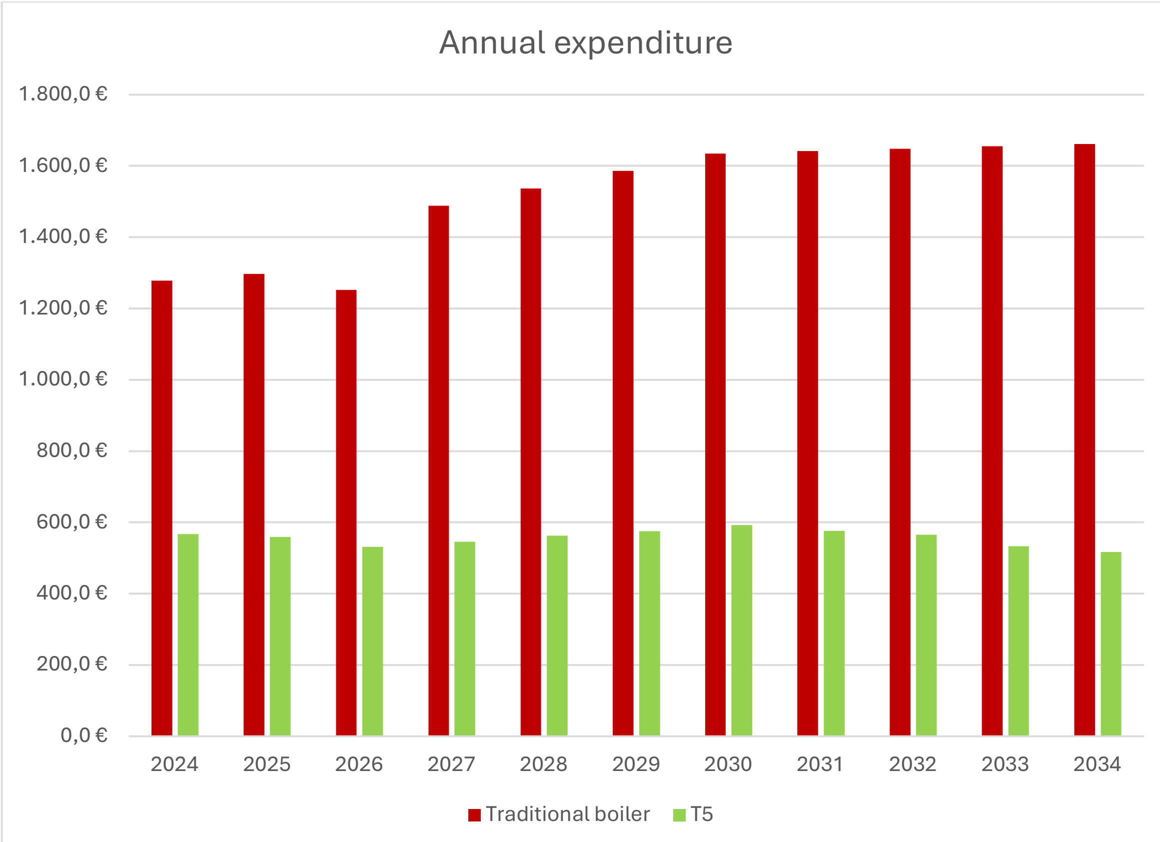


Figure 3.15: Annual expenditure in the two different cases

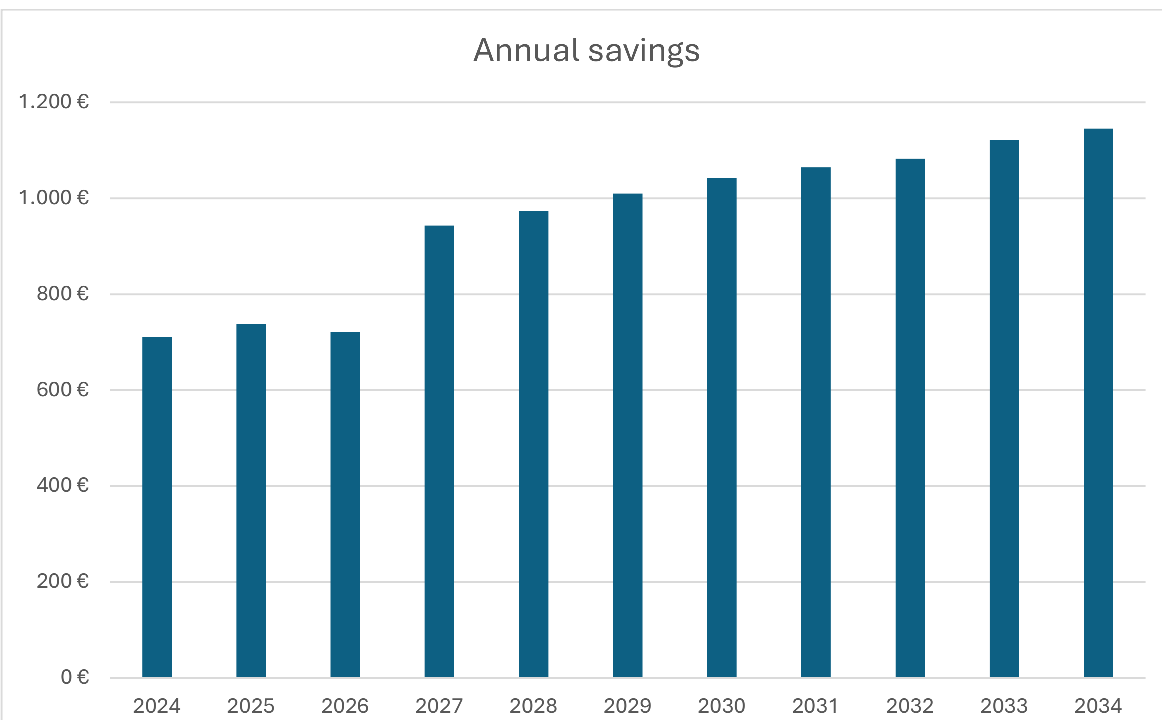


Figure 3.16: Annual savings installing T5

The annual savings from installing T5 remain substantial. Obviously, they are lower compared to the previous case, due to the lower energy consumption.

- **Cashflow analysis**

The cashflow analysis followed the same procedure as described before. The only difference is related to the T5 price imposed by Teon s.r.l., corresponding to 2250 €

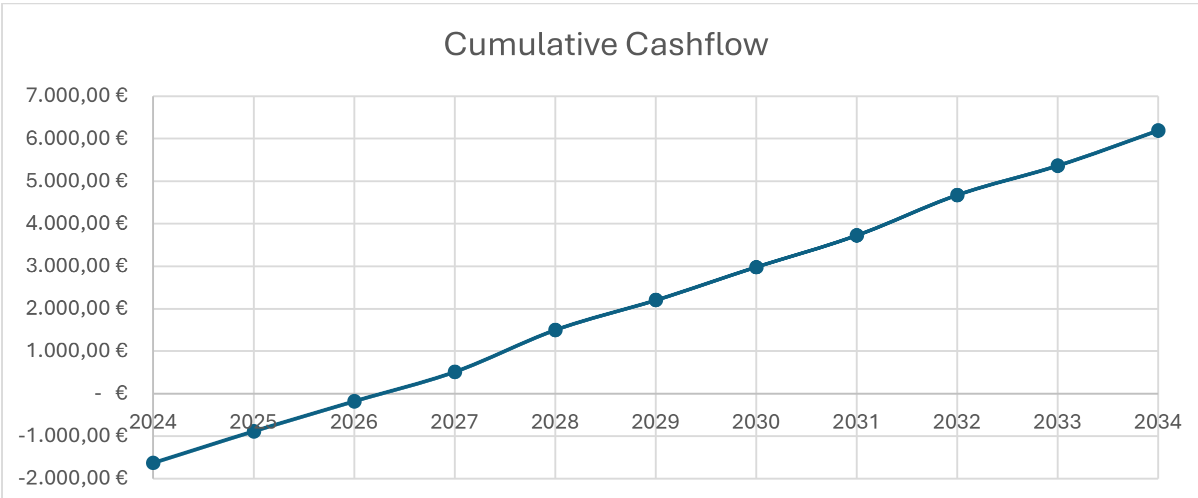


Figure 3.17: Cashflow analysis

In this case, the payback time resulted slightly lower, equal to 2,5 years, due to the lower capital expenditure. Observing the economic savings over the years, this solution also guarantees significant savings, though it is less convenient with respect to the previous case, amounting to about 6.000 € saved after 10 years. This is due to the lower energy consumptions, as domestic hot water production was excluded.

3.4 Emission analysis

This section is dedicated to the comparison between environmental impacts caused by traditional combustion-based boilers and T5 technology. Emissions are divided in two typologies:

- In loco emissions, regarding the ones produced directly by the device at its installation site.
- Global emissions, which account for both the direct emissions of the device and indirect emissions from the energy needed to operate it, regardless of location.

For this analysis, it has been considered as case study a hypothetic apartment with domestic heating regulated by a gas boiler and no cooling system. The same heating demand data (16) considered in the economic analysis will be used.

Firstly, the reference emission factors distinguished into modern thermal plants and electricity from the grid in $[{}^{t}/_{MWh}]$ must be considered. Their values are reported in Table 3.6.

Emission factors $[{}^{t}/_{MWh}]$	Electric energy	Thermal energy
NO_X	0,000310	0,000120
PM_{10}	0,000003	0,000010
CO_2	0,470000	0,240000

Table 3.6: Reference emission factors (22)

By multiplying these factors with the annual consumption data for both the case of gas boiler and T5, Table 3.7 and Table 3.8 have been produced.

The first one is referred to the local emissions, as explained above.

Local emissions $[{}^{kg}/_{year}]$	NO_X	PM_{10}	CO_2
Gas boiler	1,58	0,13	3.156,48
T5	-	-	-

Table 3.7: Local emissions comparison

Since T5 doesn't utilize any combustion process but only requires electric energy, the local emissions result to be null.

A different result would be obtained considering global emissions:

Global emissions $[kg/year]$	NO_X	PM_{10}	CO_2
Gas boiler	1,58	0,13	3.156,48
T5	1,07	0,01	1.627,45

Table 3.8: Global emissions comparison

In this case, T5 shows non-null values, while gas boiler system shows the same results as the previous case, meaning that all boiler emissions are local. However, T5 emission values result to be lower than the ones obtained by the gas boiler.

Furthermore, emission factors related to electric energy are rapidly changing, since the increasing of renewable sources in the electric energy production sector is reducing the amount of pollutant emissions. Another possibility to reduce emissions related to heat pump system is to couple the installation of the device with a renewable electricity production system, such as a photovoltaic plant.

4 T5 water-to-water heat pump

This final chapter of the thesis thoroughly explores the designed technology, offering a comprehensive overview that includes the design process, technical data, and various representations that aid in understanding the technology's development. The chapter is meticulously structured into several sections, each focusing on a critical component of the technology, to provide a thorough understanding of its design, function and application.

The first part focuses on the visual representations of the system's working principles, meticulously distinguishing the different operational modes based on varying customer requirements. These representations illustrate the key components of T5 system and the connections with the domestic system in which the technology operates. By highlighting the different pathways utilized across various heat pump applications, these visuals not only explain how the system functions but also demonstrate the flexibility and adaptability of the technology in meeting diverse needs.

Following the explanation of the working principles, the next section delves into the detailed description of the sizing procedure. This procedure is a crucial aspect of the design process, as it directly influences component selection. A thorough understanding of the sizing procedure is essential for appreciating the rationale behind each component choice. The result of this careful process is a comprehensive list of the components utilized, accompanied by their performance characteristics. This list not only reflects the meticulous planning behind the design but also serves as evidence of the technology's efficiency and effectiveness.

Furthermore, a detailed solid model of the technology has been developed and will be included in this section. This model is instrumental in providing a clear understanding of the technology's dimensions and aesthetic considerations. By visualizing the technology in this manner, the model highlights the primary objectives that guided the design process, as well as the innovative solutions implemented to achieve these goals. The solid model also serves as a tangible representation of the technology, offering a glimpse into its physical presence and how it might be perceived in real-world applications.

Finally, the thesis concludes with an in-depth analysis of the heat pump assembly process. This analysis provides valuable insights into the construction and assembly stages, detailing how the components come together to form the final product. Understanding the assembly process is crucial, as it sheds light on the practical steps to bring the design from concept to reality, ensuring that the technology not only meets, and even exceeds, expectations in terms of performance and reliability.

In conclusion, this final section encapsulates the entire development process of the designed technology, from the initial design stages to the final assembly. Through detailed descriptions, visual representations, and a solid model, it offers a holistic view of the technology, emphasizing its innovation, efficiency, and potential for practical application. The careful attention to detail in each step of the process reflects the commitment to excellence that has driven this project, ultimately resulting in a cutting-edge solution that is both technically sound and aesthetically pleasing. This thesis, therefore, not only contributes to the academic discourse but also lays the foundation for future advancements in the field.

4.1 Working principles

The aim of this section is to provide simplifying schemes to better explain the working principle of T5 system.

First of all, a general scheme representing the heat pump system, its source connection and its integration into the domestic distribution system is required.

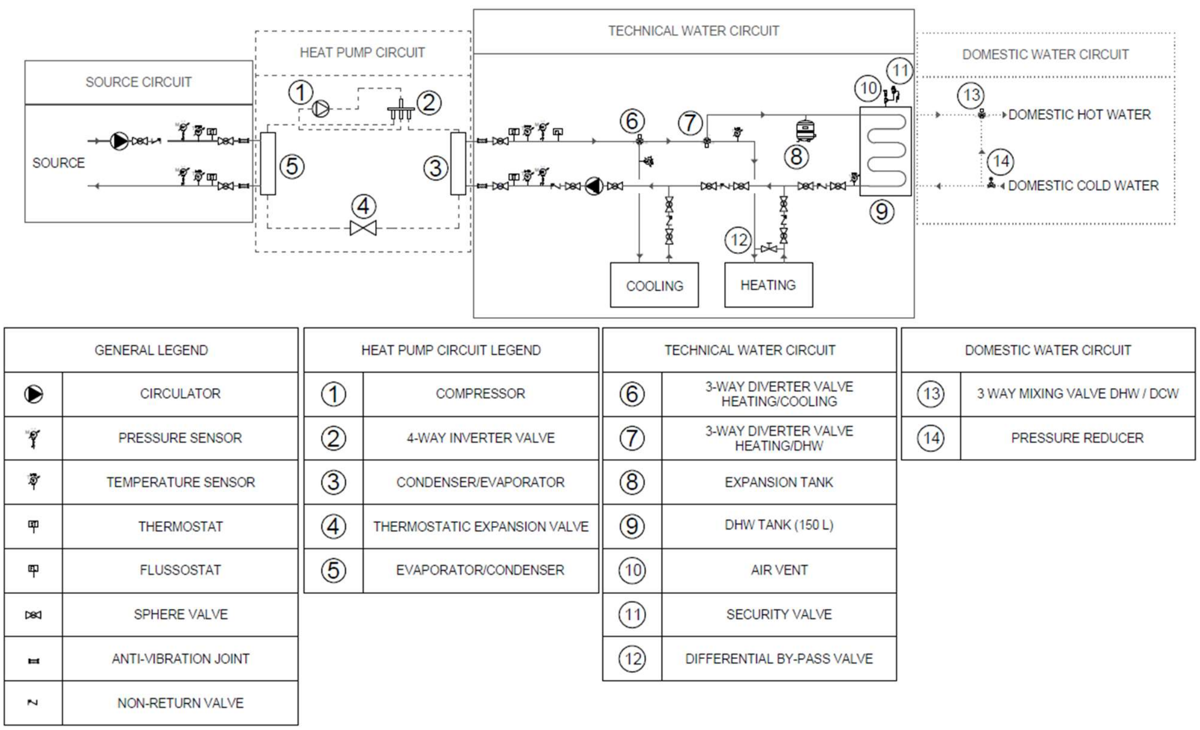


Figure 4.1: T5 system scheme

Figure 4.1 shows that the system is divided into 4 separated circuits, interfacing one to another only by means of heat exchangers, without any fluid mass transferring. Below are reported detail schemes of the different circuits.

- Source circuit

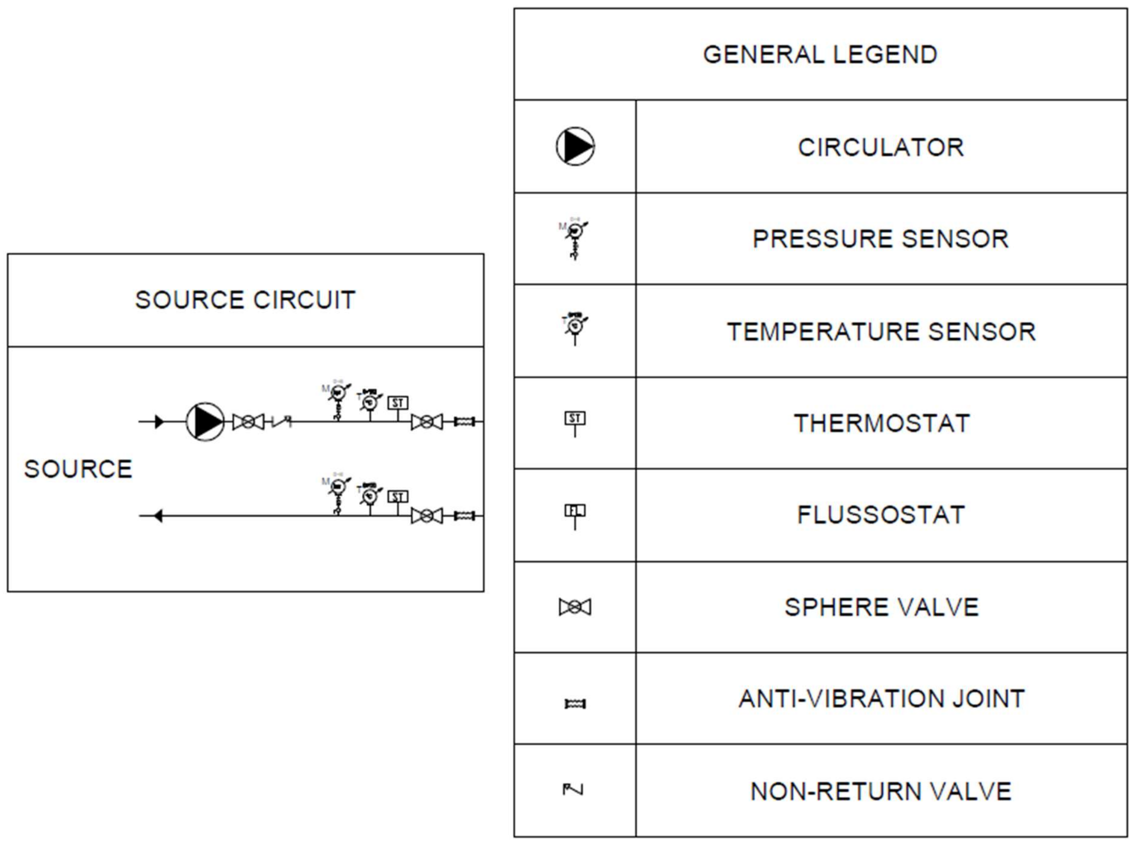
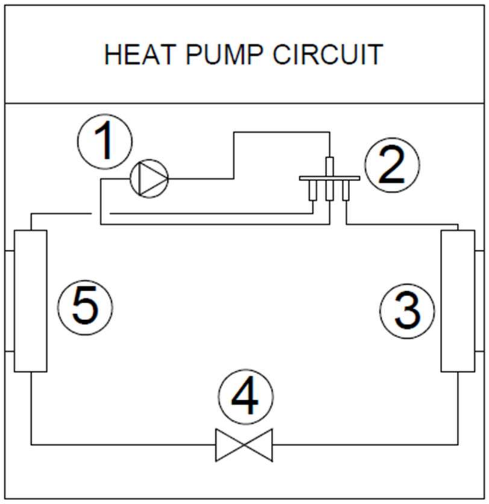


Figure 4.2: Source circuit scheme

By observing the scheme reported in Figure 4.2 it can be noticed that a set of sensors measuring temperature and pressure are present. These result necessary to control the heat pump operations controlled by an electronic board that will be introduced in the next section.

Anti-vibration joints are also necessary in order to limit the vibrations generated both by the compressor present in the heat pump circuit and the circulator present in the source circuit. As will be shown also in the other parts of the circuit, sphere valves and non-return valves must always be coupled with circulators in order to allow them to operate optimally.

- Heat pump circuit

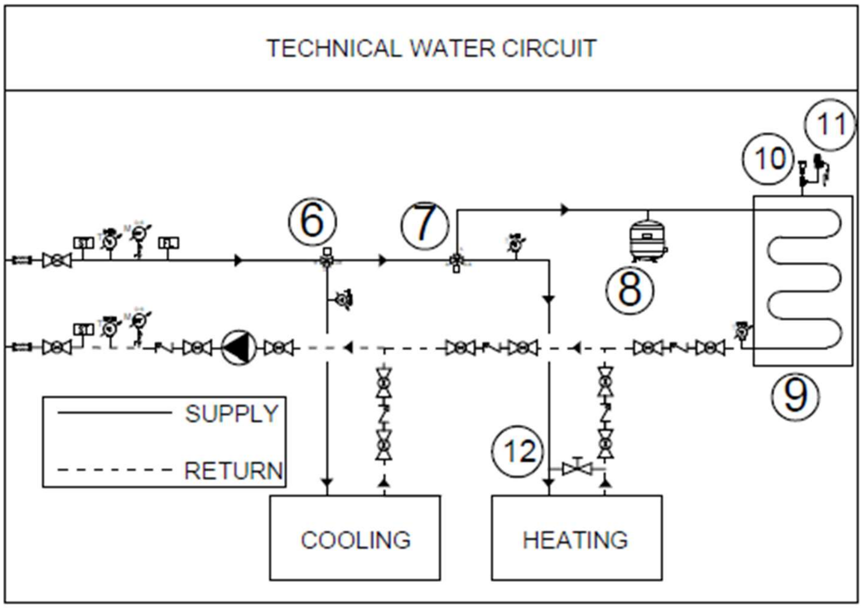


HEAT PUMP CIRCUIT LEGEND	
1	COMPRESSOR
2	4-WAY INVERTER VALVE
3	CONDENSER/EVAPORATOR
4	THERMOSTATIC EXPANSION VALVE
5	EVAPORATOR/CONDENSER

Figure 4.3: Heat pump circuit scheme

No further descriptions of the functions of the components reported in Figure 4.3 will be reported, since they have already been discussed in the section 2.5. However, the 4-way inverter valve has not been introduced. Its function is to invert the heat pump cycle, allowing it to switch from heating mode to cooling mode. This reversal changes the direction of the cycle, resulting also in the inversion of heat flows through the heat exchangers. This process will be discussed later in the cooling mode discussion.

- Technical water circuit



GENERAL LEGEND	
	CIRCULATOR
	PRESSURE SENSOR
	TEMPERATURE SENSOR
	THERMOSTAT
	FLUSSOSTAT
	SPHERE VALVE
	ANTI-VIBRATION JOINT
	NON-RETURN VALVE

TECHNICAL WATER CIRCUIT	
6	3-WAY DIVERTER VALVE HEATING/COOLING
7	3-WAY DIVERTER VALVE HEATING/DHW
8	EXPANSION TANK
9	DHW TANK (150 L)
10	AIR VENT
11	SECURITY VALVE
12	DIFFERENTIAL BY-PASS VALVE

Figure 4.4: Technical water circuit scheme

This circuit is the most complex since it represents the connection between T5 heat pump and the pre-existing distribution system of the building.

To obtain further clarity on the circulating verse of the fluid, in this scheme supply and return has been distinguished by means of continuous and dashed lines (Figure 4.4).

It can be seen that the same sensors introduced in the discussion about source circuit are present and they have the same objectives. The anti-vibration joints in this section assume even a more crucial role since this part of the system will be directly inserted in the apartment and therefore it requires to be as silent as possible.

There are two distinguished 3-way diverter valves that are necessary to change the pathway of the technical water depending on the selected operating mode. The first one (6 in Figure 4.4) divide heating (non-deviated) from cooling and the second one (7 in Figure 4.4) heating (non-deviated) and domestic hot water production.

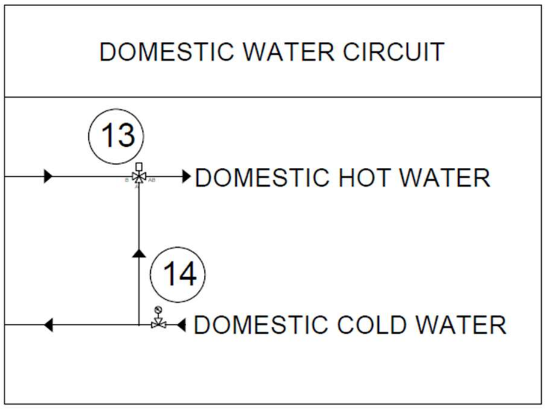
As water tank (9 in Figure 4.4), it was chosen an indirect water heater, equipped with coil in which technical water flows exchanging heat without contaminating domestic water. The technical detail of the storage will be discussed later on, analysing the choice of components.

Air vent and security valve are mandatory to be connected to the water tank, since they are necessary in emergency cases.

Expansion tank is useful to maintain pressure values in an acceptable range, it is necessary in closed circuits.

Last component in the scheme is the by-pass differential valve, it allows the supply technical water to directly return to the condenser of the heat pump, creating a recirculation. This phenomenon could be necessary to reduce pressure losses, especially in the case in which the majority of heating terminals are in OFF state, but heating is still requested by the only ones turned ON.

- Domestic water circuit



DOMESTIC WATER CIRCUIT	
13	3 WAY MIXING VALVE DHW / DCW
14	PRESSURE REDUCER

Figure 4.5: Domestic water circuit scheme

Final circuit regards domestic water (Figure 4.5), extracted cold from the aqueduct and heated in the boiler. In this section only two components are present:

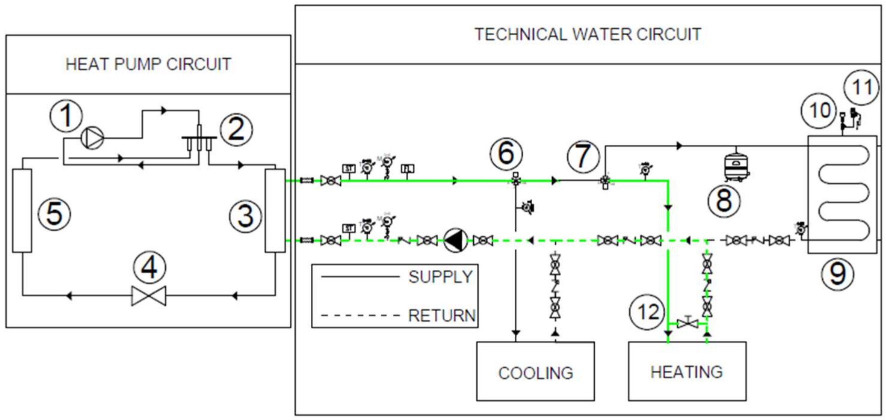
- 3-way mixing valve, that has a security function: mixing hot water from the boiler with cold one from the aqueduct, it ensures that a limit temperature, defined in Italy by UNI 9182:2014 (23), between 48°C and 50°C cannot be exceeded
- Pressure reducer, it is necessary to avoid damages in the circuit due to high pressures since exiting pressure form aqueducts depends on geographical location.

To obtain further clarity, other distinguished schemes showing the different pathways related to the different possible operational modes of the system are reported below. To simplify the representation, only heat pump and technical water circuits will be reported, since the only differences are visible in these two subsystems.

Regarding technical water circuit, the fluid follows different paths, highlighted by means of green lines.

While the pathway in heat pump circuit is always the same, although in cooling mode the refrigerant flow is inverted and also the function of heat exchangers is inverted in comparison with the other operational modes: the exchanger connected to the source becomes the condenser and the other one becomes the evaporator.

- Heating



GENERAL LEGEND	
	CIRCULATOR
	PRESSURE SENSOR
	TEMPERATURE SENSOR
	THERMOSTAT
	FLUSSOSTAT
	SPHERE VALVE
	ANTI-VIBRATION JOINT
	NON-RETURN VALVE

HEAT PUMP CIRCUIT LEGEND	
1	COMPRESSOR
2	4-WAY INVERTER VALVE
3	CONDENSER
4	THERMOSTATIC EXPANSION VALVE
5	EVAPORATOR

TECHNICAL WATER CIRCUIT	
6	3-WAY DIVERTER VALVE HEATING/COOLING
7	3-WAY DIVERTER VALVE HEATING/DHW
8	EXPANSION TANK
9	DHW TANK (150 L)
10	AIR VENT
11	SECURITY VALVE
12	DIFFERENTIAL BY-PASS VALVE

Figure 4.6: Heating mode scheme

- Cooling

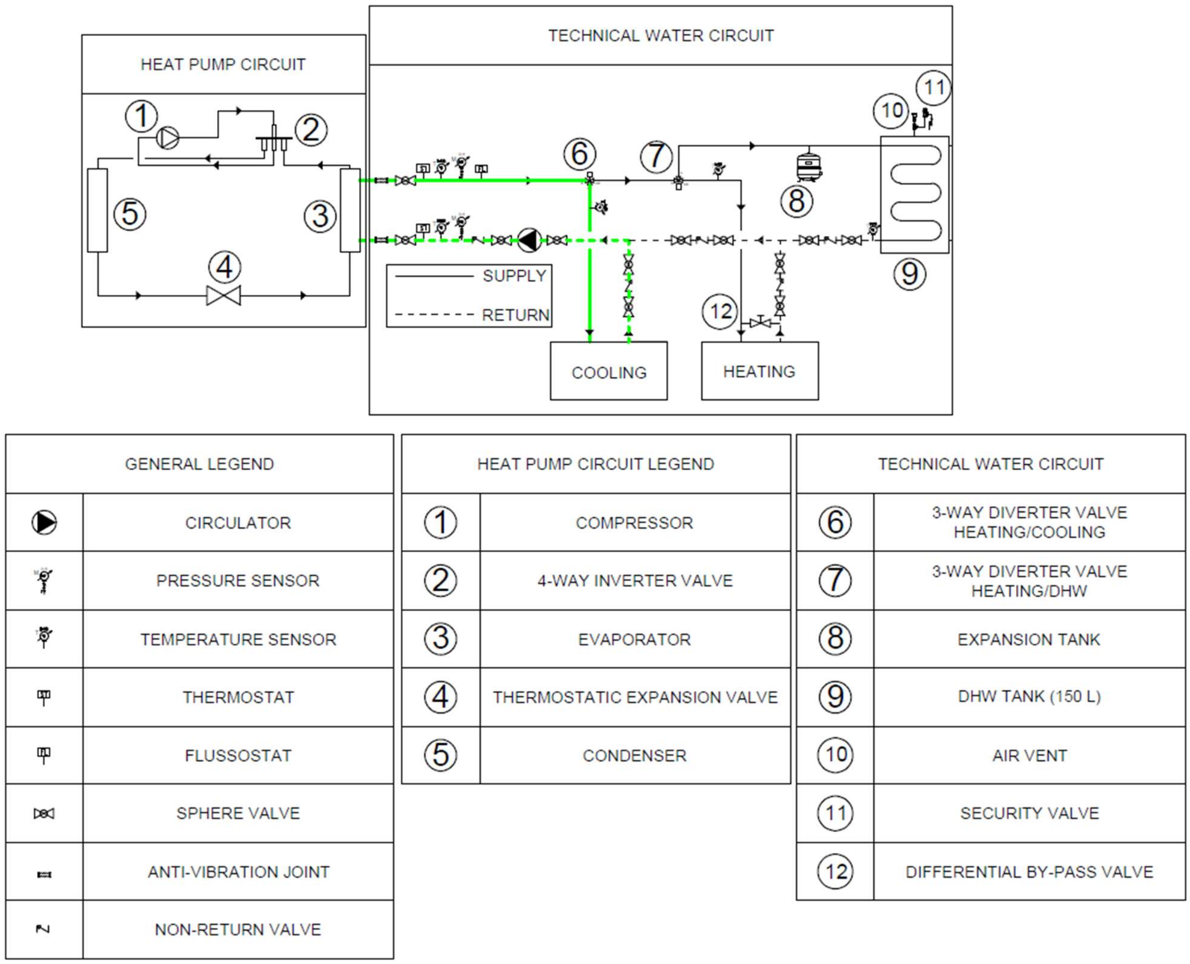
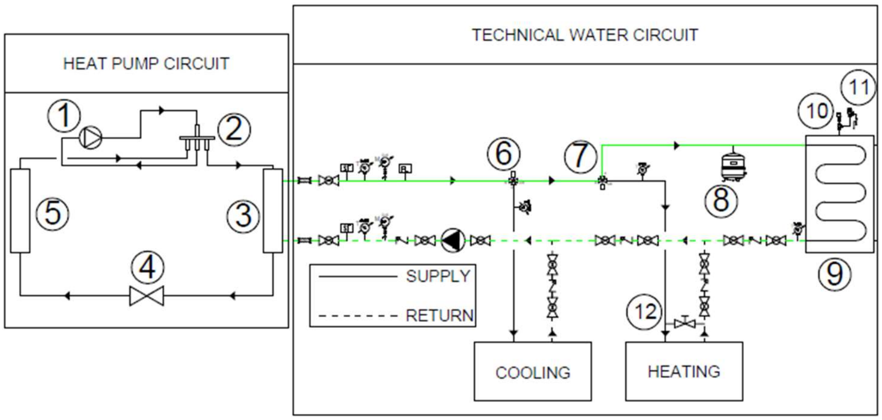


Figure 4.7: Cooling mode scheme

As already reported, heat pump circuit is inverted in this operational mode by means of 4-way inverter valve, it can be noticed by looking at the arrows in the scheme.

This inversion is due to the fact that heat exchanger (3), that in the other operational modes releases heat to the technical water circulating in the domestic plant, is now used to absorb heat from the internal ambient of the building, resulting in functioning as an evaporator. In this case heat is then ejected from the heat pump on the source side, therefore the heat exchanger (5) is used as a condenser.

- Domestic hot water



GENERAL LEGEND	
	CIRCULATOR
	PRESSURE SENSOR
	TEMPERATURE SENSOR
	THERMOSTAT
	FLUSSOSTAT
	SPHERE VALVE
	ANTI-VIBRATION JOINT
	NON-RETURN VALVE

HEAT PUMP CIRCUIT LEGEND	
1	COMPRESSOR
2	4-WAY INVERTER VALVE
3	CONDENSER
4	THERMOSTATIC EXPANSION VALVE
5	EVAPORATOR

TECHNICAL WATER CIRCUIT	
6	3-WAY DIVERTER VALVE HEATING/COOLING
7	3-WAY DIVERTER VALVE HEATING/DHW
8	EXPANSION TANK
9	DHW TANK (150 L)
10	AIR VENT
11	SECURITY VALVE
12	DIFFERENTIAL BY-PASS VALVE

Figure 4.8: Domestic Hot Water mode scheme

It is always reminded that domestic hot water production is available only in the case of hot water tank coupled with T5 heat pump.

4.2 Designing process and component choice

The objective of this section is to describe the chosen components that will form T5 heat pump explaining the decisional procedure. It will be divided in several paragraphs each dedicated to different components or phases of the designing process.

4.2.1 Refrigerant

First decision to be taken is the choice of the refrigerant utilized. As already mentioned previously, TEON S.r.l. utilizes two different natural refrigerants: R290 and R600a.

The fluid choice is strictly related to the compressor used, that will be discussed in the next section. However, in this section the different behaviour of compressors depending on the refrigerant will be discussed.

Leading parameters for this decision are, as always, the cost of the compressor to be utilized, depending both on the economic price of the component and on its performances, and the working pressures of the refrigerants at operating temperature, since high pressures could damage the pipe circuit of the heat pump. Further attention must be paid to the dimensions of the component, since it should be as compact as possible.

Regarding the pressures, R600a resulted to be the best choice, due to the lower value obtained, as shown in Table 4.1.

Refrigerant	**R600a**	**R290**
Temperature [°C]	60	
Pressure [bar]	8,96	21,17

Table 4.1: Operating pressure comparison

The outcomes of Table 4.1 were obtained using Ref Tools software developed by Danfoss (24).

To analyse compressor performances depending on refrigerants, different compressors with same displacement or capacity were examined to obtain practical data on different refrigerants. Embraco compressors were selected, and three different models were considered: NEK6187Y, NEK2160U and EMX6181U. All data were taken from Embraco website (25).

The first analysis focused on two compressors with same displacement (equal to 16.8 cm^3), with the resulting data are shown in Table 4.2.

Refrigerant	**R600a**	**R290**
Producer	Embraco	
Model	NEK6187Y	NEK2160U
T_{cond} [°C]	55	
T_{ev} [°C]	-10	
Displacement [cc]	16,8	
Capacity [kW]	0,701	1,954
COP	1,61	2,55
Weight [kg]	10,4	11,9
Height [mm]	200	200
Length [mm]	241	243
Width [mm]	152	152

Table 4.2: Constant displacement compressor comparison

The results showed that R290 offers better performances in terms of capacity at same displacement, while R600a achieves a better COP.

Next, compressors with comparable capacities (around 1,4 kW) were selected.

Refrigerant	**R600a**	**R290**
Producer	Embraco	
Model	NEK6187Y	EMX6181U
Tcond [°C]	55	
Tev [°C]	10	
Displacement [cc]	16,8	6,92
Rated capacity [kW]	1,4	
COP	2,49	3,06
Weight [kg]	10,4	8
Height [mm]	200	171
Length [mm]	241	235
Width [mm]	152	154,5

Table 4.3: Constant rated capacity compressor comparison

R290, as expected, reaches this value of capacity with a smaller displacement and, in this case, it provides also a better COP.

Regarding the weight of the models, this time R290 offers a lower value and also considering the dimensions, it resulted to be more compact.

From the data reported above, R290 resulted to be the best solution. Especially considering constant rated capacity comparison, that is the most interesting analysis in this chapter, it results that R290 can lead to better performances with more compact dimensions and lighter solutions. Choosing R600a would lead to the necessity of oversizing of the compressor to reach the same nominal capacity.

Furthermore, R290 compressors are way more present in the market resulting in wider choice possibility and lower prices.

The leading choice for designing process have been taken, therefore now is possible to proceed selecting the different components.

4.2.2 Compressor

The first component to be chosen is the compressor, which defines the nominal power of the device.

In order to gain the final decision, long market research was conducted, looking for a very wide range of compressors belonging to the different types described in 2.5.1. no further technical description of the differences between these technologies will be reported.

Finally, rotary compressor EDTM310D85EMT by GMCC (26) was chosen. Technical data are listed in Table 4.4.

Type	Hermetic rotary
Power source	DC inverter
Revolution range	12 - 120 rps
Sound power level	69 dB
Displacement	30,6 cm^3
Weight	12,2 kg
Height	325 mm
Diameter	116 mm

Table 4.4: EDTM310D85EMT technical data

Specific working conditions (Table 4.5) were considered based on the average underground water in Turin and temperature values suitable for traditional domestic heating systems, with the revolution rate set to 50 rps:

Source supply temperature	15 °C
Source return temperature	10 °C
Condensing temperature	50°C
Evaporating temperature	8 °C
Revolution rate	50 rps

Table 4.5: Rated working conditions

Finally, performance data of the compressor provided by GMCC were elaborated to evaluate the rated values of power and COP of the heat pump (Table 4.6).

Thermal power	6,347 kW
Electrical power	1,339 kW
Cooling power	5,008 kW
COP	4,740

Table 4.6: EDTM310D85EMT rated performance data

The same calculations were performed also considering different working conditions (Table 4.7), in order to understand the behaviour of the technology in different operational cases.

To be as clear as possible, it is necessary to highlight that source temperatures are strictly related to evaporating temperature, in particular the following values were utilized:

Source supply temperature	Source return temperature	Evaporating temperature
7	4	2
10	7	5
15	10	8
20	15	13

Table 4.7: Evaporating temperature variation with respect to source temperatures variation

Finally, Figure 4.9, Figure 4.10 and Figure 4.11 report the performance curves obtained for the considered compressor as a function of temperature.

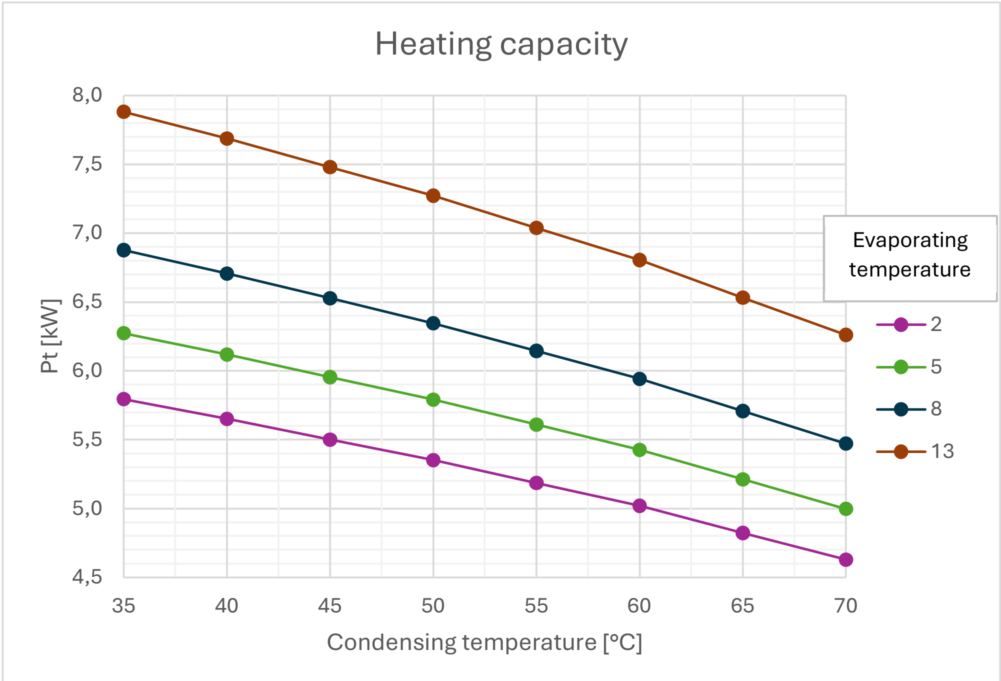


Figure 4.9: Heating capacity variation

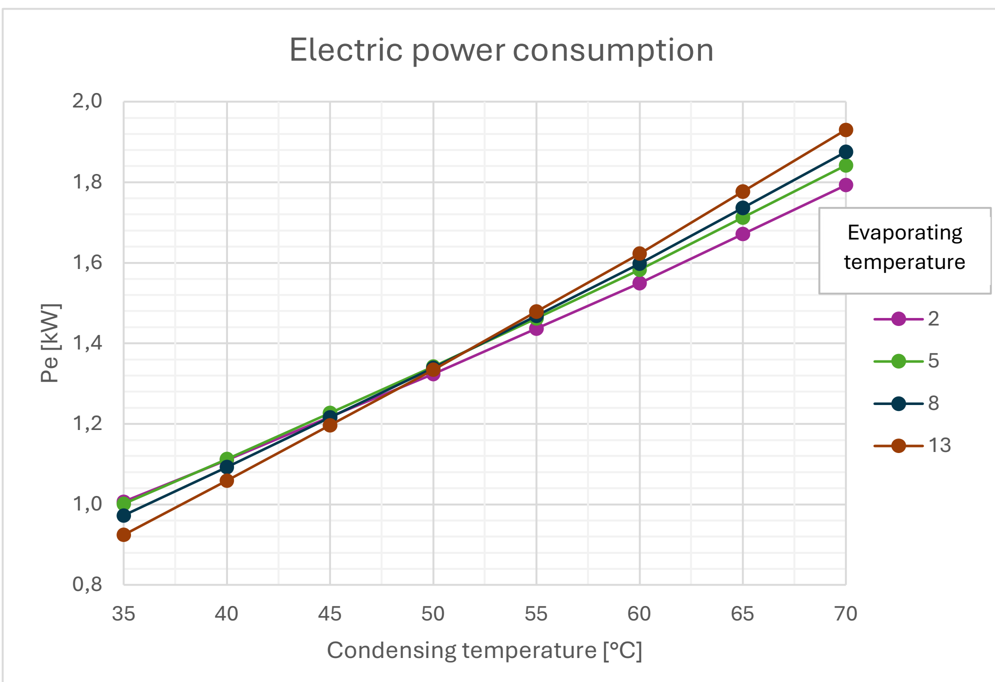


Figure 4.10: Power consumption variation

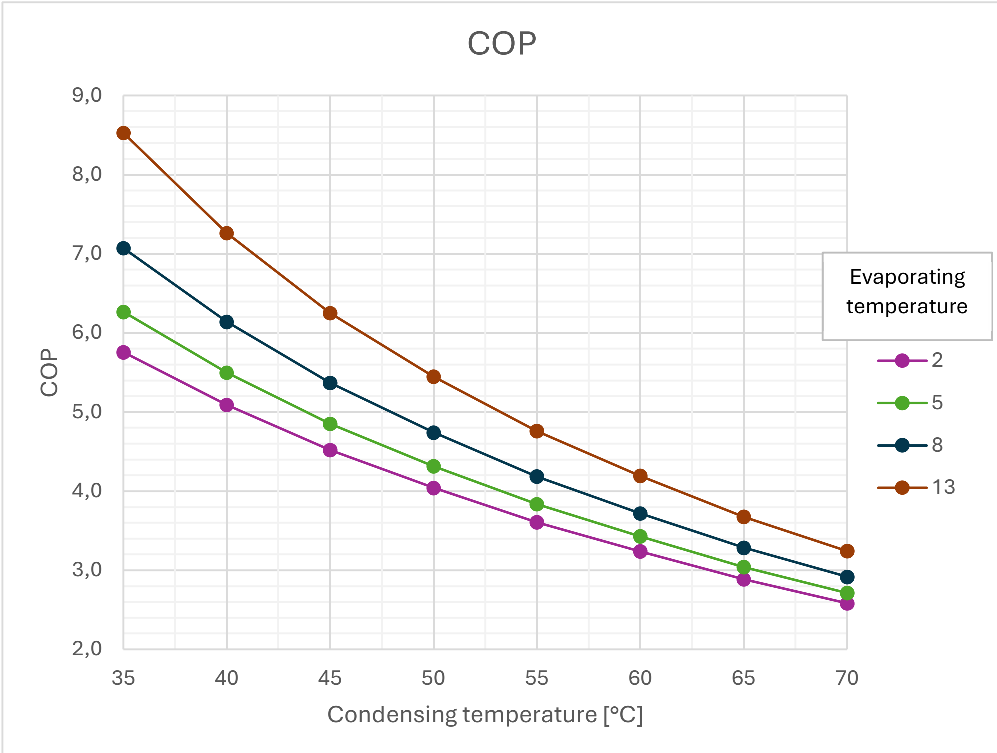


Figure 4.11: COP variation

It can be noticed that Heating capacity and COP have similar behaviour: their values increase with the evaporating temperature and decrease when condensing temperature increases.

Regarding electric power consumption, it can be noticed that the variation with respect to the difference evaporating temperatures is almost negligible, while the consumption is strictly related to condensing temperatures, with direct proportionality.

4.2.3 Heat exchangers

Once the compressor was chosen, the heat exchangers needed to be sized. The company's policy was to use the same heat exchangers installed in the other Teon machines, so plate heat exchangers by SWEP were considered.

To evaluate the correct size for our purpose, SWEP software (27) was utilized. With specific input data, including refrigerant underutilization, rated power values (cooling capacity for the evaporator and heating capacity for condenser), condensing and evaporating temperatures (maintaining evaporating temperature constant at 8 °C as this case study assumed a constant source side temperature), subcooling title (set to 0,3) and superheating temperature difference (set to 5 K), the software identified the appropriate heat exchanger in SWEP catalogue, evaluated the correct number of plates required and provide the pressure drop across the component.

This procedure must be performed at least considering three different working conditions, in order to ensure the proper operation of the component in a wide range of working scenarios:

1. First simulation must be performed considering worst working conditions from the component point of view, meaning highest value of heat to be exchanged therefore minimum condensing temperature (equal to 35°C)
2. The heat exchanger with the specific number of plates selected by first simulation is then utilized setting the lowest vale of heat to be transferred, imposing maximum condensing temperature (70°C)
3. Finally, the same component behaviour is tested at rated operating conditions (reported in Table 4.5)

Following this procedure twice, one for each heat exchanger, a particular model, named FI22ASM (28), was individuated. For the evaporator, 34 plates were determined to be sufficient, while 30 plates were adequate for the condenser.

The FI22ASM is a highly efficient counter-flow heat exchanger, specifically designed for reversible heat pumps. Its main features are related to the low pressure drop on both sides and the minimized refrigerant charge requested. The device is a Brazed Plate Heat Exchanger (BPHE), constructed as a plate package of corrugated channel plates with a filler material between each plate forming a brazed joint at every contact point between plates. This solution allows media at different temperatures to come into proximity, separated only by channels that enable an efficient heat transfer. Final features of this technology are the more compact dimensions in comparison with traditional heat exchangers, since FI22ASM doesn’t necessitate the presence of gaskets and frame parts.

Table 4.8 reports dimension data of the heat exchangers.

Height	362 mm
Length	92 mm
Width (evaporator)	51 mm
Width (condenser)	46 mm

Table 4.8: Heat exchangers dimensions

4.2.4 Thermostatic expansion valve

Final main component to realize the heat pump cycle is the thermostatic expansion valve. Since this technology has already been introduced in the section 2.5.2, no further presentation will be reported, limiting this section only to the description of the selection procedure.

As anticipated for the heat exchangers, the company policy was to select a component similar to the ones installed in the other products by Teon, so Danfoss was considered as the supplier.

To correctly size the expansion valve, Danfoss software named Coolselector®2 (29) was utilized. This tool simplifies component selection by allowing input of specific data into the software, obtaining the optimal technological solution from the Danfoss catalogue. The input data and procedure are similar to those utilized for selecting the correct heat exchangers: three simulations were performed under worst, best and rated conditions.

Finally, TD1 v2-5 was selected, technical data are reported in Table 4.9.

Rated capacity	7,078 kW
Minimum capacity	1,769 kW
Pressure drop	6,166 bar

Table 4.9: TD1 v2-5 technical data

4.2.5 Domestic hot water tank

As explained in the previous sections, two different configurations for T5 were developed: with or without DHW tank, according to customer requirements.

In order to size this component some considerations were necessary. Statistical consumption data regarding shower consumptions were considered: it resulted an average water flow rate of 15 l/min (30).

A reference case in which a shower is utilized for 10 consecutive minutes, considering that while hot water is requested by the costumer, it is also constantly produced by the heat pump. Finally, a tank able to contain approximately 150 litres resulted sufficient for the purpose. This volume allows both an acceptable space occupation in the domestic environment and a limited time to restore the thermal request for domestic hot water.

Market research was performed in order to individuate the best option for T5 technology in terms of performances and dimensions. Furthermore a customization of the product in terms of external casing and hydraulic connections was requested.

Finally, WW150 by Boilernova (31) was chosen, since all the requirements were satisfied. Technical data are reported in Table 4.10.

Storage volume	160 l
Height	990 mm
Diameter	600 mm
Insulation thickness	50 mm
Weight empty	68 kg
Pipe coil surface	1 m^2
Pressure drop	12 mbar

Table 4.10: WW150 technical data

Figure 4.12 shows the dimensions of the customized WW150.

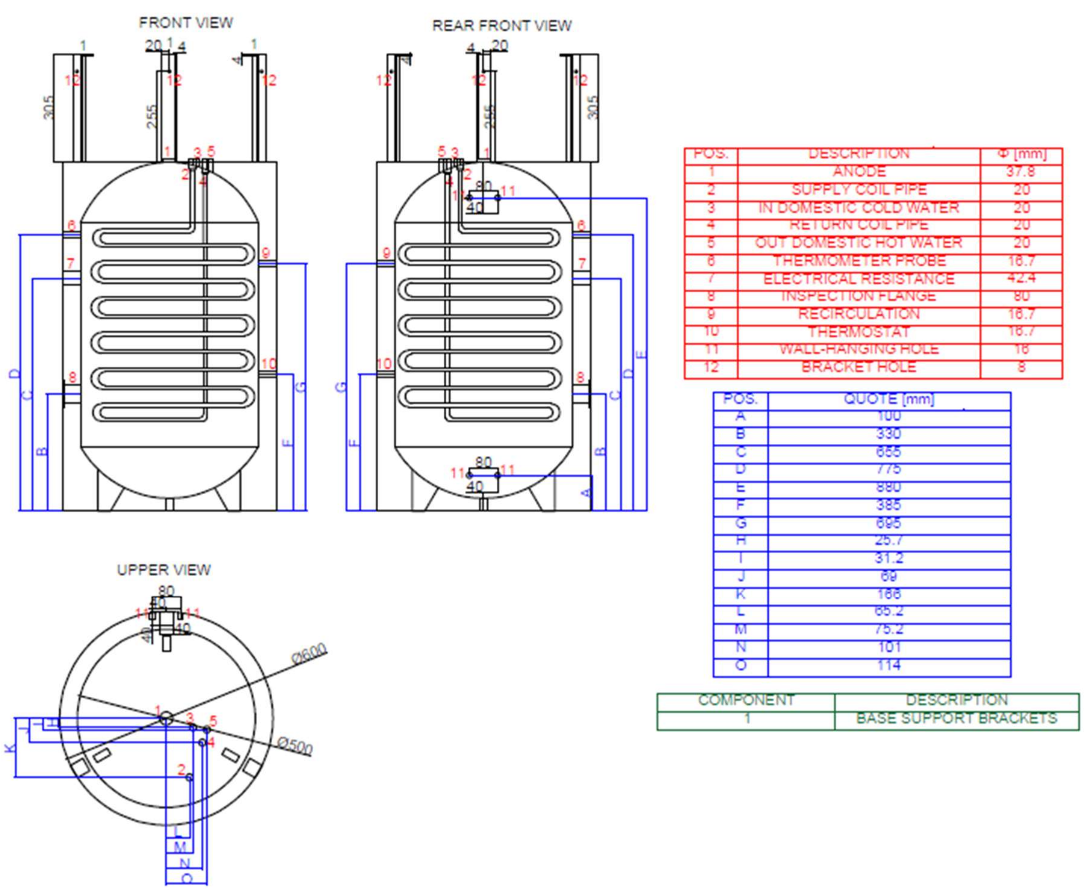


Figure 4.12: Customized WW150

4.2.6 Circulating pump

In the full optional version of T5, three circulating pumps are required: one on the source side and two on the domestic side, where a pump is necessary for both the DHW subsystem and the heating or cooling subsystem. Although only one of these pumps is included in the T5 casing, as the others must be sized considering the specific conditions of the system in which the heat pump will be installed.

Therefore, the only circulating pump sized and included into the 3D models is the one positioned on the path returning from the storage coil to the condenser of the heat pump. The aim of this section is to describe the sizing procedure of the component.

The choice of the correct circulator is strictly related to the sizing of pipe circuit, that will be discussed for each circuit in the dedicated section. The link between these sizing procedures is related to the pressure losses across the systems, that were evaluated starting from the input data reported in Table 4.11.

Pipe material	Copper
Thermal capacity	5,943 kW
Pipe diameter	1”
Water temperature in the pipe	50 °C
Temperature difference across the condenser	10 K
Water density	1000 kg/m^3

Table 4.11: Input data for pressure losses calculation

Consequently, it is possible to evaluate the flow rate and the velocity of water flowing in the pipes:

$$Q = \frac{P_t}{c_p * \Delta T} = 511{,}1 \left[{}^{l}/_{h}\right]$$

$$v = \frac{Q}{\pi * \frac{D^2}{4}} = 0{,}23 \; [{}^{m}/_{s}]$$

Then, the procedure described by the following calculations has been performed (32).

- Viscosity: $\nu = (1{,}67952 - 0{,}042328 * T + 0{,}000499 * T^2 - 0{,}00000214 * T^3) * 10^{-6} = 5{,}43 * 10^{-7} \left[{}^{m^2}/_{s}\right]$
- Reynolds number: $Re = \frac{v*D}{\nu} = 1{,}19 * 10^4$
- Friction factor: $Fa = 0{,}07 * Re^{-0{,}13} * D^{-0{,}14} = 0{,}034$

- Unitary continuous pressure drop: $r = \frac{Fa*\rho*v^2}{2*D} = 32{,}371\ [{}^{Pa}/_{m}] = 3{,}303\ [{}^{mmCA}/_{m}]$
- Distributed pressure losses: $R_{distr} = r * l = 161{,}853\ [Pa]$, where l represents the pipes length and it was set to 5 m
- Localized pressure losses: $R_{loc} = \xi * \rho * \frac{v^2}{2} * n = 63{,}794\ [Pa]$, where n represents the number of curves and it is equal to 0,3 (33)
- Total pressure losses: $R_{tot} = R_{distr} + R_{loc} = 225{,}647\ [Pa] = 0{,}023\ [mCA]$

Finally, to calculate the total head requested to the circulator it is necessary to take in account also the pressure losses through condenser and DHW tank:

$$H = R_{tot} + R_{cond} + R_{tank} = 1{,}345\ [mCA]$$

Where

- (28)$R_{cond} = 1{,}200\ [mCA]$
- (31)$R_{tank} = 0{,}122\ [mCA]$

At this point it was possible to choose the correct device for the purpose. Finally, Classic 25-4 by Shinhoo (34) was selected.

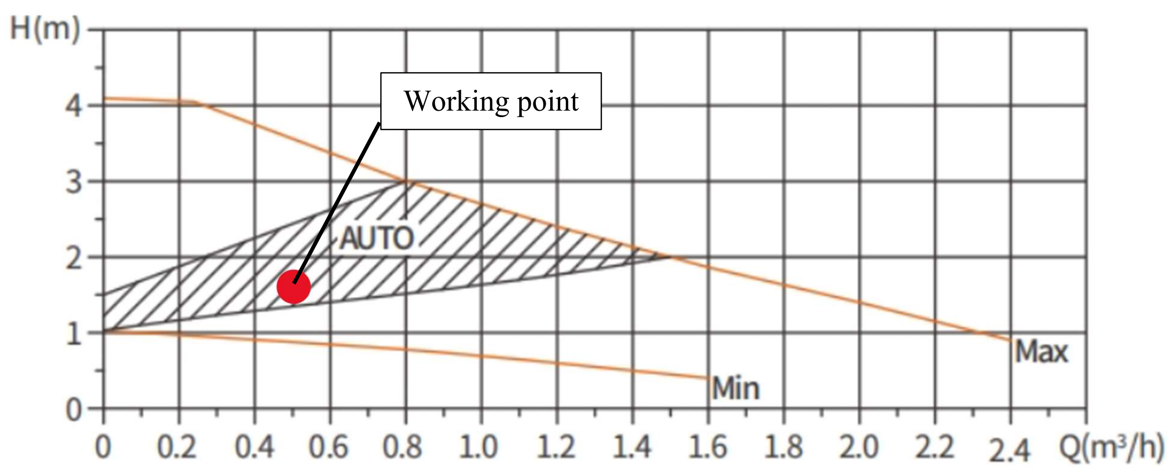


Figure 4.13: Classic 25-4 performance curve (34)

It can be seen that the chosen circulator is slightly oversized, this is due to the fact that the length of the piping system and the number of curves present in the circuit were guessed and could increase in a real case.

4.2.7 Expansion vessel

Expansion tank is another component that would be present only in full optional T5, since it must be connected to the supply path from the heat pump to the pipe coil of the DHW tank.

Dimension procedure is based on:

$$V = \frac{C * e}{1 - \frac{P_i}{P_e}} \pm 10\% = 5{,}61\ [l]$$

Where:

- $C = 250\ [l]$, total volume of water contained in the system
- $e = 0{,}01683$, expansion coefficient that is equal to the difference between expansion coefficients at maximum water temperature inside the tank and minimum water temperature injected into the system
- $P_i = 1{,}5\ [bar]$, absolute pressure at which the expansion vessel is pre-filled
- $P_e = 6\ [bar]$, maximum absolute pressure at which the safety valve is calibrated

Finally, CP 335/6 by CIMM (35) has been selected.

Volume capacity	6 l
Diameter	325 mm
Height	118 mm
Pre-charging pressure	1,5 bar

Table 4.12: CP 335/6 technical data

4.2.8 3-way diverter and mixing valves

Last components requiring a proper sizing procedure are the 3-way valves. Different procedures are necessary for diverter and mixing valves, both processes are described in the technical manual called “Valvole di regolazione” provided by Caleffi (36).

Regarding diverter valves, the procedure can be easily explained by using the following equations:

Pressure drop across the valve: $\Delta p_{valve} = 0{,}5 \div 1{,}0 * H$

Flow rate coefficient: $K_v = 0{,}10 \div 0{,}15 * \frac{Q}{\sqrt{100 * H}}$

Final results are slightly different between the two 3-way diverter valves, since the one that separates heating from cooling doesn’t need to consider the pressure losses due to the DHW tank.

Δp_{max}	13,19 [kPa]
Δp_{min}	6,60 [kPa]
Kv_{max}	3,01 [m^3/h]
Kv_{min}	4,51 [m^3/h]
Kv_{ave}	3,76 [m^3/h]

Table 4.13: 3-way diverter valve DHW/heating

Δp_{max}	11,99 [kPa]
Δp_{min}	6,00 [kPa]
Kv_{max}	4,73 [m^3/h]
Kv_{min}	3,15 [m^3/h]
Kv_{ave}	3,94 [m^3/h]

Table 4.14: 3-way diverter valve heating/cooling

Then, 3-way motorized diverter ball valve 644356 (37) was selected both for the valve regulating DHW and heating and the one regulating cooling and heating.

Regarding mixing valves only slightly differences with respect to the previous procedure are necessary:

Pressure drop across the valve: $\Delta p_{valve} = 0{,}05 \div 0{,}15 * H$

Flow rate coefficient: $K_v = 0{,}25 \div 0{,}45 * \frac{Q}{\sqrt{100*H}}$

Final results are reported in the following table.

Δp_{max}	1,98 [kPa]
Δp_{min}	0,66 [kPa]
Kv_{max}	13,51 [m^3/h]
Kv_{min}	7,50 [m^3/h]
Kv_{ave}	10,50 [m^3/h]

Table 4.15: 3-way mixing valve

Finally, thermostatic control unit 16605 (38) was selected.

4.2.9 Piping circuits

As introduced in the sections above, three separated circuits are present in the system. Their sizing strongly depends on the installed components and influences the pressure losses across the system.

Regarding water circuits, both on source side and domestic system side, it was decided to set a standard diameter of 1” in order to simplify the connections with the possible pre-existing system and starting from this point the losses were calculated following the procedure explained in the section 4.2.6.

Regarding the refrigerant circuit, software LineSize (39) was utilized. The following pictures were taken from the software interface and represent the sizing procedure.

The input data are the ones reported in the table on the left, while data on the right side of the picture are the output of the process. Worst working condition was considered, meaning that condensing temperature was set as low as possible, resulting in the highest cooling duty.

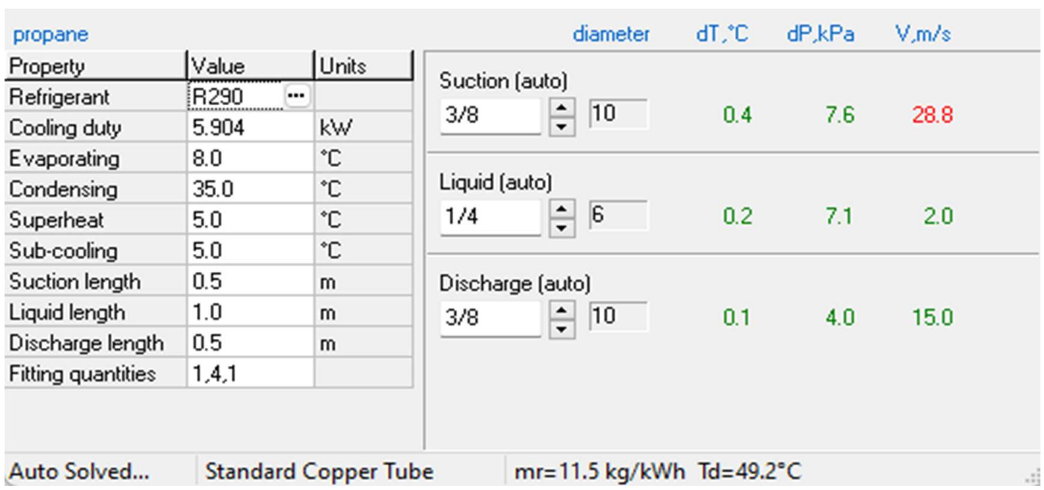


Figure 4.14: LineSize interface reporting first sizing simulation

It can be seen that a warning is present in the picture above, that means that suction pipe diameter must be changed to avoid issues.

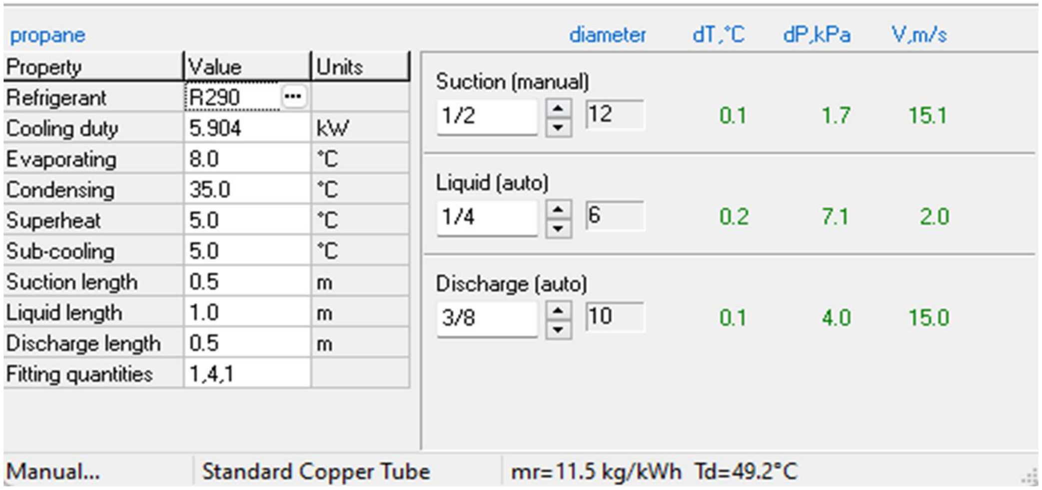


Figure 4.15: LineSize interface reporting final results

Finally, varying the suction diameter, the warning was solved and final configuration was obtained.

To obtain further clarification, it is necessary to explain the nomenclature used by the software:

- Suction refers to the section of the circuit in which the refrigerant flows out from the evaporator toward the compressor
- Liquid refers to the section of the circuit in which the refrigerant flows out from the condenser toward the expansion valve and then also from the valve to the evaporator
- Discharge refers to the section of the circuit in which the refrigerant flows out from the compressor toward the condenser

Obviously, those dimensions must be respected as much as possible, but are strongly dependent on welding limitations due to the different connection dimensions of the components.

4.3 Solid representation

Finally, once selected every component and piping circuits diameters, it was possible to create a 3D representation of the entire T5 system. The aim of this section is to present these models, which separately depict the two versions of the technology. The final dimensions of the machine are reported, along with specific design features that were implemented to simplify the assembly of the heat pump system.

4.3.1 T5 basic version

Figure 4.16 is a representation of the pure T5 technology, without the DHW storage.

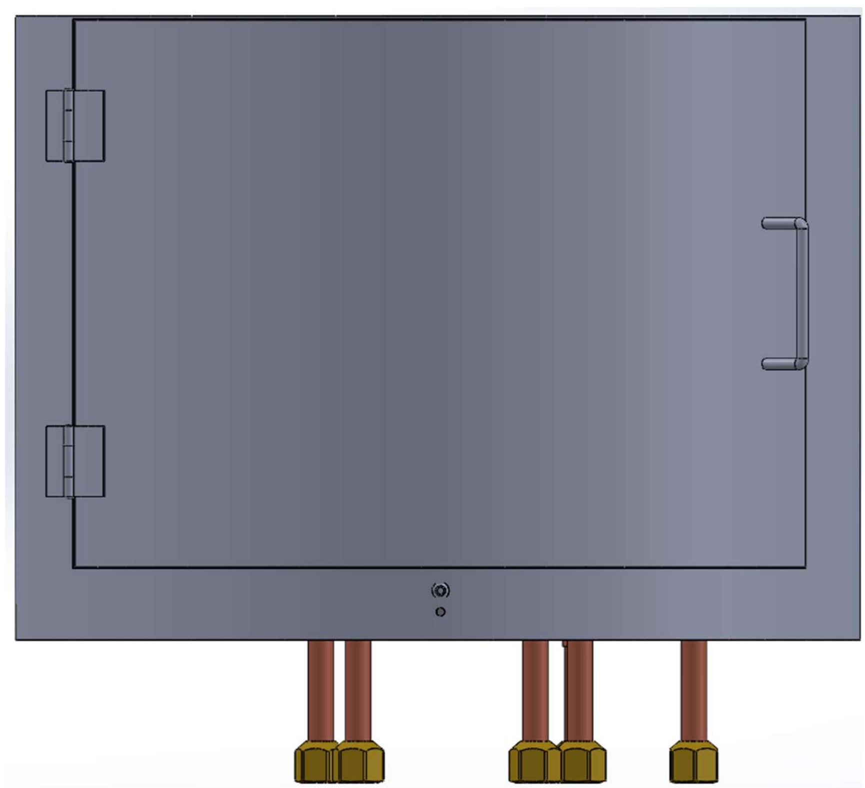


Figure 4.16: Basic T5 final appearance

The body of the heat pump is based on a circular plate and encapsulated in a cylindrical lid with a flap useful to access to the refrigerant circuit for maintenance operations. Figure 4.17 represents the technology with open flap.

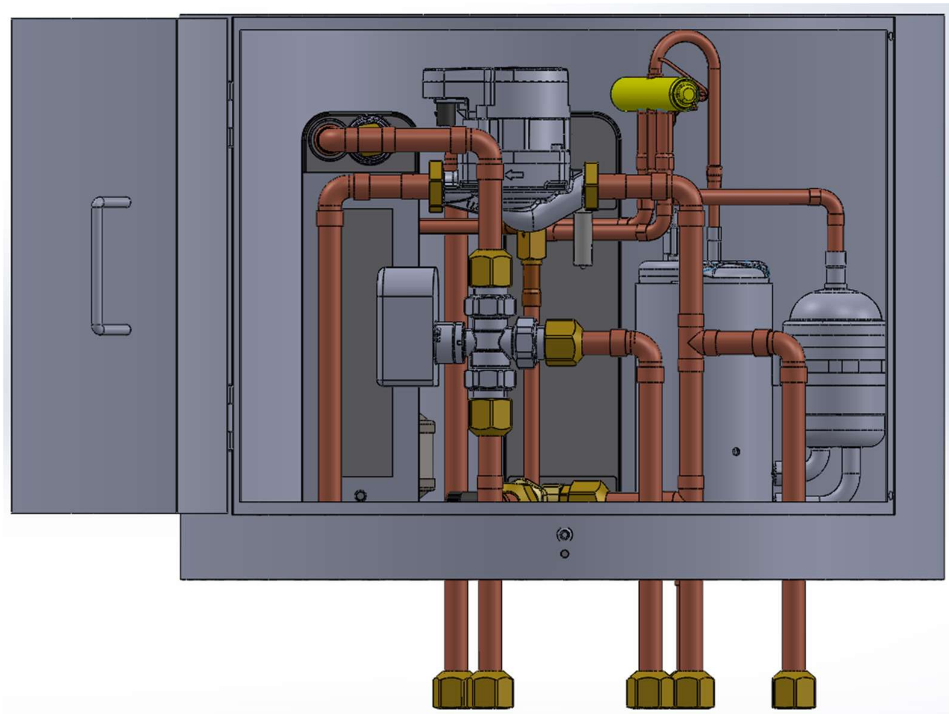


Figure 4.17: Basic T5 appearance during maintenance operation

The cylindrical lid is directly connected to the base plate of the heat pump by means of screws inserted in three L-shaped plates welded onto the base. To simplify assembly operations, the lid can be backed on the L-shaped plates by means of rivets fixed onto the cover, particular of this solution are reported in Figure 4.18: L-plate connection particular.

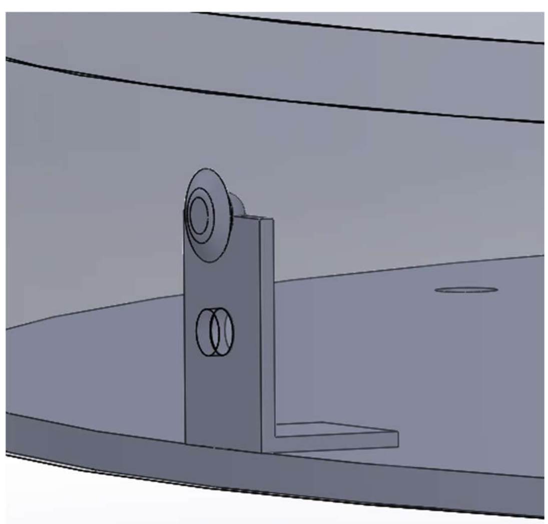


Figure 4.18: L-plate connection particular

Base plate (Figure 4.19) supporting the heat pump was specifically designed in order to guarantee mechanic resistance to the load of the heat pump and to allow the pass through of the pipes exiting from the system. This component remains the same in both the versions of T5, resulting in a simpler assembly of the different parts of the system. This feature is particularly evident in Figure 4.20, where the plate is represented with quotes. In fact connection holes with the DHW storage are present also in this version.

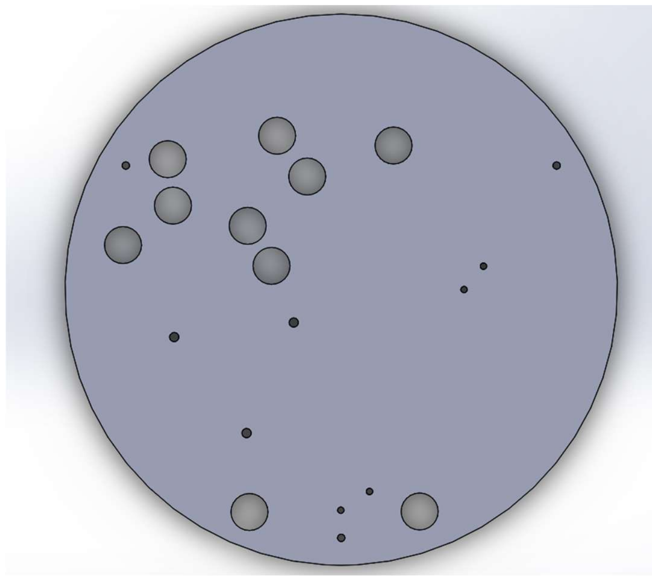
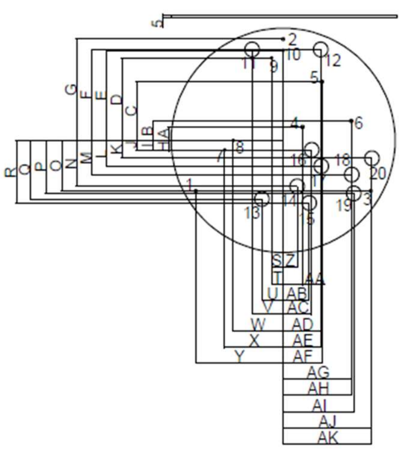


Figure 4.19: Base plate upper view



POS.	DESCRIPTION	Φ [mm]
1	TANK CONNECTION	8
2	TANK CONNECTION	8
3	TANK CONNECTION	8
4	COMPRESSOR CONNECTION	10
5	COMPRESSOR CONNECTION	10
6	COMRPESSOR CONNECTION	10
7	CONDENSER CONNECTION	7
8	CONDENSER CONNECTION	7
9	EVAPORATOR CONNECTION	7
10	EVAPORATOR CONNECTION	7
11	IN EVAPORATOR	40
12	OUT EVAPORATOR	40
13	HEATING / DHW PIPE COIL SUPPLY	40
14	HEATING RETURN	40
15	COOLING SUPPLY	40
16	IN DCW	40
17	DHW PIPE COIL RETURN	40
18	COOLING RETURN	40
19	HEATING SUPPLY	40
20	OUT DHW	40

POS.	QUOTES [mm]
A	35.53
B	51.27
C	155.07
D	218.19
E	238.45
F	240.35
G	268.33
H	0.1
I	25.36
J	25.72
K	48.2
L	69.02
M	90.84
N	122.3
O	134.16
P	141.02
Q	155.82
R	166.39
S	0.45
T	30.1
U	56.44
V	83
W	132.06
X	155.14
Y	232.28
Z	36.67
AA	51.69
AB	69.18
AC	75.65
AD	99
AE	100.95
AF	102.09
AG	180.19
AH	181.55
AI	187.19
AJ	232.38
AK	235.44

Figure 4.20: Base plate and relative quotes

Figure 4.21, Figure 4.22 and Figure 4.23 are reported with the aim to indicate the different components and their positions in the system. It must be noted that the same configuration has been designed for both T5 versions to simplify assembly operations, with slightly difference due to the higher number of components present in the full optional version.

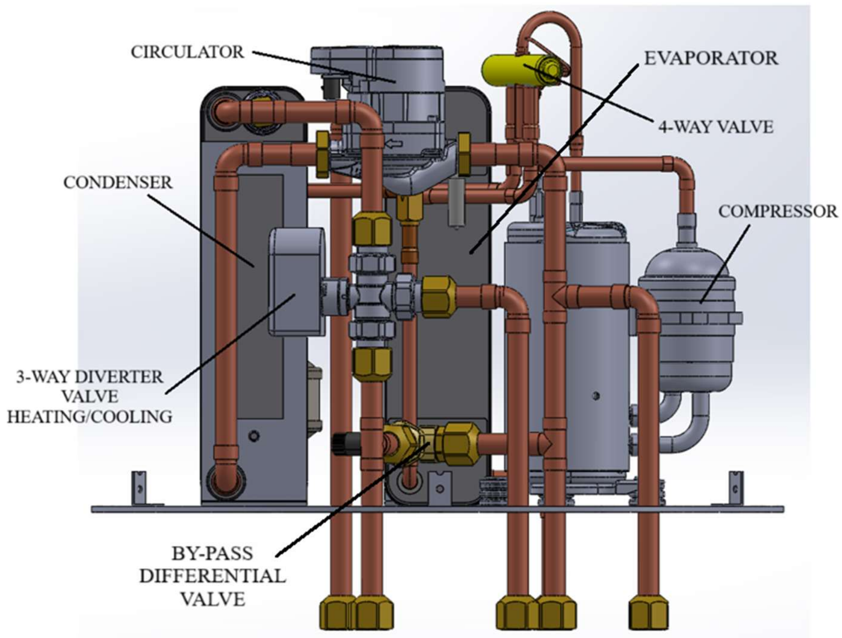


Figure 4.21: Basic T5 front view

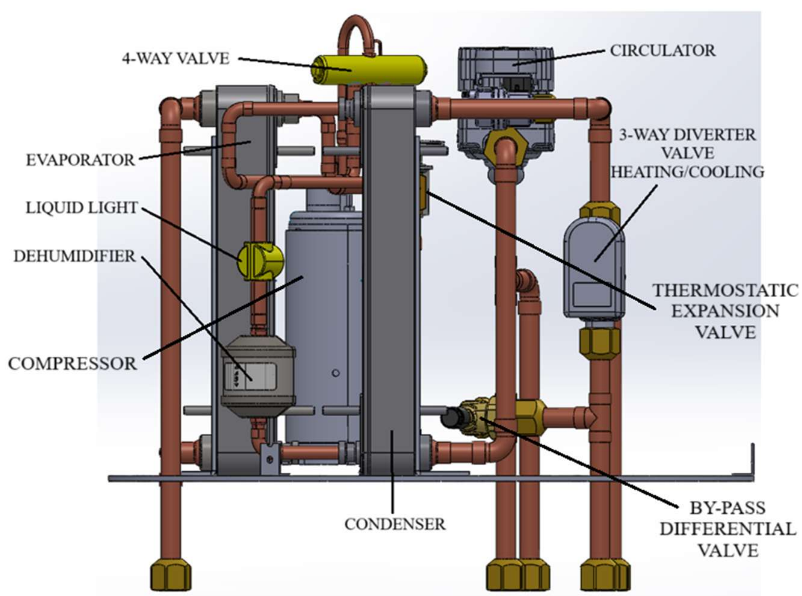


Figure 4.22: Basic T5 lateral view

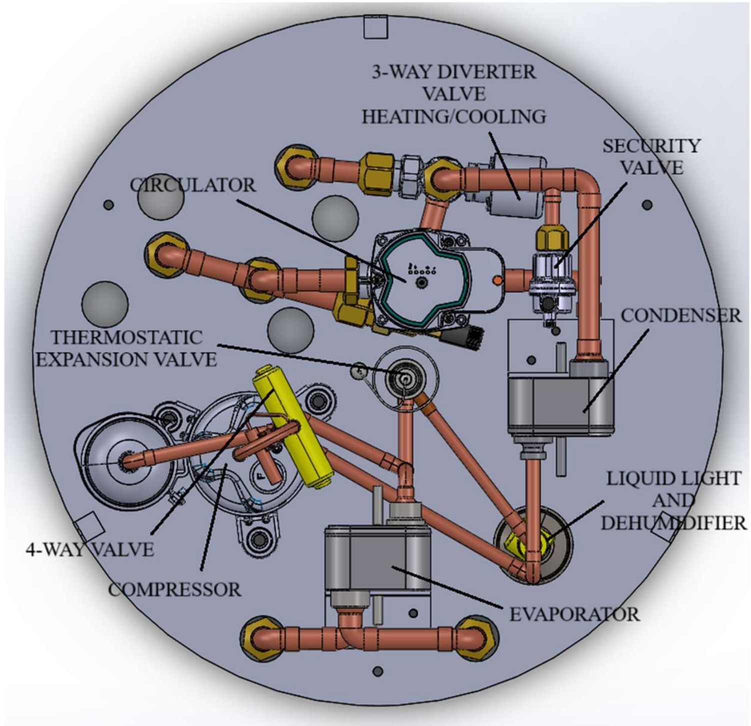


Figure 4.23: Basic T5 upper view

All the designing process was performed with the aim of reducing as much as possible the final dimensions of the heat pump, with some limitations due to spatial restrictions to allow and simplify as much as possible the welding process.

To simplify the connection of the heat pump with the domestic systems, all the pipes exiting from the machine end with threated brass joints.

Final dimensions are reported in the following table

Height	443 mm
Diameter	600 mm
Tube outlet length	100 mm

Table 4.16: Basic T5 dimensions

4.3.2 T5 full optional version

The full optional representation is reported below.

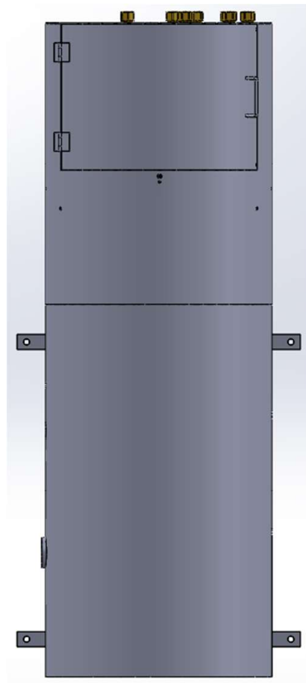
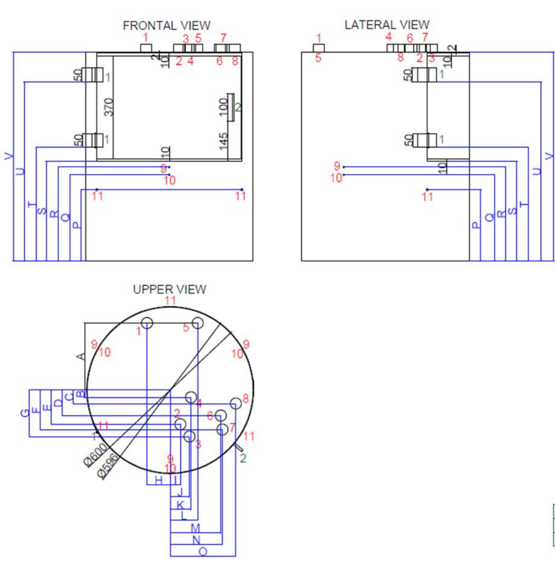


Figure 4.24: Full optional T5 final appearance

Similar cover to the one present in the basic version has been developed for this model, although some important differences are present. In the following figure cover representation and dimensions are reported.



POS.	DESCRIPTION	Φ [mm]
1	OUT EVAPORATOR	40
2	HEATING RETURN	40
3	COOLING SUPPLY	40
4	IN EVAPORATOR	40
5	OUT DHW	40
6	IN DCW	40
7	COOLING RETURN	40
8	HEATING SUPPLY	40
9	RIVET HOLE	6
10	HOLE FOR HEAT PUMP FIXING	6
11	HOLE FOR TANK BRACKET	8

POS.	QUOTA [mm]
A	240.3
B	25.7
C	48.2
D	90.8
E	122.3
F	141
G	166.4
H	83
I	36.7
J	69.2
K	75.2
L	99
M	181.6
N	187.2
O	235.4
P	255
Q	308.7
R	336.6
S	355.7
T	406.7
U	641.7
V	747.7

COMPONENT	DESCRIPTION
1	ZIPPER
2	HANDLE

Figure 4.25: Full optional T5 cover

The most relevant difference is that pipe exit from heat pump pass through the upper face of the cover, instead of the base plate. Although the length of every pipe has been specifically designed to remain constant in the two different T5 versions, this means that the copper pipes to be ordered are always the same simplifying as much as possible serial production of the machine. It is sufficient to simply weld the connections of the pipes in reverse.

The following figures result necessary in order to better explain differences between the heat pump configurations.

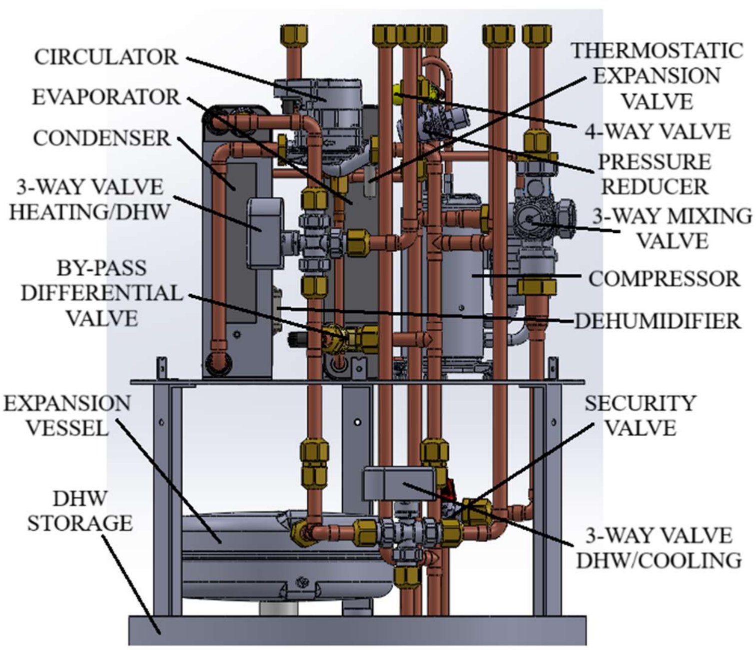


Figure 4.26: Full optional T5 front view

Since the main parts of the system are equal to the previous case, only pictures representing specific sections with the aim to highlight differences are reported below.

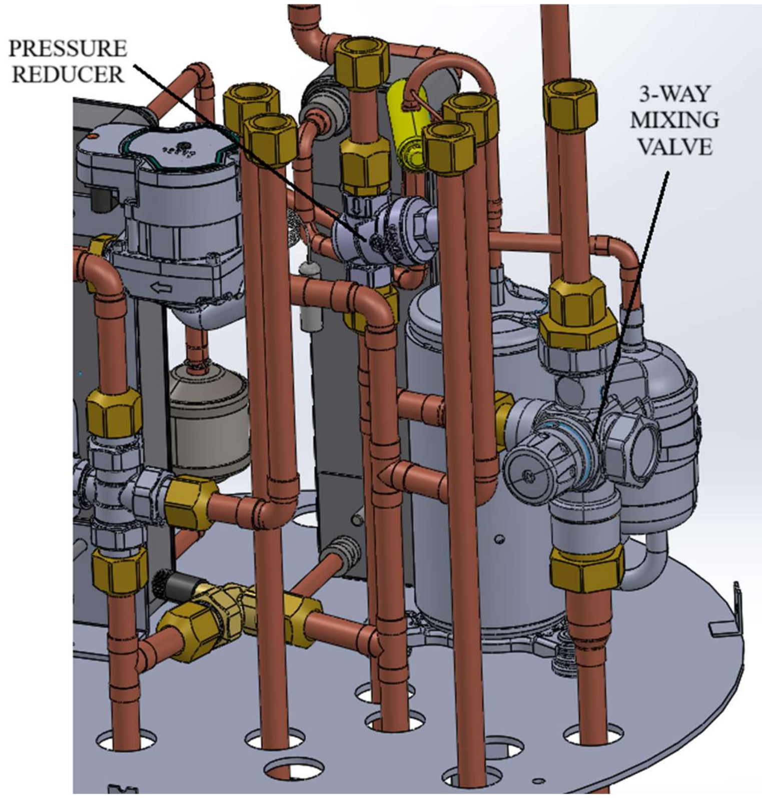


Figure 4.27: Pressure reducer and mixing valve

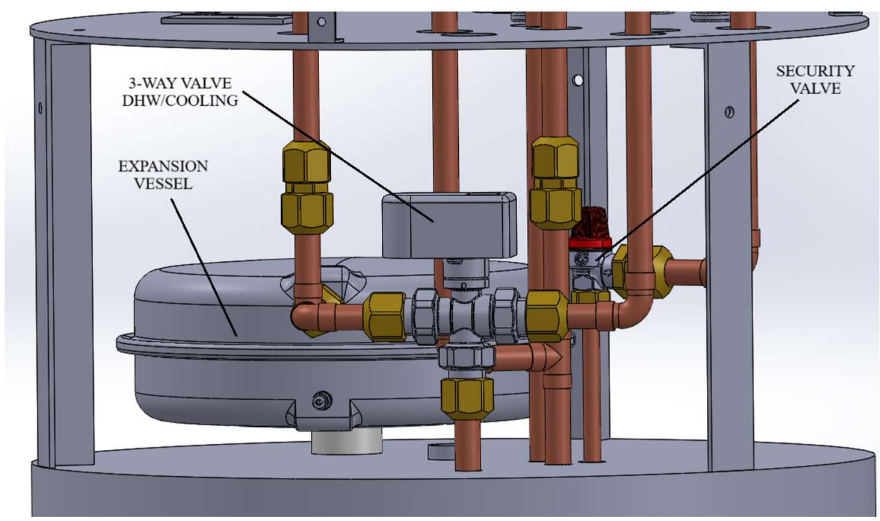


Figure 4.28: Components located under the base plate

The connection between base plate and DHW storage is entrusted to three brackets directly welded on the tank and screwed to the plate and to the cover of the heat pump, as shown below.

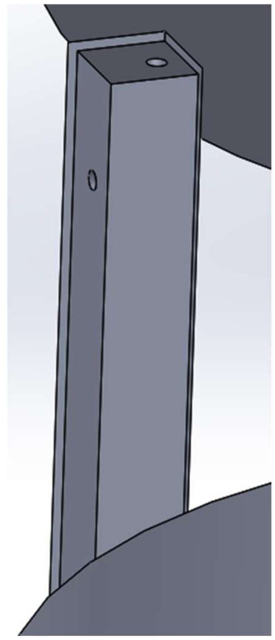


Figure 4.29: DHW storage - plate base connection

Final particular is the connection between the full optional T5 system and the wall, performed by means of two brackets located on the rear of the DHW storage to be screwed directly to the wall, the system is shown in the following picture.

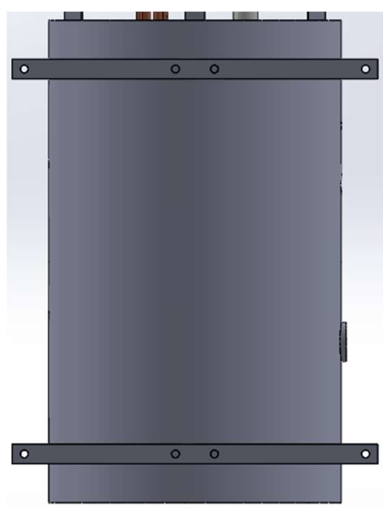


Figure 4.30: DHW storage rear, wall connections particular

As explained previously, the lengths of the pipes are equal in both versions of the T5, just differently welded. The main difference in the assembly process is related to the connections of the evaporator, in which inlet and outlet pipes are reversed in the two cases:

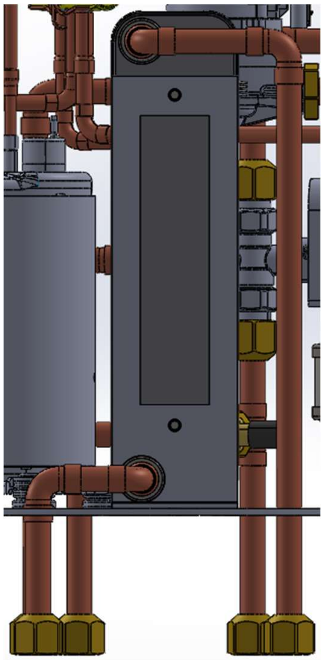


Figure 4.31: Basic T5 - evaporator particular

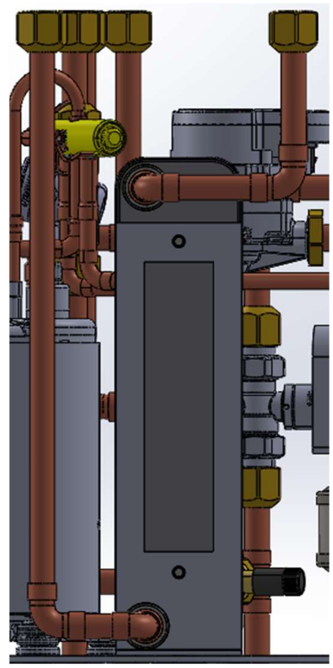


Figure 4.32: Full optional T5 - evaporator particular

Final dimensions are reported in the following table.

Height	1740 mm
Diameter	600 mm
Tube outlet length	30 mm

Table 4.17: Full optional T5 dimensions

5 Conclusion

This thesis presents an examination and development of the T5 water-to-water heat pump, which shows how modern heat pump technology may be used to produce hot water and heat homes sustainably. The T5 project addresses the pressing need for residential systems that deliver high performance, minimal environmental impact and interoperability with existing infrastructure.

This thesis emphasizes the promise of cutting-edge heat pump technology as an environmentally friendly option for home heating, cooling, and hot water generation through the construction and analysis of the T5 water-to-water heat pump. The T5 project provides excellent performance, minimal environmental effect, and easy connection with current infrastructure, thereby fulfilling a vital demand for residential systems.

From a technical perspective, the T5 research aims to demonstrate how using natural refrigerants - particularly R290 - can result in systems with higher thermal efficiency than traditional fossil fuels-based systems. Operating on a reverse thermodynamic cycle, the T5 system harnesses renewable thermal energy from water, resulting in significant energy savings and pollution reductions. Since the T5 design maximizes the Coefficient of Performance (COP), it is the best option for heating and cooling applications in residential buildings, according to an analysis of various thermodynamic cycles and system components.

A key finding of this study is that the T5 system can operate effectively across a variety of environmental conditions, offering reliable heating in colder climates and effective cooling in warmer ones. This adaptability, along with its small size and compatibility with current water-based heating systems, puts the T5 heat pump in a competitive and scalable position when compared to conventional gas boilers, especially considering the housing market in Italy. Compared to air-source heat pumps, the system can function more reliably and efficiently since it uses water as both a source and a sink for heat transfer.

The economic analysis further highlights the T5 system’s financial viability. The cash flow study showed that, even with a larger initial investment than traditional heating systems, the payback period is competitive when taking into account installation costs, operating savings, and potential government incentives. The T5 system is more and more appealing as yearly savings grow over time as a result of growing energy costs and the implementation of programs like the European Union Emissions Trading Scheme (EU ETS). The T5 heat pump's economic viability is further increased by incentive schemes like Italy's Conto Termico 2.0, which offer substantial financial support and greatly offset initial installation costs.

The T5 technology also demonstrates a superior environment performance compared to the conventional heating methods. Since the heat pump doesn't use combustion processes, local emissions are completely removed, and worldwide emissions—including those resulting from the use of electricity—are significantly reduced. The decrease in emissions of carbon dioxide (CO2), nitrogen oxides (NOx), and particulate matter (PM10) emphasizes how the T5 heat pump helps achieve more ambitious climate targets and enhances air quality. Furthermore, the environmental advantages of heat pump systems like T5 will only grow over time as more renewable energy sources are added to the electrical grid.

The emission analysis also shows that combining the T5 heat pump with additional renewable energy sources, such solar panels, can further reduce the overall carbon footprint. This is consistent with more general energy industry trends toward integrated systems that incorporate renewable energy generation, heating, and cooling to produce almost carbon-neutral energy usage in residential applications.

Future regulatory trends are another consideration in the design of the T5 system. The use of natural refrigerants like R290 in the T5 pump positions it as a forward-thinking solution that complies with current environmental regulations and anticipates future changes, particularly in light of the increasingly strict regulations the European Union is putting in place regarding the use of fluorinated gases (F-gases) in heating and cooling systems. This guarantees the technology's durability and applicability in a market shifting toward more environmentally friendly options.

In the future, heat pumps such as the T5 are expected to play an increasingly significant role in the worldwide energy transition. The need for efficient and renewable heating and cooling solutions will increase as long as decarbonization and energy efficiency remain top priorities in national and international legislation. The T5 heat pump is well-positioned to satisfy these changing demands due to its cutting-edge design, excellent performance, and minimal environmental effect. Furthermore, improvements in technology for heat pump components - such as more effective heat exchangers, compressors, and control systems - will improve the functionality and suitability of systems like the T5 for both newly constructed and retrofitted buildings.

As demonstrated in this thesis, the T5 water-to-water heat pump presents a feasible and sustainable substitute for conventional heating systems, offering distinct advantages in energy conservation, environmental impact and long-term economic viability. The technological, financial and environmental assessments provided here offer a comprehensive understanding of how this technology can support broader objectives of sustainable development as well as the decarbonization of domestic heating. Solutions like the T5 heat pump will be essential in lowering dependency on fossil fuels, preventing climate change and increasing the integration of renewable energy into daily life as the energy landscape changes.

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