NATIONAL TECHNICAL UNIVERSITY OF ATHENS

MECHANICAL ENGINEERING SCHOOL

HEAT DEPARTMENT

REFRIGERATION, AIR CONDITIONING AND SOLAR ENERGY

BACHELOR'S THESIS

SOLAR ASSISTED GROUND SOURCE HEAT PUMP FOR HEATING

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This thesis was conducted in the Thermal Engineering Department of the School of Mechanical Engineering at the National Technical University of Athens.

With this paragraph, I would like to express my gratitude to everyone who contributed to the successful completion of this thesis, especially:

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Abstract

This university thesis addresses the urgent need to tackle the climate crisis by exploring the potential of solar-assisted ground source heat pump (SAGSHP) systems for efficient building heating. The study delves into the sources and consumption of energy, emphasizing the importance of renewable energy in mitigating environmental impacts. It provides a thorough overview of solar energy, discussing solar radiation, angles, and trends in Europe and Greece. Additionally, the thesis examines photovoltaic systems, their underlying principles, various cell technologies, and the equipment required for installation and operation. Detailed insights into heat pumps are presented, covering their components, categories, heat sources, and performance evaluation. Special attention is given to ground source heat pumps and their suitability for sustainable heating. The TRNSYS 18 simulation program is utilized to simulate the proposed SAGSHP installation, considering building design, configuration, and component interconnection. The results showcase the performance of the SAGSHP system in two contrasting climates, Athens and Helsinki. Despite the significant temperature difference, the system demonstrates stable coefficient of performance (COP) values, ensuring efficient heating. The integration of photovoltaic systems further enhances the system's capabilities and energy self-sufficiency. An economic analysis assesses the installation costs, payback periods, and life cycle costs, shedding light on the long-term viability of the SAGSHP systems.

In conclusion, this thesis presents a comprehensive evaluation of solar-assisted ground source heat pump systems, highlighting their efficiency, environmental benefits, and economic implications. The research provides valuable insights for policymakers, engineers, and stakeholders in promoting sustainable building practices and combating climate change. Finally, proposals for future research are demonstrated.

Περίληψη

Αυτή η διπλωματική εργασία αντιμετωπίζει την επείγουσα ανάγκη για αντιμετώπιση της κλιματικής κρίσης εξερευνώντας τη δυνατότητα των ηλιακών υποβοηθούμενων γεωθερμικών αντλιών θερμότητας για αποτελεσματική θέρμανση κτιρίων. Η μελέτη εξετάζει τις πηγές και την κατανάλωση ενέργειας, τονίζοντας τη σημασία των ανανεώσιμων πηγών ενέργειας στη μείωση των περιβαλλοντικών επιπτώσεων. Παρέχεται μια εκτενής επισκόπηση της ηλιακής ενέργειας, αναλύοντας την ηλιακή ακτινοβολία, τις γωνίες και τις τάσεις στην Ευρώπη και την Ελλάδα. Επιπλέον, η διπλωματική εργασία εξετάζει τα φωτοβολταϊκά συστήματα, τις βασικές αρχές τους, τις διάφορες τεχνολογίες κυψελών και τον εξοπλισμό που απαιτείται για την εγκατάσταση και λειτουργία τους. Παρουσιάζονται λεπτομερείς αναλύσεις των αντλιών θερμότητας, καλύπτοντας τα λειτουργικά στοιχεία τους, τις κατηγορίες τους, τις πηγές θερμότητας και την αξιολόγηση της απόδοσής τους. Ειδική προσοχή δίνεται στις αντλίες θερμότητας εδάφους και στην καταλληλότητά τους για τη βιώσιμη θέρμανση. Το πρόγραμμα προσομοίωσης TRNSYS 18 χρησιμοποιείται για την προσομοίωση της προτεινόμενης εγκατάστασης με ηλιακά υποβοηθούμενη γεωθερμική αντλία θερμότης, λαμβάνοντας υπόψη το σχεδιασμό του κτιρίου, τη διαμόρφωση και τη διασύνδεση των συστατικών. Τα αποτελέσματα αποδεικνύουν την απόδοση του συστήματος με ηλιακα υποβοηθούμενη γεωθερμική αντλία θερμότητας σε δύο αντίθετα κλίματα, Αθήνα και Ελσίνκι. Παρά τη σημαντική θερμοκρασιακή διαφορά, το σύστημα επιδεικνύει σταθερές τιμές συντελεστή απόδοσης (COP), εξασφαλίζοντας αποδοτική θέρμανση. Η ενσωμάτωση των φωτοβολταϊκών συστημάτων ενισχύει περαιτέρω τις δυνατότητες του συστήματος και την ενεργειακή αυτάρκειά του. Μια οικονομική ανάλυση αξιολογεί το κόστος εγκατάστασης, τα χρόνια αποπληρωμής και τον κύκλο ζωής του συστήματος, φωτίζοντας τη μακροπρόθεσμη βιωσιμότητα των συστημάτων γεωθερμικών αντλιών θερμότητας με ηλιακή υποβοήθηση.

Συνολικά, αυτή η διπλωματική εργασία παρουσιάζει μια εκτενή αξιολόγηση των συστημάτων γεωθερμικών αντλιών θερμότητας με ηλιακή υποβοήθηση , τονίζοντας την αποδοτικότητά τους, τα περιβαλλοντικά οφέλη και τις οικονομικές επιπτώσεις. Η εργασία παρέχει πολύτιμες πληροφορίες για τους πολιτικούς, μηχανολογικούς και ενδιαφερόμενους φορείς, προωθώντας τις βιώσιμες πρακτικές κατασκευής και την αντιμετώπιση της κλιματικής αλλαγής. Τέλος, προτείνονται προτάσεις για μελλοντικές έρευνες.

Contents

1. INTRODUCTION

1.1 Climate crises

The current climate crisis is one of the greatest challenges facing humanity today. Climate change is causing rising global temperatures, sea level rise, extreme weather events, and the loss of biodiversity [1.1]. The Intergovernmental Panel on Climate Change (IPCC) has reported that the Earth's surface temperature has increased by 1.1°C above pre-industrial levels, and is expected to reach 1.5°C by as early as 2030, with devastating consequences for ecosystems and human societies, including food insecurity, water scarcity, and displacement of people from coastal areas and low-lying islands [1.2].

The main driver of climate change is the emission of greenhouse gases, primarily carbon dioxide (CO2), from human activities such as burning fossil fuels, deforestation, and industrial processes [1.3]. The concentration of CO2 in the atmosphere has reached a level not seen in at least 800,000 years . The effects of climate change are not evenly distributed, with the most vulnerable populations being the ones who suffer the most. Climate change exacerbates existing inequalities and contributes to global poverty. Urgent action is needed to address the climate crisis, including reducing greenhouse gas emissions, increasing renewable energy use, and implementing adaptation measures to protect vulnerable populations and ecosystems[1.4].

1.2 Sources and energy consumption

Energy consumption is a crucial factor in the global economy and has a significant impact on the environment. The demand for energy has been increasing steadily, and it is expected to continue to rise in the future due to population growth, economic development, and changing lifestyles. As a result, there is a need to increase the share of renewable energy sources and reduce the reliance on fossil fuels to ensure sustainable development.

Globally, fossil fuels are the dominant source of energy, accounting for approximately 84% of the total primary energy supply in 2020 [1.5]. Oil, coal, and natural gas are the most commonly used fossil fuels. The consumption of fossil fuels is projected to continue to rise in the coming years, with developing countries expected to account for the majority of the increase in demand [1.6]. However, the use of renewable energy sources is also growing rapidly. In 2020, renewable energy accounted for approximately 11% of the global primary energy supply[1.5] . The largest sources of renewable energy are hydropower, wind power, and solar energy.

In Europe, the energy mix is more diversified than in the rest of the world. Fossil fuels accounted for 69% of the total primary energy supply in 2020, with oil, natural gas, and coal being the primary sources [1.7]. Renewables accounted for 20% of the total energy supply, with hydropower, wind power, and solar energy being the most significant sources. Europe is committed to increasing the share of renewables in its energy mix to achieve its climate goals. The European Union has set a target of producing at least 32% of its energy from renewables by 2030 [1.8]. Moreover, the EU is working towards achieving climate neutrality by 2050, which requires a significant reduction in greenhouse gas emissions and increased use of renewables [1.9].

In Greece, the primary energy consumption is heavily dependent on fossil fuels, accounting for 91% of the total primary energy supply in 2020 [1.10]. Oil, natural gas, and lignite are the primary sources of energy. Renewables accounted for 9% of the total energy supply, with hydropower, wind power, and solar energy being the most significant sources. Greece has set a target of producing 35% of its energy from renewables by 2030 [1.11]. The Greek government is working towards achieving this target by promoting the use of renewables and improving energy efficiency.

To sum up, energy consumption is a critical factor in the global economy and has a significant impact on the environment. Fossil fuels are the dominant source of energy globally, but the use of renewables is increasing rapidly. Europe is committed to increasing the share of renewables in its energy mix, while Greece has set a target of producing 35% of its energy from renewables by 2030. The transition to a low-carbon economy requires a significant reduction in greenhouse gas emissions and increased use of renewables, which will require significant investments in infrastructure and technological innovation.

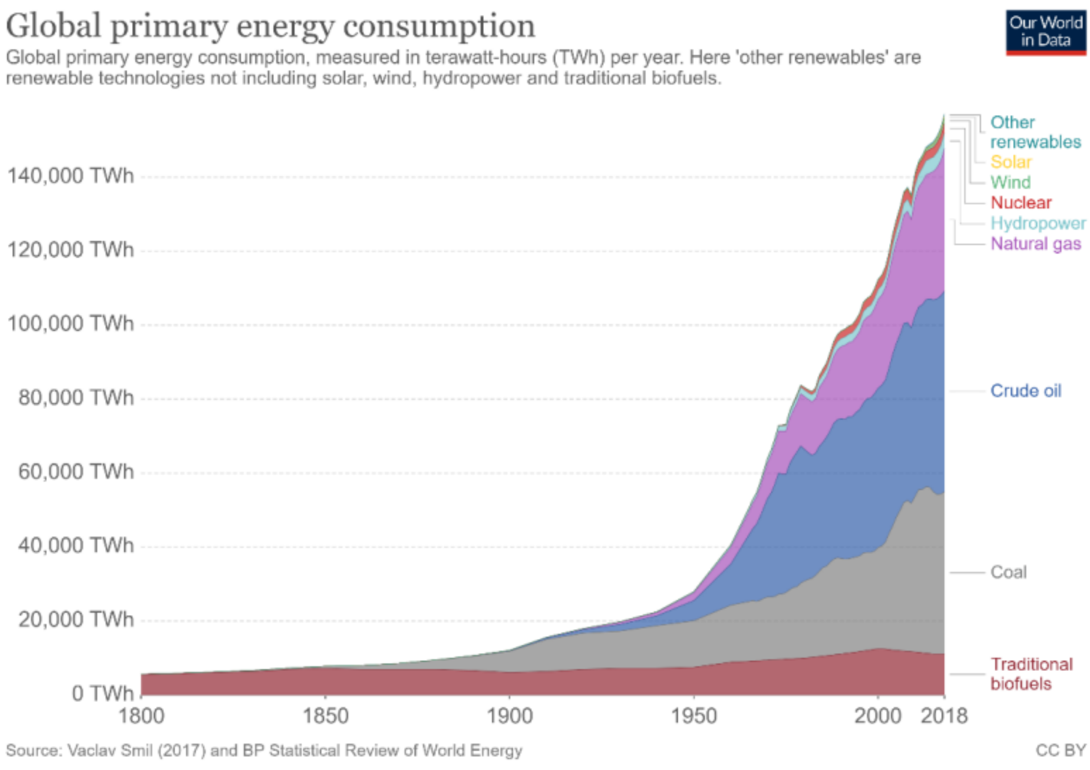

Figure 1.1: Global primary energy consumption [1.12]

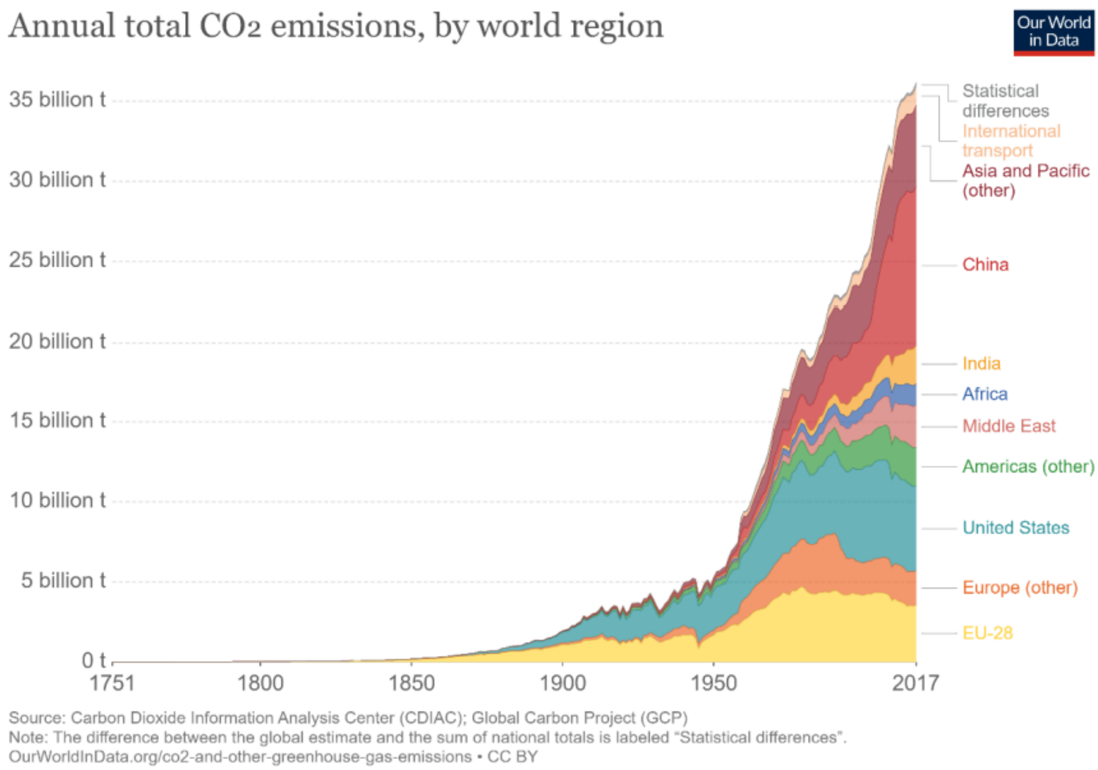

Figure 1.2:Annual total CO2 emissions, by world region [1.12]

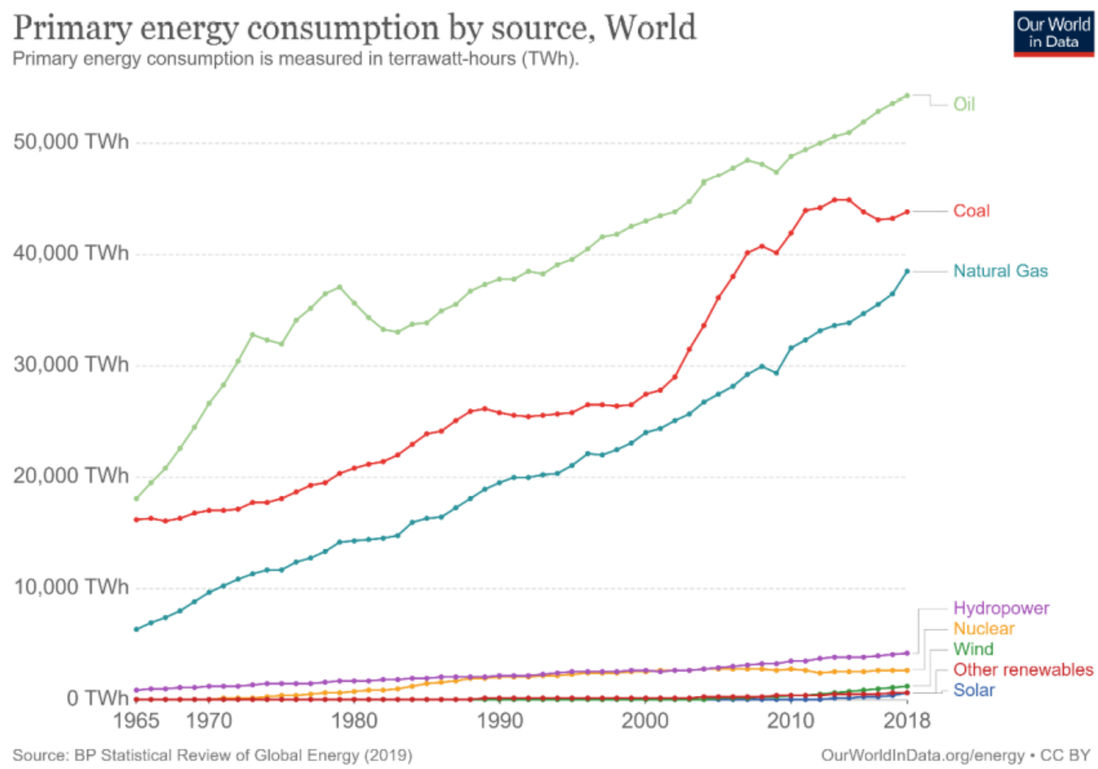

Figure 1.3: Primary energy consumption by source [1.12]

1.3 Renewable Energy

Renewable energy has gained significant attention in recent years as a viable and sustainable source of energy. As the world continues to experience rapid population growth and economic development, the demand for energy has also increased, leading to an increase in carbon emissions and climate change. Renewable energy provides a promising solution to address these challenges, and several countries around the world have made significant efforts to shift towards renewable energy sources. This thesis will analyze the current state of renewable energy consumption in global, Europe, and Greece and the challenges and opportunities for increasing the share of renewable energy in these regions.

- Global Renewable Energy Consumption

According to the International Energy Agency (IEA) , global renewable energy consumption has been steadily increasing over the past decade. In 2019, renewable energy accounted for 11.5% of the world's total energy consumption, up from 7.7% in 2009. The majority of the growth has been driven by the use of wind and solar power, which have become more competitive in cost and efficiency. China is the world's largest consumer of renewable energy, followed by the United States and the European Union (EU) [1.13]. In 2019, China accounted for 28% of the world's renewable energy consumption, while the United States and the EU accounted for 16% and 13%, respectively.

- Renewable Energy Consumption in Europe

The EU has set a target of increasing the share of renewable energy to at least 32% of the total energy consumption by 2030 [1.14]. According to Eurostat , renewable energy accounted for 19.7% of the EU's gross final energy consumption in 2019, up from 9.6% in 2004. The EU's renewable energy consumption is primarily driven by wind, solar, and biomass energy, with wind energy being the largest contributor. Among the EU member states, Sweden has the highest share of renewable energy consumption, followed by Finland and Latvia [1.15].

- Renewable Energy Consumption in Greece

In Greece, renewable energy consumption has also been increasing over the past decade, driven by the government's efforts to reduce carbon emissions and promote sustainable energy. According to the Hellenic Statistical Authority , renewable energy accounted for 13.6% of Greece's total energy consumption in 2019, up from 7.9% in 2010. The majority of the renewable energy in Greece is generated from solar and wind power, with hydroelectricity being the third-largest contributor. Despite the increase in renewable energy consumption, Greece still heavily relies on fossil fuels, with petroleum products accounting for 57% of the country's total primary energy supply in 2019 [1.16].

Renewable energy consumption has been increasing globally, in Europe, and in Greece over the past decade. While progress has been made, there is still a long way to go to meet the targets set by the international community and to address climate change. The shift towards renewable energy requires significant investments in infrastructure, policy reforms, and public awareness campaigns. However, the benefits of renewable energy, such as reduced carbon emissions, energy security, and job creation, make the transition worthwhile.

1.4 Energy and buildings

Energy consumption in buildings is a significant contributor to overall energy use and carbon emissions. According to the European Commission [1.18], buildings account for approximately 40% of the total energy consumption in Europe and produce about 36% of the region's CO2 emissions. In Greece, buildings account for about 33% of the total energy consumption and 25% of the country's CO2 emissions, according to the Hellenic Ministry of Environment and Energy [1.19].

To address this issue, the European Union has set targets to improve the energy efficiency of buildings. The Energy Performance of Buildings Directive (EPBD) aims to increase the energy efficiency of buildings by 32.5% by 2030 compared to 2005 levels. The EU has also established a long-term strategy for the renovation of buildings to decarbonize the building stock by 2050.

In Greece, the Ministry of Environment and Energy has implemented various policies and initiatives to promote energy efficiency in buildings. The National Energy Efficiency Action Plan (NEEAP) sets targets for improving the energy performance of buildings, including increasing the share of renewable energy sources and promoting the use of energy-efficient technologies. The ministry also offers financial incentives for the implementation of energy-efficient measures, such as subsidies for energy audits and loans for energy renovations.

The implementation of energy-efficient measures in buildings can lead to significant energy savings and greenhouse gas emissions reductions. For example, according to the European Commission [1.20], energy-efficient buildings can reduce energy consumption by up to 80% compared to traditional buildings. Additionally, the use of renewable energy sources, such as solar photovoltaic systems and geothermal heat pumps, can further reduce energy consumption and greenhouse gas emissions.

In conclusion, energy consumption in buildings is a significant contributor to overall energy use and carbon emissions in Europe and Greece. However, policies and initiatives aimed at improving energy efficiency and promoting the use of renewable energy sources can lead to significant energy savings and emissions reductions. The implementation of such measures is crucial in achieving the EU's targets for improving the energy efficiency of buildings and decarbonizing the building stock by 2050.

The study and improvement of solar assisted ground source heat pumps for heating is crucial due to their potential to significantly reduce energy consumption and greenhouse gas emissions. Ground source heat pumps use the constant temperature of the earth to provide heating and cooling, and when combined with solar thermal systems, they can provide an even more efficient and sustainable heating solution. This technology can also help to reduce reliance on fossil fuels and increase energy security, particularly in areas with high heating demands. Further research and development of solar assisted ground source heat pumps is needed to improve their performance and reduce their costs, making them more accessible and attractive to a wider range of consumers. Ultimately, the adoption of this technology can contribute to the transition to a more sustainable and low-carbon energy system, helping to mitigate the impacts of climate change.

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2. SOLAR ENERGY

2.1 Introduction to Solar Radiation

Solar energy arises from the thermonuclear fusion that occurs in the sun. It is absorbed by water or the surface of the Earth, converted into thermal energy and then released back into space according to the principles of the Second Law of Thermodynamics. Solar energy refers to the various forms of energy that come from the sun, such as light, heat, and various radiations. The use of solar energy to meet human needs does not affect the energy balance of the biosphere. Solar energy is available everywhere on Earth. It is free and unaffected by rising energy prices. It can be used in various ways, such as for heating, lighting, and generating mechanical and electrical energy. Interest in solar energy intensified with the discovery of the practical possibility of easy, direct, and efficient conversion of solar energy into electrical energy through the photovoltaic phenomenon by constructing photovoltaic generators. Thus, the use of solar energy to meet human needs is now widely and successfully used [2.1].

2.2 Sun and surface angles

Geographic Latitude, ϕ, is the angular distance of a location on Earth's surface north or south of the equator. It is measured in degrees and ranges from -90° to 90°.

Zenith Angle, θ_z, is the angle between the vertical and the direction of the sun, measured at the observer's location. It is measured in degrees and ranges from 0° (sun directly overhead) to 90° (sun at horizon).

Solar Altitude, α, is the angle between the horizontal and the direction of the sun, measured at the observer's location. It is measured in degrees and ranges from 0° (sun at horizon) to 90° (sun directly overhead).

$\alpha = 90^o - \theta z$ (2.1)

Azimuth Angle, γ, is the angle between the observer's meridian (a line from true north to the observer's location) and the projection of the sun's direction onto the observer's horizontal plane. It is measured in degrees and ranges from 0° to 360°, with 0° being true north, 90° being east, 180° being south, and 270° being west.

Sun azimuth, γs: It is the angle between the projection of the line of sight to the sun on the horizontal plane and the southern direction.

Plane tilt, β: It is the angle that a flat surface forms with the horizontal plane.

Hour angle, ω: It is the angular displacement of the sun to the east or west of the local meridian due to the rotation of the Earth around its axis at a rate of 0.25°/min. The hourly angle of sunset, ωs, is calculated from the equation:

$\cos \omega s = -\tan \phi * \tan \delta$ (2.2)

The optimal orientation of a collector is south for the northern hemisphere and north for the southern hemisphere, meaning that the collector should be facing towards the equator. Deviations up to 20° cause small reductions in the incident energy[2.2.].

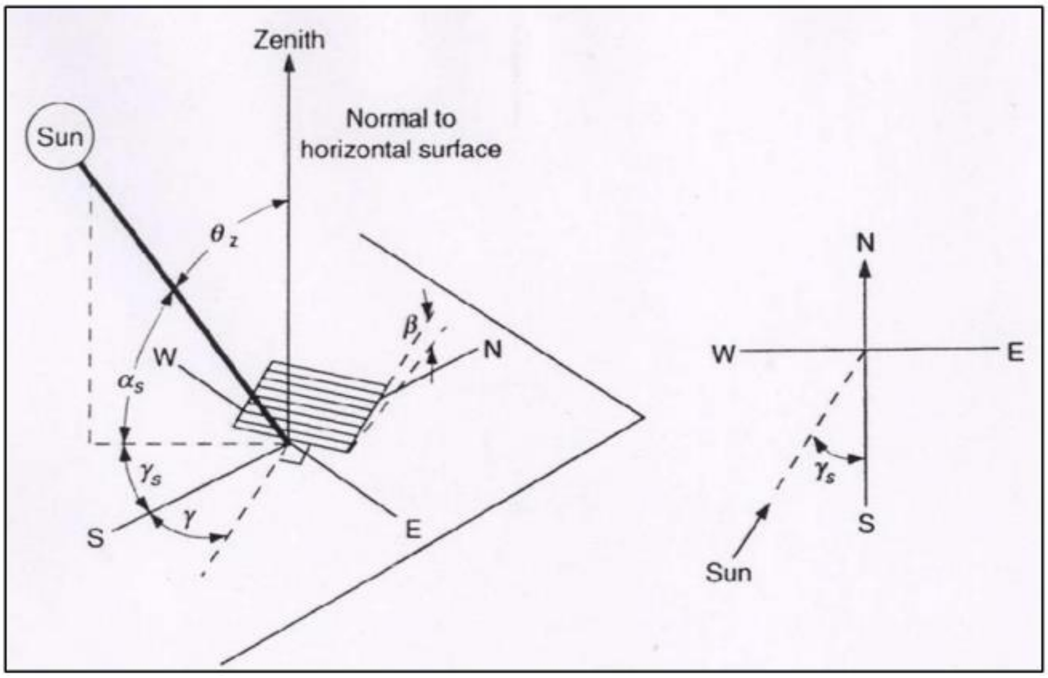

Figure2.1:Zenith angle θz, azimuth of the surface γ, azimuth of the sun γs, collector tilt β[2.2]

2.3 Instruments for measuring solar radiation

There are two main categories of sensors. Thermal sensors indicate based on the heating of a black surface made of a specific material, while electronic excitation sensors measure the energy transitions of electrons in the material during photon absorption.

Thermal sensors:

For increased sensitivity of thermal sensors, care is taken to ensure that the mass of the plate that absorbs radiation is small, so that small amounts of absorbed energy cause significant changes in its temperature. This category includes:

a) pyranometer

b) pyroelectric crystal

c) bolometers

- Pyranometer

A pyranometer is a thermal sensor that plays a critical role in the field of solar energy. It measures the solar irradiance, or the amount of solar energy, that reaches a particular surface. By measuring both direct and diffuse solar radiation, pyranometers provide accurate information about the potential for solar energy generation at a specific location. Pyranometers are commonly used in photovoltaic and solar thermal power systems, as well as in meteorological applications. According to the International Electrotechnical Commission (IEC), the accuracy of a pyranometer should be within +/- 5% for reliable solar energy measurements.

- Pyroelectric crystal

Pyroelectric crystals are another type of thermal sensor that has significant implications for solar energy. These sensors generate an electric charge when exposed to a temperature change, making them useful for detecting changes in solar radiation. Pyroelectric sensors can measure both short-term and long-term changes in solar radiation, making them valuable for monitoring solar energy systems and predicting changes in solar irradiance. Pyroelectric sensors are commonly used in concentrated solar power systems and in solar radiation monitoring equipment.

- Resistance-based thermometers

Resistance-based thermometers, or thermistors, are thermal sensors that can be used to measure temperature changes in solar energy systems. By measuring the temperature of solar cells and other components, thermistors can help monitor the performance of a solar energy system and ensure that it is operating efficiently. These sensors are typically made of ceramic or polymer materials and have a high sensitivity to temperature changes. Thermistors are commonly used in photovoltaic and solar thermal power systems, as well as in solar radiation monitoring equipment[2.4].

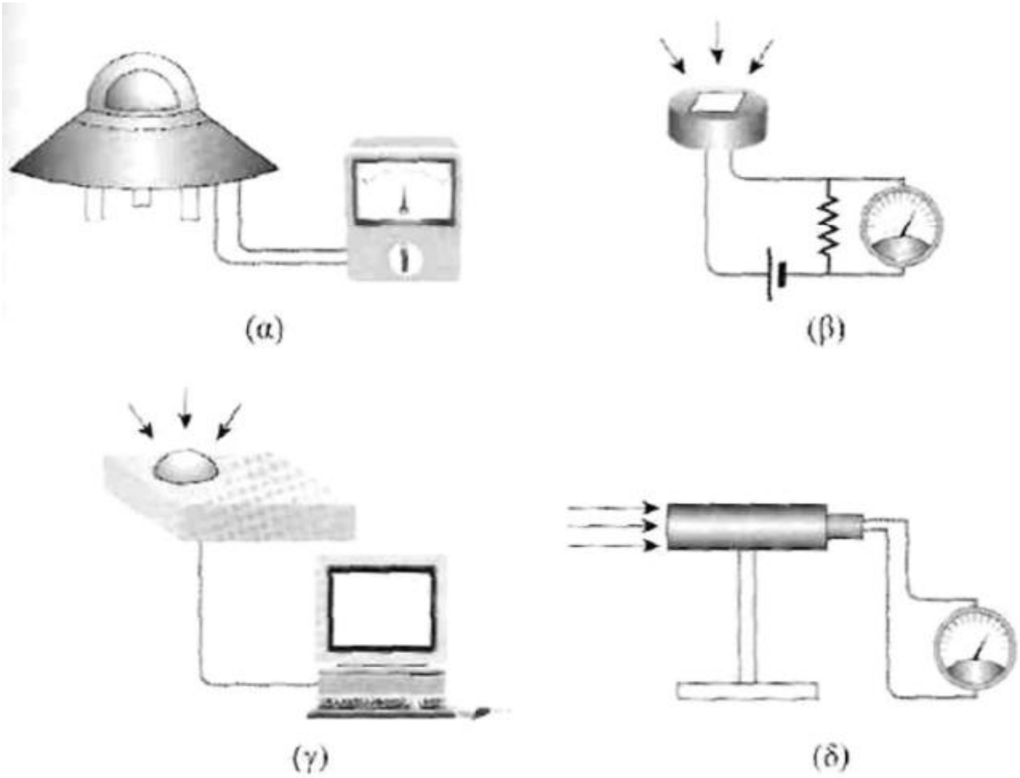

Image 2.2: a) Pyranometer b) Photodiode c) Spectroradiometer d) Pyroelectric Crystal[2.5]

<u>Electronic stimulation sensors</u>

These sensors operate based on either the photoelectric phenomenon, which involves the emission of electrons from the surface of a metal, or the excitation of electrons from the valence band to the conductivity band in the case of semiconductors.

There are different categories of electronic stimulation sensors that are based on different principles of operation. One category of sensors is based on the photoelectric effect, which involves the emission of electrons from the surface of a metal due to the absorption of light.

Photoelectric sensors are commonly used in various applications, including automation, robotics, and industrial control. They can be classified into two main categories: through-beam and reflective. Through-beam sensors consist of a transmitter and a receiver that are placed opposite to each other, and a beam of light is emitted from the transmitter to the receiver. When an object interrupts the beam, the receiver detects the change in light intensity and sends a signal to the control system. Reflective sensors, on the other hand, emit and detect the light from the same device. They are commonly used in proximity and position sensing applications.

Another category of electronic stimulation sensors is based on the photoconductivity of materials. In these sensors, the electrical conductivity of a material is increased when it absorbs light. These sensors are commonly used in applications that require the detection of light intensity or color, such as in cameras, photometers, and colorimeters[2.6].

Photoconductivity sensors can be further classified into two categories: intrinsic and extrinsic. Intrinsic sensors are made of pure semiconductor materials, such as silicon or germanium, and their conductivity increases when they absorb light. Extrinsic sensors, on the other hand, are made of doped semiconductor materials, which means that impurities have been intentionally added to the material to alter its electrical properties. Extrinsic sensors are more sensitive to light than intrinsic sensors and can be used in applications that require high sensitivity[2.7].

In addition to photoconductivity sensors, there are also photovoltaic sensors, which are based on the photovoltaic effect. In these sensors, the absorption of light generates a voltage across a p-n junction, which can be measured and used as a signal. Photovoltaic sensors are commonly used in applications that require the detection of solar radiation or the conversion of light into electricity, such as in solar panels[2.8].

2.4 Solar Energy Potential and Trends in Europe and Greece

The sun is a virtually unlimited source of energy that can be harnessed and used to power our daily lives. Globally, the sun provides an estimated 173,000 terawatts (TW) of energy to the Earth's surface, which is more than 10,000 times the world's total energy use. In Europe, the annual amount of solar energy received ranges from around 800 kilowatt-hours (kWh) per square meter in the north to more than 2,000 kWh per square meter in the south.

In Greece, due to its geographical location, the country receives high levels of solar irradiance, with an annual average of around 1,600 kWh per square meter. This makes Greece one of the best locations in Europe for solar energy generation. As a result, the country has seen a significant increase in the use of solar power over the last few years, with many homes and businesses investing in solar panels to generate their own electricity[2.9].

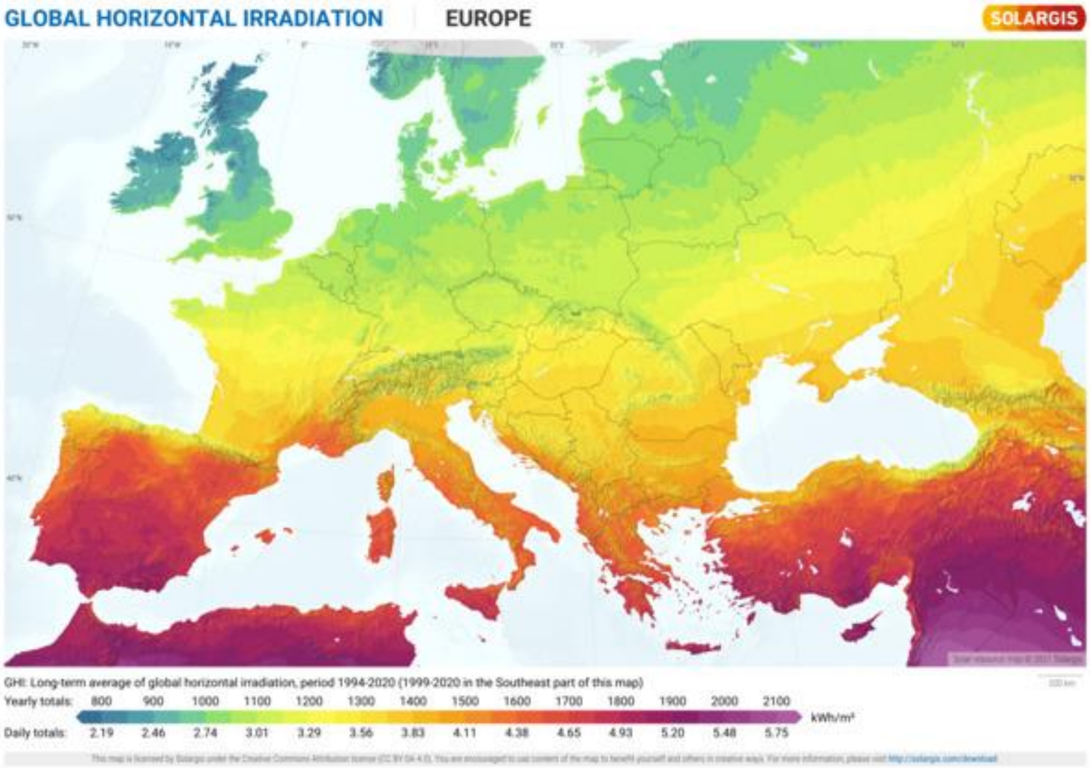

Figure 2.2: Global Horizontal Irradiation (Europe) [2.10]

Figure 2.3:Global Horizontal Irradiation (Greece) [2.10]

Greece has a wide range of geographical locations that are ideal for solar energy production. Some of the best areas for solar energy are the southern and eastern parts of the country, including the islands in the Aegean Sea. These regions have high levels of solar irradiance due to their proximity to the equator and the Mediterranean climate. Specifically, the islands of Crete, Rhodes, and Kos have the highest solar irradiance levels. Furthermore, the mountainous areas of mainland Greece, such as the Peloponnese and Central Greece, also have significant potential for solar energy due to the abundance of clear skies and high altitudes. Additionally, urban areas with flat roofs, such as Athens and Thessaloniki, are also suitable for solar energy production through the installation of solar panels.

2.5 Advantages and disadvantages

Solar energy has been increasingly considered as a promising renewable energy source for sustainable development. There are several advantages and disadvantages of solar energy use that should be taken into account. One of the most significant advantages is that solar energy is a clean and renewable source of energy, which can reduce carbon dioxide emissions and help combat climate change[2.11]. Moreover, solar energy can be harnessed in remote areas where it is difficult or impossible to access grid electricity, making it a particularly suitable source of energy for developing countries. Solar panels also require very little maintenance and can last up to 25 years, making them a cost-effective source of energy in the long run[2.12].

On the other hand, one of the major disadvantages of solar energy is that it is an intermittent source of energy, as it is only available during daylight hours and is affected by weather conditions. This means that energy storage is necessary in order to provide continuous power supply, which can add to the cost of the system. Additionally, the production of solar panels requires a significant amount of energy and resources, which can have negative environmental impacts[2.13].

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3.PHOTOVOLTAIC SYSTEMS (PV)

3.1 Introduction

Photovoltaic (PV) systems convert sunlight into electricity using solar panels made up of photovoltaic cells. These systems have become increasingly popular as a sustainable source of energy for homes, businesses, and communities. Although challenges such as high costs and energy storage remain, the potential benefits of PV systems for reducing greenhouse gas emissions make them an important area of research and development.

3.2 Photovoltaic phenomenon

The photovoltaic phenomenon is a process by which certain materials are able to convert light into electrical energy. This process occurs in a device called a photovoltaic cell, also known as a solar cell, which is the basic building block of a solar panel.

The photovoltaic phenomenon was first discovered in 1839 by French physicist Alexandre-Edmond Becquerel. He observed that certain materials, when exposed to light, generated a small electrical current. This phenomenon was later explained by the photoelectric effect, which is the emission of electrons from a material when it absorbs light.

In a photovoltaic cell, the material used to absorb light and generate electricity is typically silicon, although other materials such as cadmium telluride and copper indium gallium selenide are also used. The silicon is doped with impurities to create a p-n junction, which is a boundary between regions of positive and negative charge.

When light strikes the p-n junction, it causes electrons to be knocked loose from the atoms in the silicon, creating electron-hole pairs. The electric field created by the p-n junction then separates these pairs, with the electrons moving to one side of the junction and the holes moving to the other. This separation creates a potential difference, or voltage, between the two sides of the cell, which can be used to generate an electrical current.

The efficiency of a photovoltaic cell is determined by its ability to convert incoming light into electrical energy. Factors that can affect efficiency include the wavelength and intensity of the light, the material and design of the cell, and the temperature of the cell.

The photovoltaic phenomenon is the basis for solar energy, which is a renewable and sustainable source of electricity. The ability of photovoltaic cells to convert sunlight into electricity without moving parts or emissions makes solar power an attractive option for meeting the growing demand for clean energy[3.1].

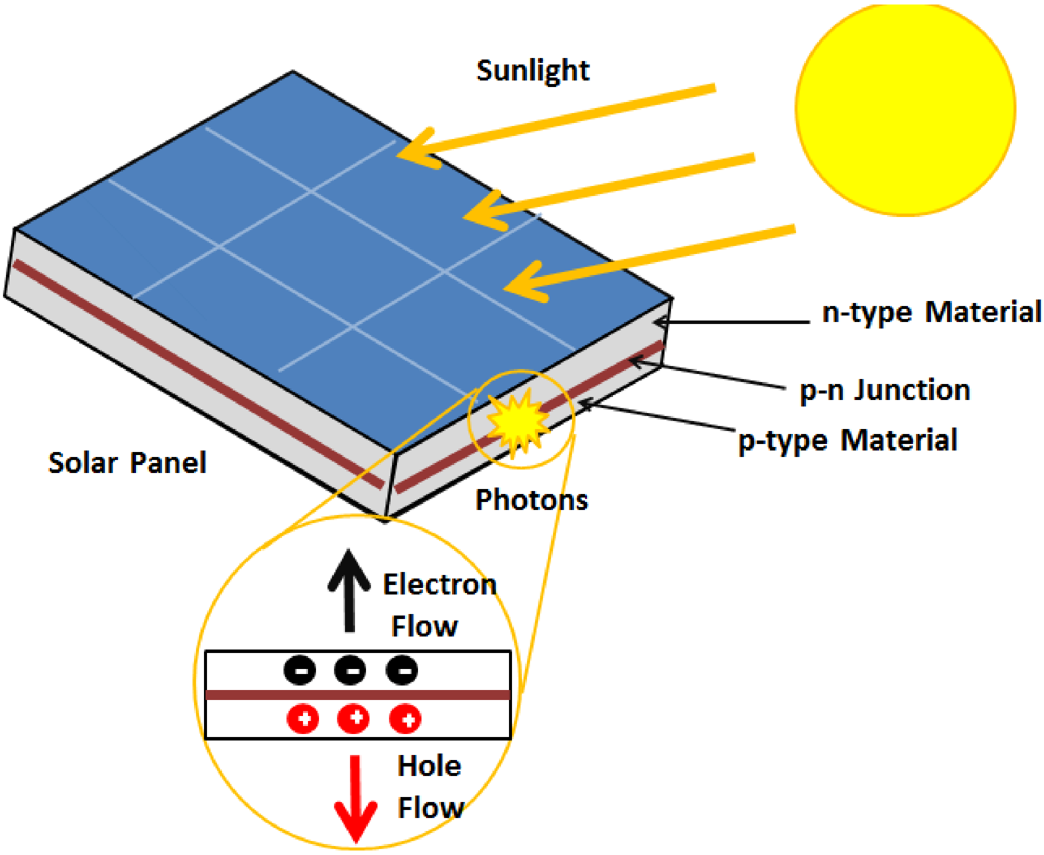

Image3.1: Photovoltaic phenomenon[3.1]

3.3 Photovoltaic Cell Technologies

Photovoltaic cells are the heart of any PV system, and their design and materials play a crucial role in determining the system's efficiency and performance. There are several types of photovoltaic cells available on the market, each with its unique set of advantages and disadvantages.

- Monocrystalline cells are made from a single crystal of silicon, which is grown from a high-purity silicon seed. The cells have a uniform structure and a higher efficiency rate than other types of cells, typically ranging from 15% to 22% [3.2]. However, the manufacturing process of monocrystalline cells is complex and time-consuming, making them more expensive to produce.

- Polycrystalline cells, on the other hand, are made from multiple smaller crystals of silicon, which are melted together to form a solid block. The cells have a lower efficiency rate than monocrystalline cells, typically ranging from 13% to 18% [3.3].

However, the manufacturing process of polycrystalline cells is simpler and less expensive, making them more cost-effective for larger-scale installations.

- Thin-film cells are made from a thin layer of semiconductor material, typically silicon, cadmium telluride, or copper indium gallium selenide. The cells have a lower efficiency rate than crystalline cells, typically ranging from 7% to 13% [3.4]. However, they are lightweight, flexible, and can be produced using less material, making them ideal for applications where weight and flexibility are important.

- Tandem cells, also known as multi-junction cells, are a newer type of photovoltaic cell that combines two or more layers of different semiconductor materials to increase efficiency. Tandem cells can achieve efficiency rates of up to 40% . However, they are still relatively expensive to produce and are mainly used in specialized applications such as space exploration.

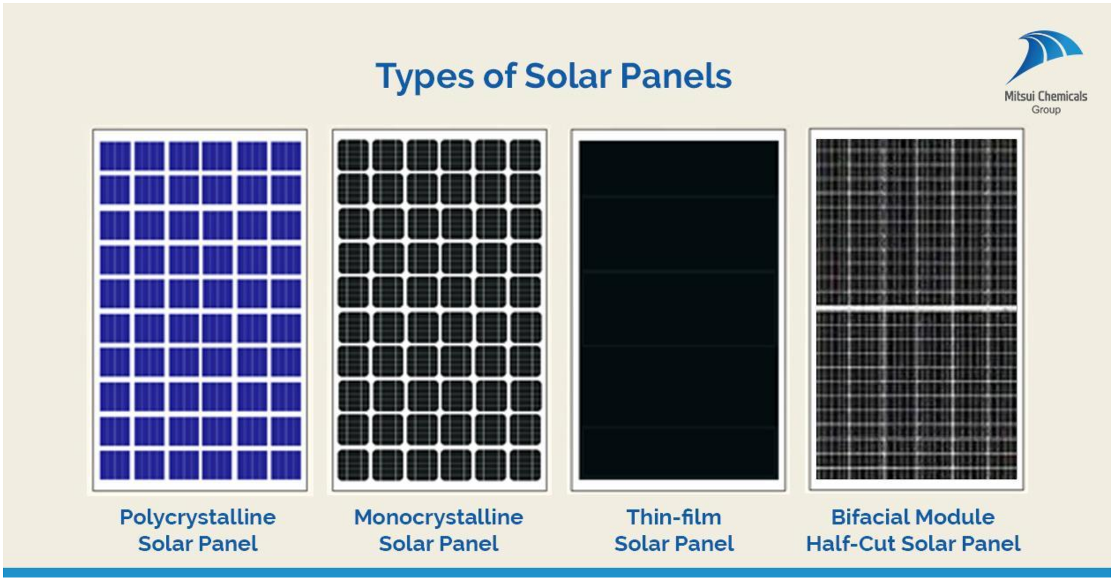

Image3.2: Types of solar panels [3.6]

In recent years, there has been a growing interest in alternative materials for photovoltaic cells, including organic and perovskite materials. Organic solar cells are made from organic polymers and have the potential for low-cost and flexible production, but their efficiency rates are currently much lower than crystalline cells, typically ranging from 5% to 10% . Perovskite solar cells, on the other hand, have achieved impressive efficiency rates of up to 25% in the laboratory, but their long-term stability and durability remain a concern [3.5].

The choice of photovoltaic cell technology depends on a variety of factors, including efficiency, cost, durability, and flexibility. While crystalline cells remain the dominant technology in the market, the development of alternative materials such as organic and perovskite cells may provide new opportunities for the future of photovoltaics.

3.4 Basic equipment for the installation and operation of PV systems

A PV system is composed of several components that work together to convert solar energy into electrical energy. The main components of a typical PV system include PV modules, inverters, batteries, charge controllers, and monitoring systems.

PV modules are the primary components of a PV system, and they are responsible for converting sunlight into electrical energy.

An inverter is an electronic device that converts the direct current (DC) produced by solar panels into alternating current (AC) that is compatible with the power grid. As a result, a solar inverter, or photovoltaic inverter, converts the DC output of a PV panel into AC frequency that can power the grid or an isolated load. Inverters can be small (string inverters) or centralized, depending on the system's requirements. They operate autonomously and their efficiency depends on the load, providing a maximum efficiency of approximately 95.6%.

The various categories of inverters are as follows:

- Inverters for autonomous systems, which are used in isolated systems where the inverter draws energy from batteries that are charged by photovoltaics.
- Inverters for connection to the public grid, which match their output frequency with that of the grid.
- Backup battery inverters, which are specialized converters designed to transfer energy from a battery, manage the battery charge through an integrated charger, and inject excess energy into the grid.
- In terms of their input source, they are categorized as:
    - Voltage source inverters (there is a DC voltage source on the DC side of the inverter)
    - Current source inverters (there is a DC current source on the DC side of the inverter)

Finally, they have the following network parameters:

- Alternating current voltage range: +15% to -20% of nominal voltage (230V)
- Alternating current frequency range: ±0.5% Hz of nominal frequency (50Hz)
- Current distortion factor: < 4%
- DC-Current Injection: < 0.5% of nominal current.

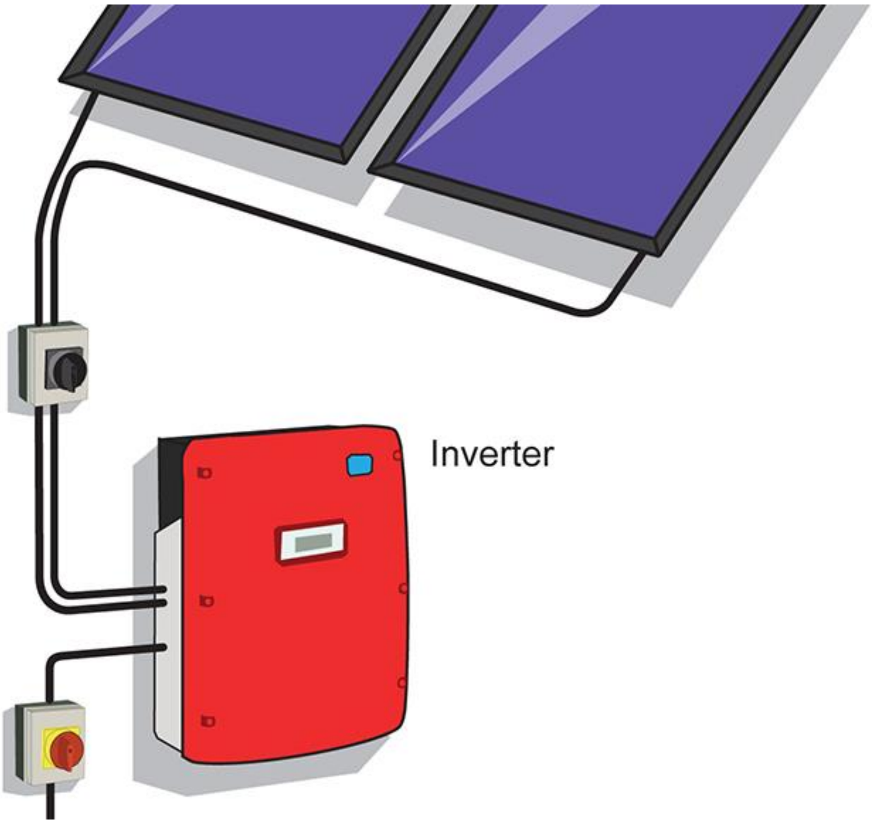

Image 3.3: PV inverter[3.7]

Charge Controller is a device used in autonomous systems to regulate the charging of accumulators.

Image 3.4: charge controller [3.8]

Diode: The diode is placed in the series connection of the three in parallel connected frames in order to avoid current reversal phenomena.

Image3.5: Diode[3.9]

Control System: The connection boxes are connected by optical fiber to the central one ENERGRID system, which is hosted in the control center. The data which are transferred are power, intensity, voltage and frequency.

Image3.6: Control system[3.10]

Circuit breakers: A medium voltage field is used, in which it is contained an SF6 gas circuit breaker, which has the ability to protects the system from overvoltage, undervoltage, overvoltage and undervoltage as well as any frequency anomaly.

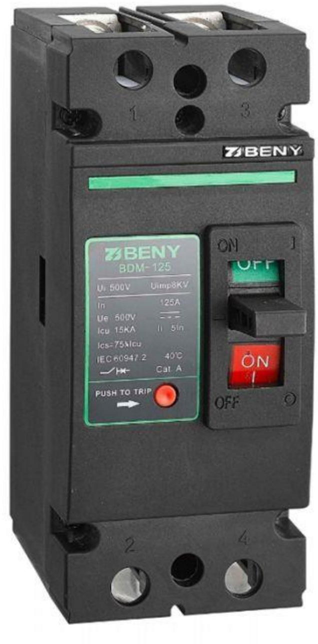

Image3.7: circuit brakers[3.11]

Meters: Suitable medium voltage fields are used, which contain current and voltage transformers properly connected. The readings of the above transformers constitute the measurements and are recorded in one ENERGRID system. ENERGRID DATA allows the measurement of all energy flows from the solar photovoltaic generator. His role is also important in supervision, through the remote notification system (inverter alerts and performance alerts). With the practical design, ENERGRID DATA provides access to all information from the portable digital LCD screen, from any PC.

Image3.8: Meters for P/V [3.12]

Cables - connections: The cables that go inside the P/V are against mainly low voltage cables, suitable for underground routing. The cross-sections they differ according to the intensity of the current through which they flow.

Image3.9: Cables for P/V [3.13]

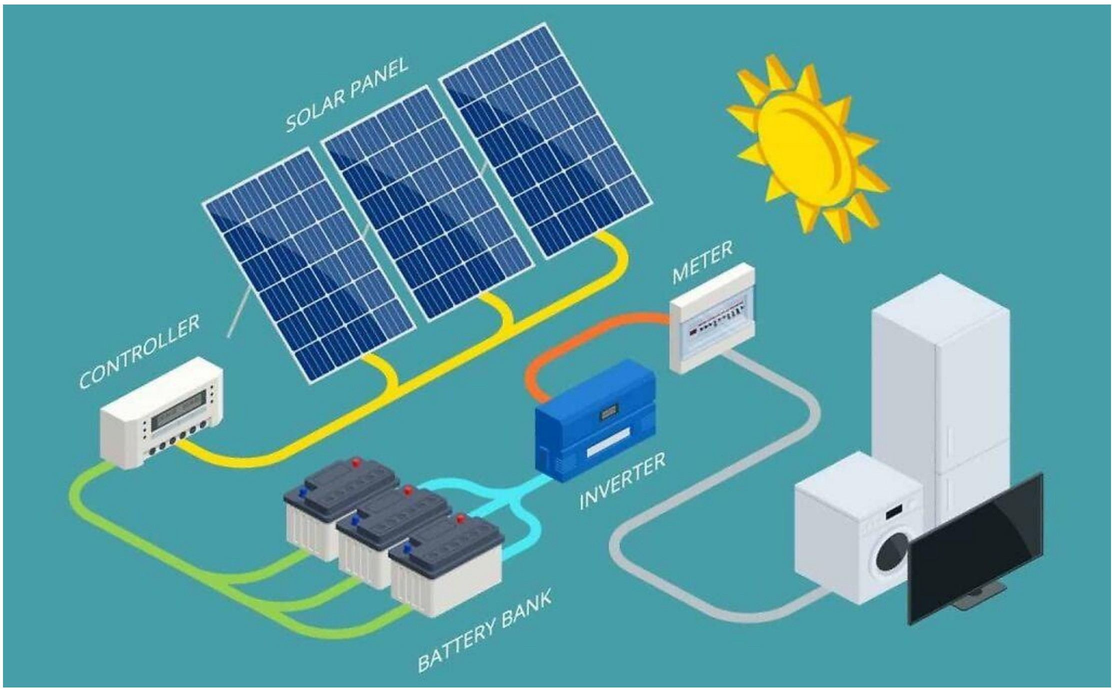

Image3.10: The individual components of a PV system [3.14]

3.5 Performance and Efficiency

PV Efficiency Rating:

The efficiency rating of a photovoltaic (PV) module is an important metric that measures the amount of electricity produced by the module compared to the amount of sunlight it receives. The efficiency rating is expressed as a percentage, and typically ranges from around 15% to 25% for commercial PV modules. Higher efficiency modules are generally more expensive, but can be worth the investment in certain applications where space is limited or where maximum energy output is required [3.16].

The efficiency rating is given by the equation:

η = Qgen / Qsolar (3.1)

Where:

Qgen: the energy produced by the PV system in (kWh)

Qsolar: the solar energy collected by the PV system in (kWh)

The solar energy is given by the equation:

Qsolar= $A*$ Rad (3.2)

Where:

A: the surface area of the collector in (m^2)

Rad: the solar radiation in (kWh)

The typical performance rating of a photovoltaic system remains relatively low compared to other types of systems, such as conventional, wind, hydroelectric, etc. This means that a large surface area is required for the photovoltaic system to generate the desired electrical power. However, the performance of a given system can be significantly improved by placing the photovoltaic panels on a sun tracker [3.17].

Tilt of the PV Panels:

Solar photovoltaic (PV) panels are widely used to convert sunlight into electricity. The efficiency of these panels depends on several factors, including the tilt angle of the panels. The tilt angle is the angle between the horizontal plane and the surface of the panel.

The optimum tilt angle for a solar panel varies depending on the location and time of year. The general rule is to set the tilt angle equal to the latitude of the location, with a small adjustment for seasonal changes. This is because the angle of the sun changes throughout the day and year, and setting the panel to the latitude angle ensures that it captures the most sunlight during the year.

In addition to latitude, the orientation of the panels also affects their performance. In the northern hemisphere, panels facing south will receive the most sunlight. In the southern hemisphere, panels facing north are ideal. East-facing panels will receive the most sunlight in the morning, while west-facing panels will receive the most sunlight in the afternoon.

The tilt angle can be adjusted for different seasons by changing the angle of the panel a few times a year. In the winter, the panel should be tilted at a steeper angle to capture more sunlight, while in the summer, the panel should be tilted at a shallower angle to avoid overheating.

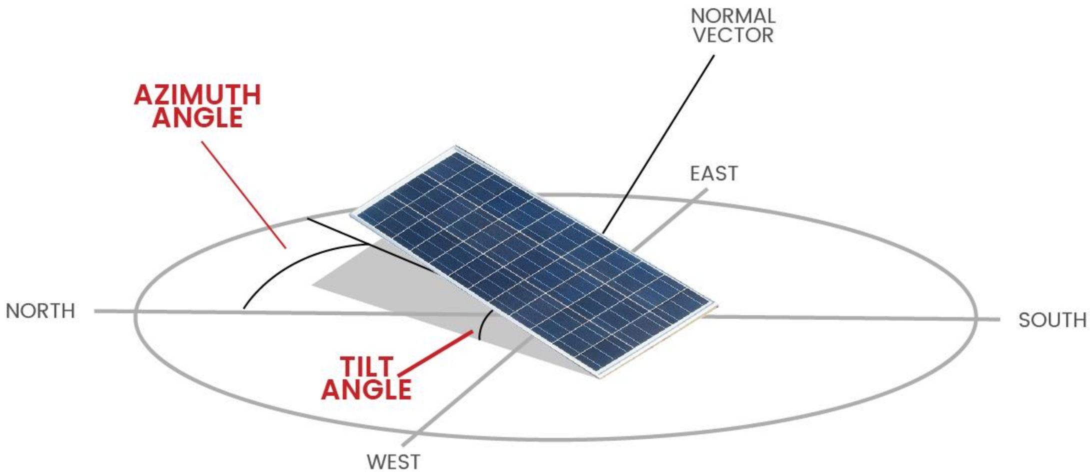

Image 3.11: Tilt angle of P/V [3.18]

Calculation of optimum tilt angle using solar altitude and azimuth angles:

$$cos(\theta opt) = cos(\varphi)cos(\alpha)cos(\beta) + sin(\varphi)sin(\alpha) \quad (3.3)$$

where:

θopt = Optimum tilt angle in degrees

ϕ = Latitude of the location in degrees

α = Solar altitude angle in degrees, which is the altitude of the sun above the horizon

β = Solar azimuth angle in degrees, which is the angle between the sun and the south direction

Calculation of energy output of a PV panel:

$$E = \eta * A * I * t \tag{3.4}$$

where:

E = Energy output in watt-hours (Wh)

η = Efficiency of the PV panel

A = Area of the PV panel in square meters (m^2)

I = Solar irradiance in watts per square meter (W/m^2)

t = Time in hours

<u>Maintenance of PV Systems</u>:

One of the most important maintenance tasks is cleaning the PV panels. Dust, debris, bird droppings, and other pollutants can accumulate on the surface of the panels and reduce their output. It is recommended to clean the panels at least twice a year, or more frequently in areas with heavy pollution or dust.

In addition to cleaning, regular inspections should be conducted to identify any defects or damage to the PV system. This includes checking the wiring, connections, and inverters for any signs of wear or damage. Any issues should be addressed promptly to prevent further damage or safety hazards.

Another important aspect of PV maintenance is monitoring the performance of the system. This involves keeping track of the power output and comparing it to the expected output based on the system specifications. Any significant drop in power output should be investigated to identify and address the cause.

Proper maintenance of batteries, if the PV system includes them, is also essential. Batteries should be inspected regularly for damage and tested to ensure they are functioning properly. It Is recommended to replace batteries every 5-7 years [3.19].

Image3.12: P/V system maintenance [3.20]

Autonomous PV Systems

Autonomous PV systems, also known as off-grid PV systems, are designed to provide electrical power to remote or isolated locations that are not connected to the utility grid. These systems typically include a PV array, a charge controller, batteries, and an inverter, which convert the DC power generated by the PV array into AC power for use by electrical appliances and equipment.

The design and sizing of autonomous PV systems are critical factors that determine their reliability and effectiveness. The system must be designed to meet the electrical demands of the load while ensuring that the batteries are not overcharged or discharged. The sizing of the PV array, charge controller, and batteries must be optimized to balance the system's energy generation and storage capacity.

Autonomous PV systems are commonly used in applications such as remote homes, cabins, telecommunications, and water pumping. These systems offer several advantages over grid-connected PV systems, including independence from the utility grid, no monthly electricity bills, and reduced environmental impact. However, they also have some limitations, such as higher initial costs, limited electrical capacity, and the need for regular maintenance[3.21].

Energy storage is a critical component of autonomous PV systems, as it allows for the storage of excess energy generated by the PV array during periods of low demand for use during periods of high demand. Energy storage systems typically include batteries, which store the excess energy in the form of chemical energy and release it as electrical energy when needed.

Energy storage batteries

The batteries used in photovoltaic systems belong to category of rechargeable batteries. Typical batteries are:

- Lead-Acid Batteries: These are the most common type of batteries used in PV systems due to their low cost and availability. They are available in two types: flooded and sealed, with flooded lead-acid batteries requiring more maintenance but offering longer lifetimes.

- Lithium-Ion Batteries: These batteries have a higher energy density than lead-acid batteries, which allows for smaller and lighter battery packs. They are also less prone to self-discharge and have longer lifetimes.

- Flow Batteries: These batteries store energy in two separate tanks of electrolyte, which allows for more flexibility in the amount of energy stored. They have longer lifetimes and can be charged and discharged simultaneously[3.22].

- Nickel-Cadmium Batteries: These batteries have a long life and are able to operate in extreme temperatures. However, they have a lower energy density than lithium-ion batteries and are less commonly used in PV systems[3.23].

Type of battery	Merits	Demerits
Flooded Lead-Acid battery (LSI type)	• Widely available • Low cost • Good for automotive use	• Shallow cycle • Heavy weight • Very poor cycle life • Contains toxic element
Flooded Lead-Acid battery (Modified LSI type)	• Deep cycle • Good for use in solar PV system and electric traction vehicles	• Heavy weight • Poor cycle life • Costlier • Contains toxic element
Flooded Lead-Acid battery (Tubular plate type)	• Improve deep cycle • Better for use in solar PV system and electric traction vehicles	• Heavy weight • More costlier • Contains toxic element
Nickel Cadmium battery	• Long cycle life • Deep cycles • Withstand harsh environment	• Expensive • Memory effect • Contains toxic element
Nickle Metal Hydride battery	• Prolonged cycle life • Deep cycles • Better performance in cold climate • Light weight • Lower operating cost • Non-toxic • No memory effect	• Up-front cost very high

Image 3.13: Types of batteries[3.24]

A proper battery selection should try to come up to the following demands:

- Adequate energy storage capacity to meet the daily energy demand of the system
- High round-trip efficiency to minimize energy losses during charging and discharging
- Long cycle life to ensure a reasonable lifespan of the battery system
- Reliable and safe operation with low maintenance requirements
- Small voltage gap between charging and discharging (allows direct connection of loads to the battery)
- Low explosive potential
- Easy voltage and capacity scalability through series and parallel connections
- Cost-effectiveness and compatibility with the overall PV system design and electrical capacity
- Environmental sustainability with low carbon footprint and proper end-of-life disposal or recycling[3.25]

The term "cycle" describes the repeated process of discharging and charging that occurs in a battery while in use. One cycle consists of a discharge followed by a charge. The battery's cycle life is a useful measure that informs us of the number of cycles a battery can deliver during its useful life. Typically, this corresponds to the number of discharge cycles for a specific DOD that the battery can achieve before its available capacity drops to a certain percentage (about 80%) of its initial capacity. The efficiency of ampere-hours (Ah) is defined as the ratio of the Ah discharged from the battery to the Ah charged into the battery during a specific period of time (typical periods are one month or one year or the period between two full charge cycles)[3.26].

Net metering

Net-metering is a tool that promotes self-generation and self-consumption of renewable energy sources, mainly for photovoltaic installations, and is implemented in various countries. It allows consumers to cover a significant portion of their self-consumption while using the grid for indirect storage of excess energy. The term "net" refers to the difference between consumed and generated energy during a specific period, usually the billing cycle for consumed energy (one year in Greece). If there is excess energy, it is usually credited to the consumer's account for a certain period (usually one year, but sometimes 36-48 months) before the final settlement is made[3.27].

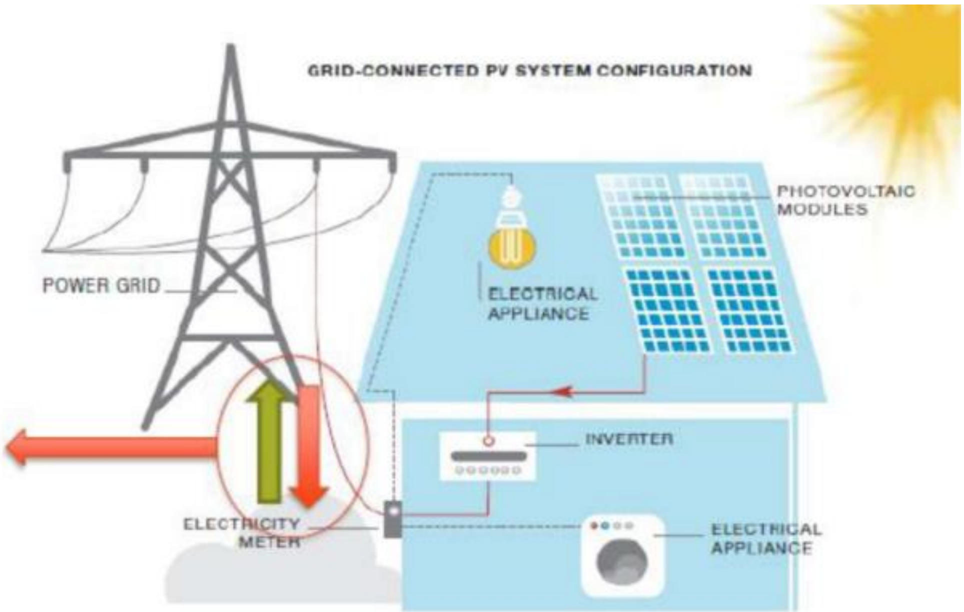

Image 3.14: The configuration of a grid-connected PV system operating under the net-metering scheme[3.28]

3.6 PV system advantages and disadvantages for assisting a heat pump in Greece.

A photovoltaic (PV) system can be a great way to power a heat pump in Greece, as it has a good solar resource and the climate is favorable for solar energy production. Some of the energy capabilities of a PV system assisting a heat pump in Greece:

Advantages:

- PV systems use sunlight to produce electricity, which is a renewable energy source. This means that it does not generate greenhouse gas emissions during operation, which is good for the environment.
- By using a PV system to power a heat pump, homeowners can become less dependent on the electric grid, which can be unreliable at times. This can provide greater energy security and reduce the risk of power outages.
- Using a PV system to power a heat pump can save homeowners money on their electricity bills. This is because the cost of producing electricity from solar energy is lower than the cost of electricity from the grid, especially during peak demand times.
- PV systems are designed to last for many years with little maintenance, making them a good long-term investment.

Disadvantages:

- The initial cost of installing a PV system can be high, which can deter some homeowners from investing in this technology.
- The amount of energy produced by a PV system depends on the amount of sunlight available, which can vary throughout the day and across seasons. This can make it difficult to predict how much energy will be available at any given time.
- PV systems typically do not have built-in storage, which means that excess energy produced during the day must be fed back into the grid or used immediately. This can limit the ability to use PV energy during times when the sun is not shining, such as at night[3.29].

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4. HEAT PUMPS

4.1 Introduction and basic components of Heat Pumps

Heat pumps (HPs) are machines that produce heating and cooling by consuming electrical energy and operate according to the so-called reverse thermodynamic cycle. During the cycle, the refrigerant of the pump absorbs heat from a low-temperature source (cold source). Then, the compressor increases its temperature, and the fluid releases its heat to the space. The most common cold sources are external air and water , while in recent years, the use of soil and solar energy is increasing. The heat is provided in the form of warm air or warm water [4.1].

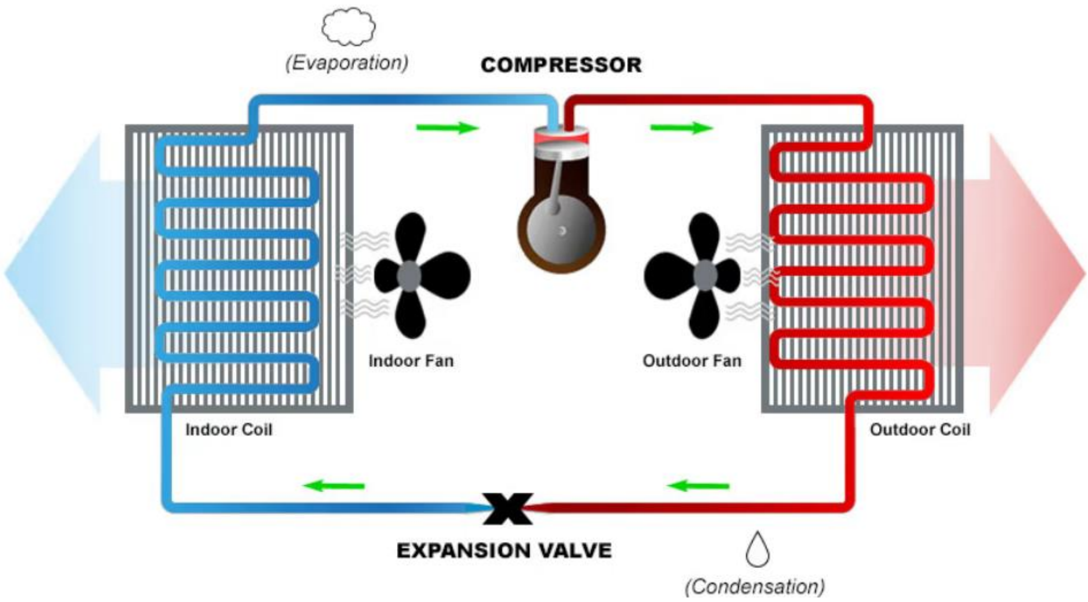

Image 4.1: Typical Heat Pump [4.2]

<u>Basic components of HPs</u>:

• The compressor, which provides the energy needed for cooling or heating,

• The condenser that releases heat from the working fluid

• The evaporator that absorbs heat

• Pressure-lowering devices (expansion valves)

• A 4-way valve, that switches the HP mode from cooling to heating and reversely.

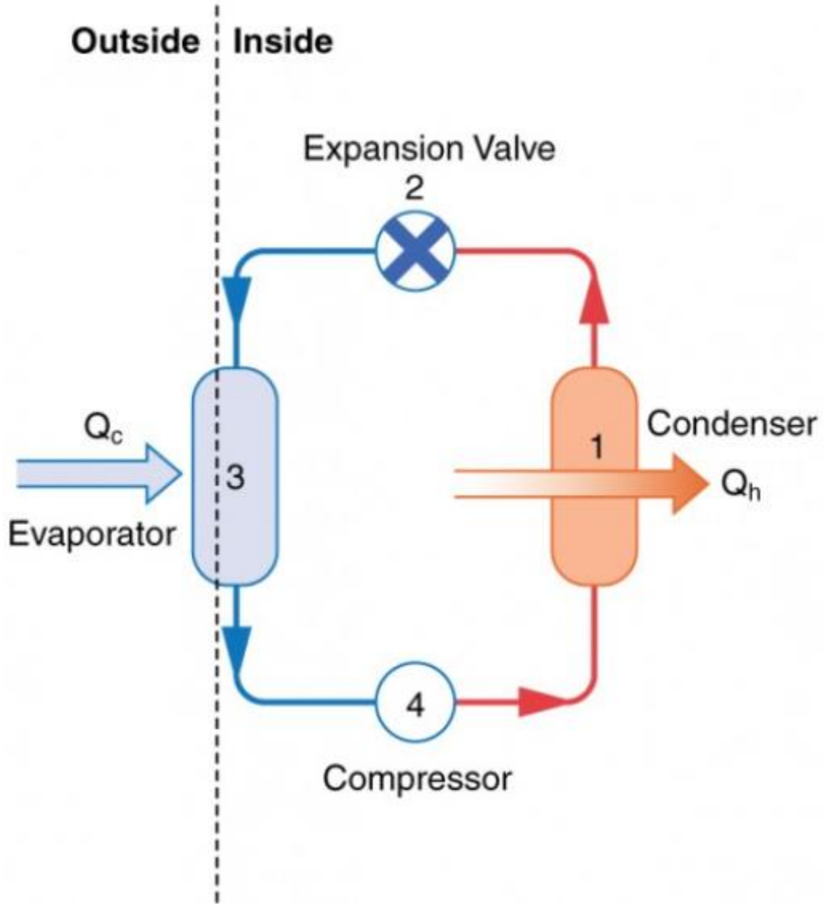

Image 4.2: Components of HPs[4.3]

The process for cooling by a Heat pump is as follows:

Cooling mode

1. The working fluid enters the evaporator through an expansion valve. The valve lowers the pressure of the working fluid, which being in ambient temperature and atmospheric pressure, evaporates, absorbing heat from the area that has cooling demands.
2. Exiting the evaporator the working fluid has become a low temperature and pressure gas. It then enters the compressor. With compression pressure and temperature rise significantly.
3. The compressed hot working fluid reaches the condenser where, by transferring heat to the surrounding environment, it cools. At this stage the compressed gas gets liquefied.
4. In the end the working fluid reaches the expansion valve which restores the pressure back to atmospheric level, so that it gets evaporated again in the next stage.

After that the cycle is repeated continuously.

Heating mode

The same stages are followed in heating mode by the working fluid, but in this case the evaporator acts as a condenser transferring heat to the designated area, while the condenser acts like an evaporator that absorbs heat from the heat source. The switch is possible thanks to a 4-way valve that reverses the flow of the working fluid.

The process is described below:

1. The working fluid exits the compressor in high temperature, pressure and flows through the condenser, where it gets cool by releasing heat to the heating location.
2. Coming from the condenser the working fluid, in dual phase and high pressure, enters the expansion valve to reduce its pressure.
3. Now as low pressure and temperature liquid it flows through the evaporator, where heat from the heat source is absorbed
4. Finally it exits in low pressure gas form and heads to the compressor to repeat the cycle again.

In thermodynamic terms the process is described below:

- 1_2: isentropic compression in the compressor, which leads to increased pressure and temperature
- 2_2’: isobar cooling in the condenser
- 2’_3: isotherm-isobar condensation in the condenser
- 3_3’: isobar subcooling in the subcooler
- 3’_4: isenthalpic lamination in expansion valve
- 4_1: isothermisobar evaporation in the evaporator[4.4]

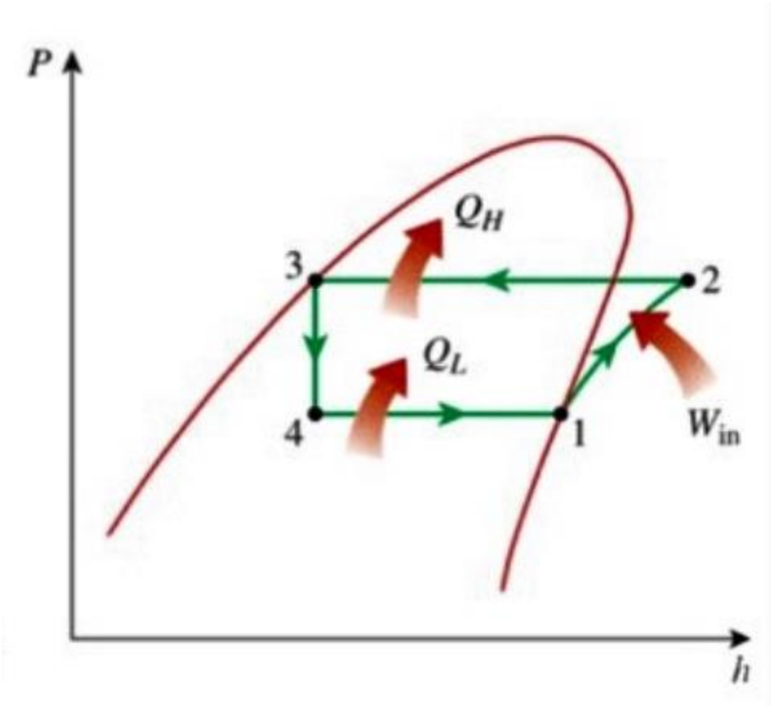

Image 4.3: P-h diagram [4.1]

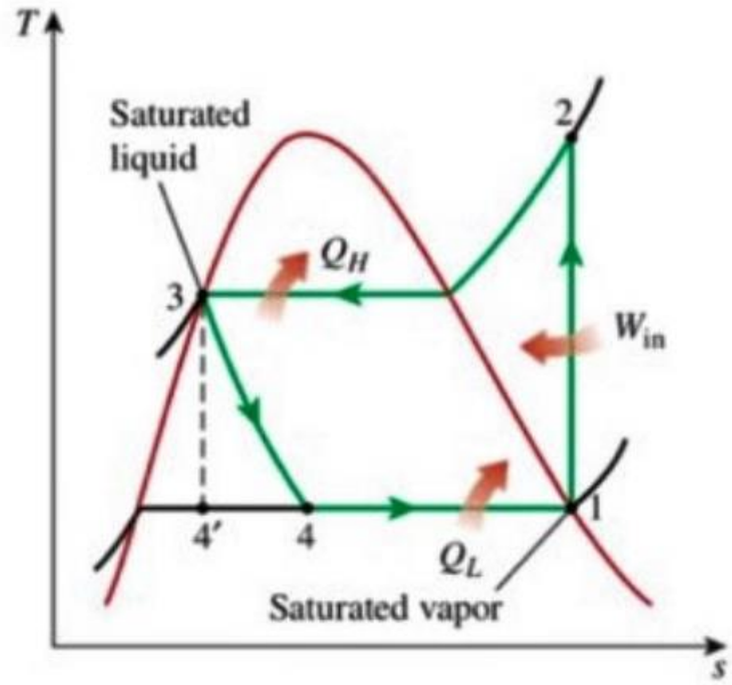

Image 4.4:T-S diagram[4.1]

The ideal heat pump

The operation of the heat pump is based on the principle of the reversible thermal machine of Carnot when it operates in reverse . Reversible machines are used as standard machines to evaluate the performance of real machines. The Carnot reverse machine can operate either as a heat pump or as a refrigeration machine. In the heating mode, the heat pump pumps a quantity of heat Q1 from the cold environment, mechanical work W is added to the compressor, and a quantity of heat Q2 is delivered to the space.

When the heat pump operates in heating mode, the space is the hot area, the environment is the cold, and the desired quantity is Q2. In cooling mode it is the opposite. The performance of the heat pump is characterized by the coefficient of performance COP (= T2 / (T2-T1)). The coefficient depends only on the temperatures T1, T2 of the thermal energy tanks and is always greater than one.

For the same temperature difference T2-T1, the COP improves as the temperature T2 is higher. Also, the smaller the temperature difference T2-T1 between the cooled and the external space, the higher the COP. These observations are particularly important for Greece due to the special climatic conditions:

- Mild winter weather with relatively high outdoor temperatures.
- Ability to use solar energy as auxiliary for the heat pump during the winter season.
- Possibility (in special cases) to use geothermal energy as auxiliary for the heat pump.

An air source heat pump with a COP of 4 transfers 4kW of energy while consuming 1kW of electricity, or in other words, energy transfer costs 25% with this specific pump. The COP depends on the cold and warm room temperatures and is not constant. The coefficients provided by the manufacturer's brochures are performance coefficients measured at specific temperatures, standardized according to the Eurovent standard. These temperatures are for heating (dry bulb temperature): indoor temperature of 20°C and outdoor air inlet temperature of 7°C.

When the heat pump operates as a cooling machine to meet cooling needs, the desired result is the amount of heat Q1. The performance of a heat pump when operating as a cooling machine is characterized by the coefficient of performance $\beta_{A/\Theta}$ (=1/((Q2/Q1)-1) or Energy Efficiency Ratio (EER)[4.4]

4.2 Heat pump categories

Depending on the medium from which the heat is extracted and the medium where the heat is rejected, we have the following categories:

- Air-to-Air (A-A) heat pumps: As the name suggests, these types of heat pumps extract heat from the outdoor air and transfer it inside your home or building through the use of ducts or air handlers. They are typically used for space heating and cooling and are most efficient in moderate climates.Air-to-air heat pumps are one of the most common types of heat pumps used in residential applications.

- Air-to-Water (A-W) heat pumps: Similar to air-to-air heat pumps, these systems extract heat from the outdoor air but transfer it to a water-based system such as a hydronic radiant floor heating system or a hot water tank. A-W heat pumps can be used for both space heating and domestic hot water production. They are most efficient in moderate climates where the outdoor air temperature does not drop too low.

- Water-to-Water (W-W) heat pumps: These systems transfer heat from a water source such as a well, lake, or river to a water-based heating system such as a radiant floor heating system or a hot water tank. W-W heat pumps are commonly used in geothermal heating and cooling systems and are highly efficient. They are one of the most efficient types of heat pumps available.

- Water-to-Air (W-A) heat pumps: These types of heat pumps transfer heat from a water source such as a well, lake, or river to a forced-air heating and cooling system. They are typically used for space heating and cooling and are most efficient in moderate climates. W-A heat pumps are less common than A-A heat pumps, but they can be more efficient.

- Ground-to-Air (G-A) heat pumps: These systems extract heat from the ground and transfer it to the air inside your home or building. They are typically used for space heating and cooling and are highly efficient. G-A heat pumps are most efficient in climates with a moderate heating and cooling load.

- Ground-to-Water (G-W) heat pumps: Similar to W-W heat pumps, G-W heat pumps extract heat from the ground and transfer it to a water-based heating system such as a radiant floor heating system or a hot water tank. G-W heat pumps are commonly used in geothermal heating and cooling systems and are highly efficient. they are one of the most efficient types of heat pumps available[4.5].

4.3 Heat Sources

There are several sources for extracting heat, such as air, water, ground, and solar energy.

Air

External air is a medium that is widely used as a cold source for heat pumps worldwide. Heat exchangers (thermal exchange units) with large surfaces and forced airflow (artificial current) are used to transfer heat between air and refrigerant. Generally, in air-to-air units, these surfaces are about 50-100% larger than those of the indoor unit. The flow of external air passing through the unit is usually larger than that of indoor air by approximately the same percentage.

The temperature difference between the external air and the refrigerant that vaporizes inside the unit during heating operation usually ranges from -12°C to -4°C. When selecting a heat pump that uses external air as a cold source, two factors should be considered: local temperature variation and the formation of frost on the unit. The heating power of the heat pump decreases as the external temperature drops.

During heating ,the choice of device for a given study temperature is more critical than in a central heating system. Therefore, the dimensions for a balancing point of the device must be given, which in practice is as low as possible for heating, so as not to end up with a cooling power greater than the design point of the study[4.4].

The advantage of this source is that it is abundant in nature. However, it presents a problem when the outside temperature is very low in winter and the pump cannot extract heat from the air. In this case, a backup conventional system is used to cover peak loads. The backup system can be an oil or gas boiler, night or day electric power, etc.

The main issue is the freezing of the vaporizer when the temperature of the external air drops below 0-2^{O}C, which causes the moisture in the atmospheric air to solidify. As more ice forms, the air flow passing through the vaporizer decreases. Initially, the problem was solved by using electrical resistances to melt the ice, but now the most well-known method is to reverse the refrigeration cycle (or bypass the hot gas towards the vaporizer through a special bypass conduit). This way, when defrosting is required, the four-way valve is activated and the refrigeration cycle is put into operation, so that the hot gas is directed to the vaporizer and melts the ice (defrosting system). During defrosting, the external fan stops providing cold air, resulting in the compressor handling only the ice loads[4.6].

Water

Water is an optimal source of cold, but it is limited in its use due to availability issues. Groundwater, which has a stable and high temperature, is becoming increasingly scarce and its use is restricted. Wells can provide sufficient water availability, but the quality of the water may cause corrosion in heat exchangers or encourage the formation of salt. Additionally, there are expenses associated with drilling, installing pipelines, pumping, and disposing of used water. Lake or river water can be used, but the temperature difference between the inlet and outlet must be minimal to avoid freezing in cold weather. In some industrial settings, water from washing machines or concentrators can be used as a thermal source. Private well water is often preferred over water from public networks due to cost, but there are operating costs for maintaining the pumps and disposing of waste water[4.4].

Ground

Ground is rarely used as a cold source with heat exchangers buried within it (known as ground loops), due to the high installation costs, the need for surface disposal, and uncertainty about performance predictions. The composition of the soil is variable, ranging from wet clay to sand, which greatly influences its thermal properties and therefore overall performance. The average soil temperatures generally follow the mean annual temperature of the climate. Ground loops in the soil generally reach the average annual outdoor temperature. Typically, the ground loops in the soil are horizontally spaced 1-2 meters apart and buried at a depth of 1-2 meters.

This source highlights two main issues related to the use of geothermal energy. The first is the maintenance of the system, as corrosion and leaks can be a problem. The second issue is the need for a large area to receive and dispose of the heat in the ground. Researchers have found ways to take advantage of the high thermal capacity of the soil and underground space, which can act as a natural storage space for thermal energy. This can lead to significant improvements in the performance of heat pump systems.

With the increasing need to reduce energy consumption, environmental pollution, and the development of technology to address system corrosion and size limitations, methods for exploiting underground energy are being applied worldwide for building heating and underground space. Today, with the development of plastic technology, the problem of corrosion has been solved, making the earth an important solution for the use of geothermal energy.

Solar Energy

The use of solar energy as a heat source is of great interest. Its main advantage as a thermal source is that it can provide heat at a higher temperature than other natural sources. Research and development of solar thermal pumps have led to two basic systems: direct and indirect. In the direct system, the tubes of the evaporator are integrated into a usually flat solar collector. It was discovered that when the collector does not have a glass cover, the same surface can be used to remove heat from the outside air. The same surface can also be used as a condenser, using outside air for the disposal of heat removed during the cooling cycle. The indirect type system uses an intermediate fluid, water or air, which circulates inside the solar collector up to the heat exchanger with the refrigerant. In all heat pump systems in which solar energy is the only cold source, during seasons with insufficient radiation, an alternative heating system or heat accumulation is required.

4.4 Performance of a HP

In normal operation, water-water heat pumps provide performance stability that depends on the stability of the cold source temperature. If water is obtained from a well or borehole, the thermal power production remains almost constant even under significant changes in external conditions. The characteristic COP curve for heating under various conditions is shown in the figure [4.8].

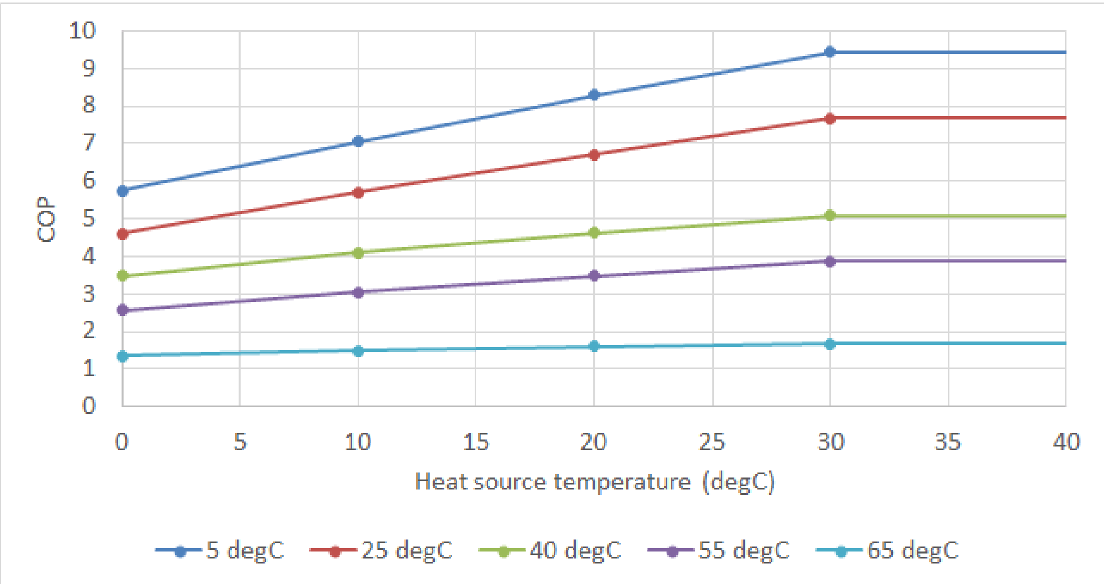

Figure 4.1: COP of the water-to-water heat pump in different load conditions[4.7].

Usually, there is a temperature difference of 5^{0}C in the cold water that feeds the heat pump and the hot water that is produced. The performance of air-to-water heat pumps is directly affected by changes in the dry bulb temperature of the external air. The thermal power generated (and cooling in the summer) is variable during the day and depends on the season of operation for this reason.

Generally, the trend of thermal power production is opposite to that of demand. At lower external temperatures, when the demand for heating is higher, the device produces insufficient thermal power, lower than the design value. When selecting the machine, this characteristic behavior cannot be overlooked. Selection based on the winter thermal load of the study may be uneconomical, in terms of investment costs as well as operating costs due to excessive energy consumption, as an oversized device would result compared to the usual demand.

Therefore, the heat pump would be forced to operate under uneconomical regulation conditions. Hence, it may be justified to create an auxiliary heating system, leaving the heat pump in higher-demand situations.

In modern and well-insulated office buildings located in commercial centers and other tertiary sector applications, heating requirements tend to decrease continuously due to internal thermal loads. This can make it easier to choose a heat pump without additional sources of heat.

The use of air-to-water heat pumps is generally more expensive than water-to-water heat pumps. Besides the more challenging operating conditions due to lower exhaust temperatures in winter, one must also consider the energy required by the external fans and defrosting process. During the evaporation phase of the refrigerant, the outdoor unit tends to accumulate frost in contact with the colder surface in temperatures ranging from +5 to 0^{O}C. This reduces the airflow passage through the unit and forces the device to operate at lower evaporation temperatures, which accelerates the formation of frost. As a result, the thermal power generated decreases while energy consumption increases.

The actual performance of air-source heat pumps that use outdoor air as a cold source shows a significant drop in this temperature field. The most common system for defrosting the outdoor unit involves a momentary reversal of the refrigeration cycle, during which the superheated gas from the compressor enters the unit and melts the frost.

This system is activated at the critical temperatures mentioned above, repeated at regular intervals that are selected according to the local climate conditions, and lasts a few minutes. At the same time, the outdoor fans stop.

In air-to-air heat pumps, the internal fan usually remains operational, activating an electric supplemental unit to prevent the distribution of cold air into the environment.

Since the performance coefficient of a heat pump depends significantly on the temperature of the heat source, i.e. the surrounding air or the available geologic mass, the values of the cooling and heating operation coefficients (EER/COP) are not constant.

It is also noted that the higher the temperature of the heat source in the range of 0 to 30^{O}C and the closer it approaches the operating temperature, the higher the EER/COP coefficient. Therefore, a heat pump can be distinguished by:

- The EER/COP factor expresses the performance of a heat pump under specific environmental and operating temperature conditions. The manufacturer of the heat pump provides the theoretical value of the EER/COP.

- The annual or seasonal coefficient of performance (SCOP) is given by the ratio of the thermal energy produced by the heat pump to the energy consumed within a year or during a heating or cooling season. When measurements from several years of operation are available, the average annual SCOP factor of the heat pump can be determined. The average seasonal performance factor SCOP, calculated for most regions of the country, is higher than the nominal COP, because the average temperature during the winter season is higher than the nominal air temperature of 7°C. For more accurate calculations of the energy performance of a building, it is recommended to use the average seasonal performance factor of heat pumps.
- The seasonal energy efficiency ratio (SEER) is the overall performance coefficient of the device, defined as the ratio of the annual cooling requirement to the total annual energy consumed for cooling. The average seasonal energy efficiency ratio (SEER) is lower than the nominal EER when the average temperature during the day in the summer period is higher than the nominal air temperature of 35°C.
- The seasonal performance factor (SPF) refers to the performance of a heat pump over an entire season. The input and output power are accumulated for the season, and then the total output energy is divided by the total input energy to give the SPF, which is expressed as: Total Output Power (kWh) / Total Input Energy (kWh) = SPF[4.9].

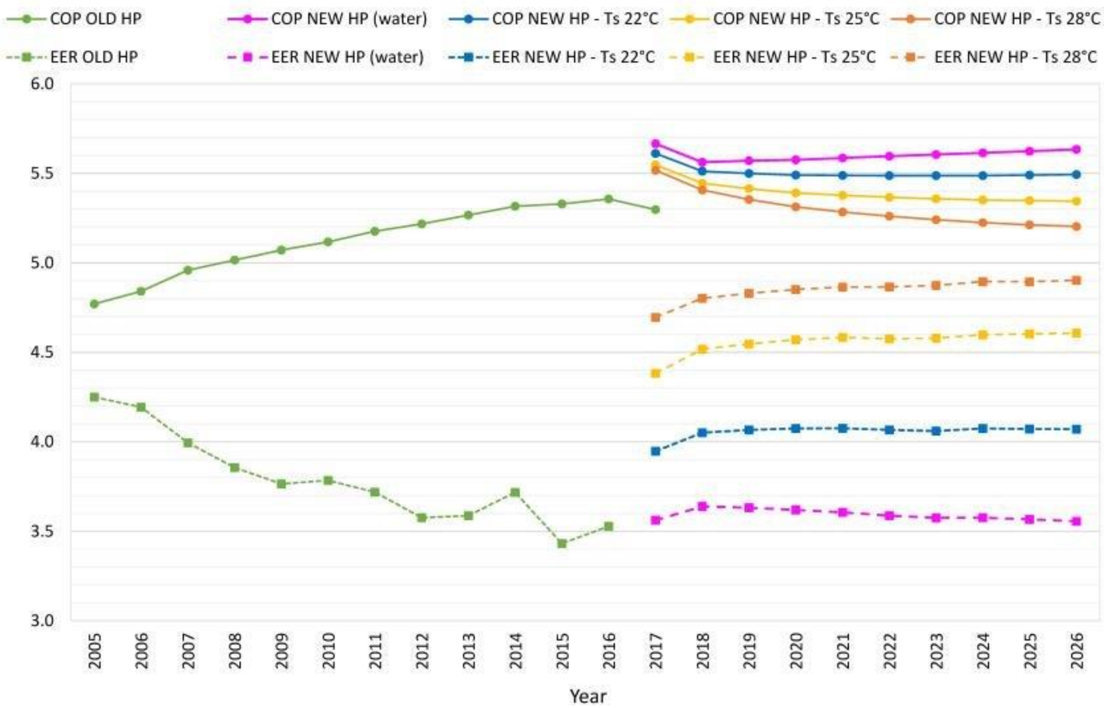

Figure 4.2: Profiles of seasonal COP and EER of the heat pump, under different hypotheses of air temperature switch[4.10]

The SPF is a good method for comparing the performance of heat pumps, as it provides a more accurate estimate of operating costs over an entire period.

Another factor affecting the economic performance of heat pumps is the total amount of energy that can be produced during a year. This quantity depends on the energy potential of the source, whether it is air, water, or rock mass, as well as on the height and type of the building's thermal needs.

These two factors are more favorable in Greece compared to Western and Northern European countries. Therefore, the incentives for developing the use of heat pumps in Greece are stronger. The ground temperatures in the Greek region can be determined by both the average annual air temperatures and direct measurements that have been carried out in underground waters.

<u>Cost data for heat pumps</u>

The heat pump , utilizing amounts of heat from the natural environment, provides the most economical solution for air conditioning individual spaces or small buildings. Specifically, in heating, the heat pump is cheaper than thermal accumulation and competes with small installations of the classical heating system (radiators). The intense competition of large manufacturers has already achieved high levels of efficiency in heat pumps[4.11].

In summary, the following can be recorded:

- The cost of the initial installation of a heat pump is greater than that of conventional heating installations.
- The operating cost of the heat pump depends only on the consumption of electricity. This is significantly lower than today’s operating and maintenance cost of a small heating installation, resulting in quickly balancing the total cost (operation and initial installation) to that of conventional heating installations in many cases.
- It does not contribute to environmental pollution. The efficiency of heat pumps in each period is much higher than that of boiler installations, resulting in reduced environmental pollution.
- The installation does not require large spaces.
- The installation has the ability to cool or heat a space, depending on the consumer’s requirements, something that common heating installations do not offer.
- For mild climates, such as that of Greece, the heat pump has a high COP and EER coefficient of performance.
- In large heat pump facilities, a machine such as a diesel engine provides the power. This method of generating heat has a significantly higher efficiency rate than using an electric heat pump, which incurs losses during production and transportation of electricity.
- The heat pump has several advantages, such as its ability to utilize very low environmental temperatures, making it a strong contender against any other heating system in the future.

4.5 Ground Source Heat Pumps

This chapter provides an overview of ground source heat pump (GSHP) systems, which are energy systems that utilize ground resources to provide heating and cooling in buildings. The use of geothermal energy makes GSHPs a "green" system with the potential to reduce CO2 emissions and fossil fuel consumption. The chapter discusses the main components of a GSHP system, including indoor distribution systems, ground source heat exchangers, and heat pump units. In-depth discussions are provided on topics such as geothermal resources, heat storage technologies, economics, and environmental impacts of GSHP systems.

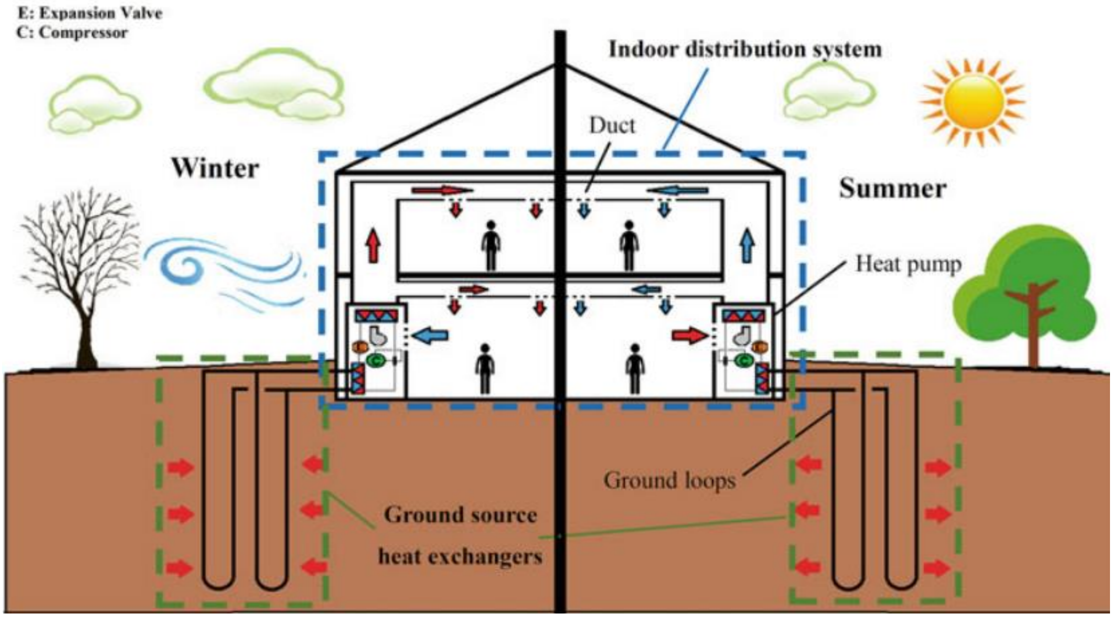

Image 4.5: A typical GSHP system used in winter and summer[4.4]

Geothermal Resources

Geothermal energy is a type of renewable energy that is generated from the Earth's internal heat. It has been utilized in various ways, including for electricity generation and direct heating/cooling applications. Geothermal resources are classified into three categories based on their temperature: high ground temperature ($T \geq 150°C$), intermediate ground temperature ($32°C < T < 150°C$), and low ground temperature ($T \leq 32°C$).

High ground temperature resources are suitable for electricity generation, typically using conventional steam or binary power plants. Binary power plants can utilize lower ground temperatures (around 90°C or lower) by using modular units that are linked together. Despite the high capital cost, geothermal electricity generation is attractive due to its potential as a renewable energy source and reduction of greenhouse emissions.

Intermediate ground temperature resources are less efficient for electricity generation, but can be used directly for heating without any supplemental input power. This is the oldest application of geothermal energy and has been used for hundreds of years. Direct-use geothermal systems can supply free heating and cooling by transferring heat from underground to user loads [4.12].

Low ground temperature resources are typically used for ground source heat pump (GSHP) systems. GSHPs use the nearly constant temperature below the frost line to provide heating and cooling for buildings. The ground is the heat/cool source for GSHPs, which reject building heat into the ground during summer and extract heat from the ground during winter.

Geothermal resources are widely distributed on the Earth and relatively easy to access. The U.S. Geological Survey estimates that the U.S. has over 100 gigawatts of geothermal resources, which is equivalent to 10% of the country's electricity-generating capacity. Other countries such as Iceland and Kenya have a significant portion of their electricity generated from geothermal resources. However, the availability of high ground temperatures at reasonable depths for drilling limits the wide application of geothermal energy [4.13].

Categorization of GSHP systems

Shallow geothermal systems, which use water with a temperature below 25°C, function similarly to deep systems and rely on ground source heat pumps (GSHP) to meet heating and cooling needs. GSHPs come in various forms that use ground-water, ground, or surface water as heat sources or sinks. ASHRAE has categorized these systems into three subgroups

1. ground-water heat pump (GWHP) systems,

2. surface water heat pump (SWHP) systems,

3. ground-coupled heat pump (GCHP) systems.

Similar terms for these systems include earth energy system (EES) and geothermal heat pump (GHP).

GSHP systems are also categorized on the loop kind they utilize. Those are the closed loop and open loop geothermal systems.

To transfer heat, closed loop geothermal systems use a mixture of water and antifreeze that circulates through buried pipes instead of extracting fresh groundwater. These systems can be divided into various subcategories:

• One type of closed loop geothermal system is the horizontal system, where pipes are buried horizontally in the ground. These systems require a large area to cover the entire length of the loops.

• Another type is the slinky system, which is a variation of the horizontal system. In this system, multiple semi-loops are laid close to each other in a flattened and spread-out slinky shape. This reduces the total length required while increasing the heat transfer area per square meter.

• A third type is the vertical system, where pipes are installed vertically in several wells instead of horizontally. The pipes can encase each other coaxially or be linked together at the bottom with a U-bend. Grout is used to fill the boreholes to achieve favorable thermal conductivity.

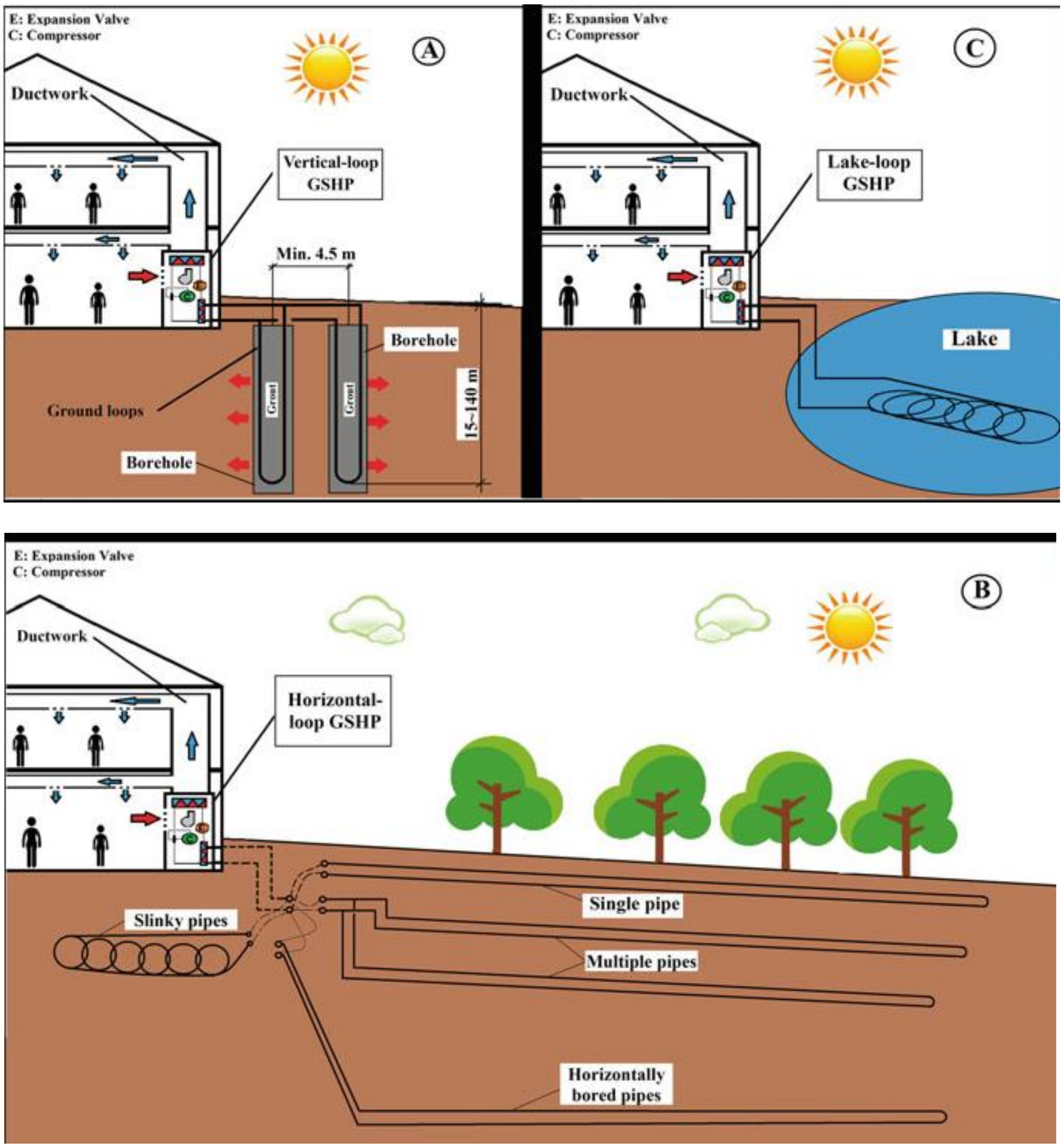

Image 4.6: Closed-loop ground source heat exchangers[4.4]

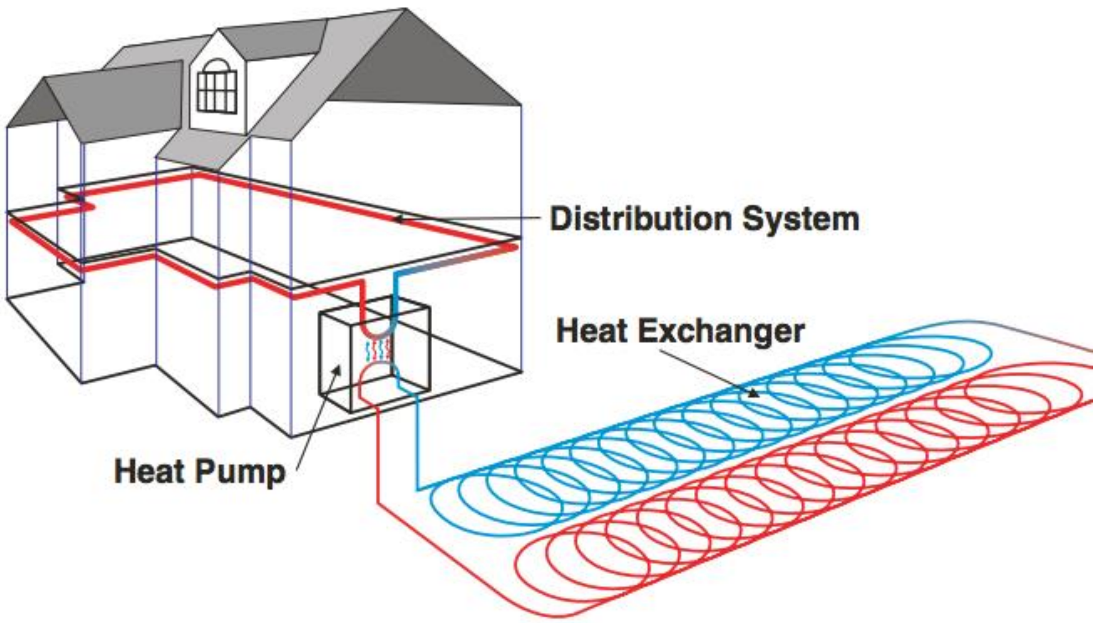

Image 4.7: Slinky system[4.14]

System Design

When creating a vertical closed-loop heat pump system, the first thing you need to do is figure out how much heating and cooling the building will require. After you have that information, you can begin designing the VCS. There are many things to consider during the design process, including the layout of the piping, the size and length of the pipes, how powerful the pump needs to be, and the diameter, depth, and separation of the borehole. All of these factors are interconnected, so it's important to thoroughly integrate, optimize, and evaluate the design in order to find the best solution for your specific project. This will take into account the initial cost, performance of the system, and any potential environmental impact.

The most important variables to take in count when designing a GSHP are:

1.The specifications of the heat pump when it operates at rated conditions.

2.The specifications of the water pump, including the size of the expansion tank and air separator.

3.Fluid specifications for the system.

4.Design operating conditions for the system.

5. The layout of the pipe header with the ground heat exchanger.
6. The approximate borehole diameter and depth.
7. Material specifications for piping, as well as the requirements for visual inspection and pressure testing.
8. Specifications for the grout or fill material.
9. Provisions for purging and flow requirements.
10. Instructions for connecting the system to building loops and coordinating flushing of the building and ground heat exchanger.
11. If applicable, a drilling report for the borehole thermal response test.
12. The sequence of operation for the controls of the system.

Aside from the different types of piping configurations within each borehole (such as single/double U-tube or simple/complex coaxial tubes), the arrangement of the underground piping circuits can also differ depending on the situation. Generally, there are two types of layouts: series and parallel.

The size and length of underground pipes are crucial aspects of a VCS. The typical water flow rate in a VCS is around 2.7-3.2 L/min/kW, and the nominal pipe diameter can vary depending on the layout. For a series layout, the diameter can range from 20-50 mm, while a parallel layout typically uses a larger size of 20-32 mm with a 40 mm header. The performance of a VCS depends on the depth of the boreholes and the length of the underground pipes. For a single U-tube configuration in a parallel layout, a reasonable pipe length is between 26-43 m/kW. Meanwhile, a series layout may have a smaller value of m/kW for pipe length[4.4]

. The borehole is where the underground pipes in a VCS are inserted, and the diameter and depth of the borehole are related to the size and length of the pipes. Generally, the minimum borehole diameter for a single U-tube is 100 mm with a 20 mm nominal pipe diameter. However, if the pipe diameter and/or the number of pipes in each borehole increases, the borehole size needs to be enlarged accordingly. For example, a 40 mm single U-tube typically requires the borehole diameter to be at least 125 mm or 150 mm.

The length of the borehole is an essential factor in the VCS design and is usually half of the inserted pipe length for a single U-tube configuration. For a VCS, approximately 13 meters of borehole length is needed for each HVAC kW capacity, with the length of the borehole needed to be 22 m/kW for an efficient vertical closed-loop heat pump system.

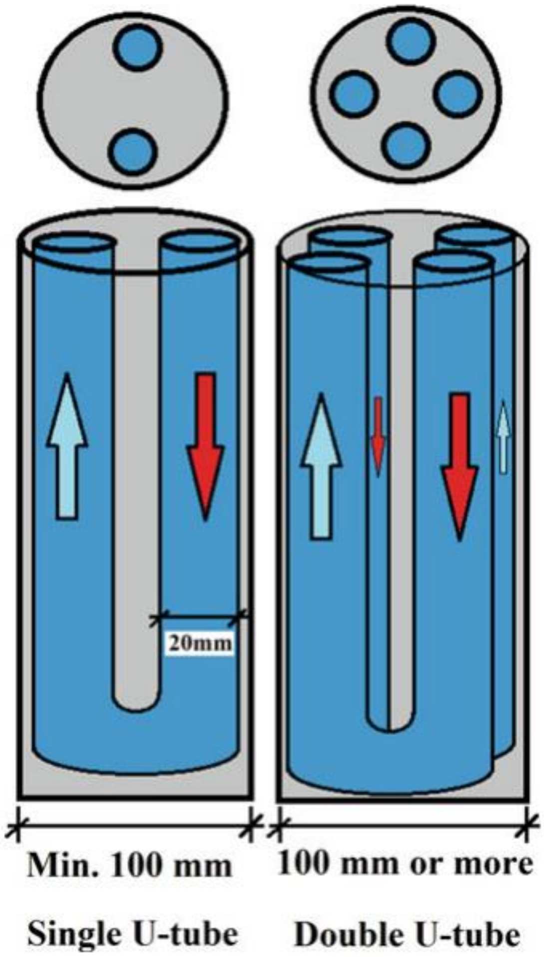

Image 4.8: Minimum borehole size{4.4]

Open loop geothermal systems

Open loop geothermal systems use water from the ground or surface as a transfer fluid to take advantage of geothermal energy. These systems are considered the most efficient for heat pumps due to the excellent thermodynamic properties of water and the fact that groundwater is naturally insulated with a temperature similar to the surrounding ground. Water wells, ponds, and lakes can be used as both sources and sinks of heat. However, every installation has unique variables that must be taken into account, and there are several factors that affect the overall efficiency and cost of the system.

Horizontal collectors are another type of open loop geothermal system, and they are installed up to a depth of 2 meters. These collectors mostly utilize solar radiation, and their effectiveness depends on the moisture concentration in the ground, shading of the collector field, and the amount of coverage. The heat exchanger can be installed in a trench or directly in the ground, installed horizontally. Generally, the area required for the loops should be twice as large as the surface designated for heating. Installation of these systems usually requires drilling and is typically done simultaneously with the construction of new private homes.

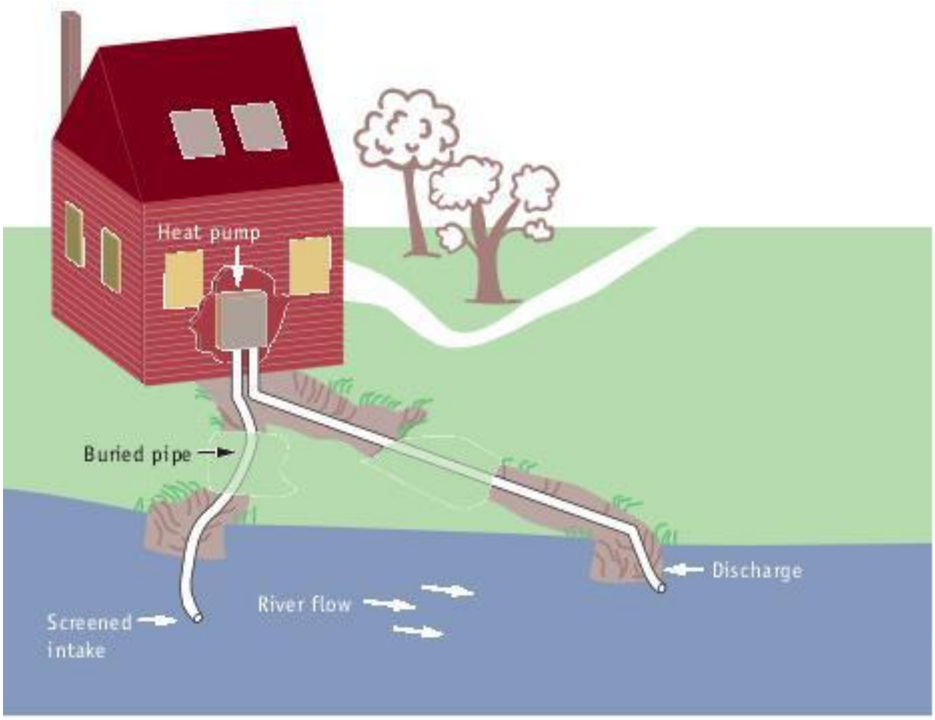

Image 4.9: open-loop surface water heat pump system[4.15]

4.6 Ground Source Heat Pumps Overview

Ground source heat pumps (GSHPs) are increasingly gaining attention as a promising technology for space heating and cooling in various parts of the world . In Europe, GSHPs are gaining popularity due to their energy-efficient and environmentally-friendly characteristics. According to recent statistics, the installation of GSHPs in Europe has grown rapidly in the last decade, with over 1.7 million units installed by the end of 2020. Germany, Sweden, and France are the leading countries in GSHP installations, with a combined share of more than 60% of the total installed capacity [4.16].

In Greece, the use of GSHPs is also increasing, mainly for space heating purposes. According to a recent study, the installation of GSHPs in Greece has increased by 50% in the last five years, with more than 1,000 units installed by the end of 2020 [4.17]. GSHPs are considered a promising technology in Greece, mainly due to the country's favorable geological conditions, which provide the potential for high energy efficiency and low environmental impact.

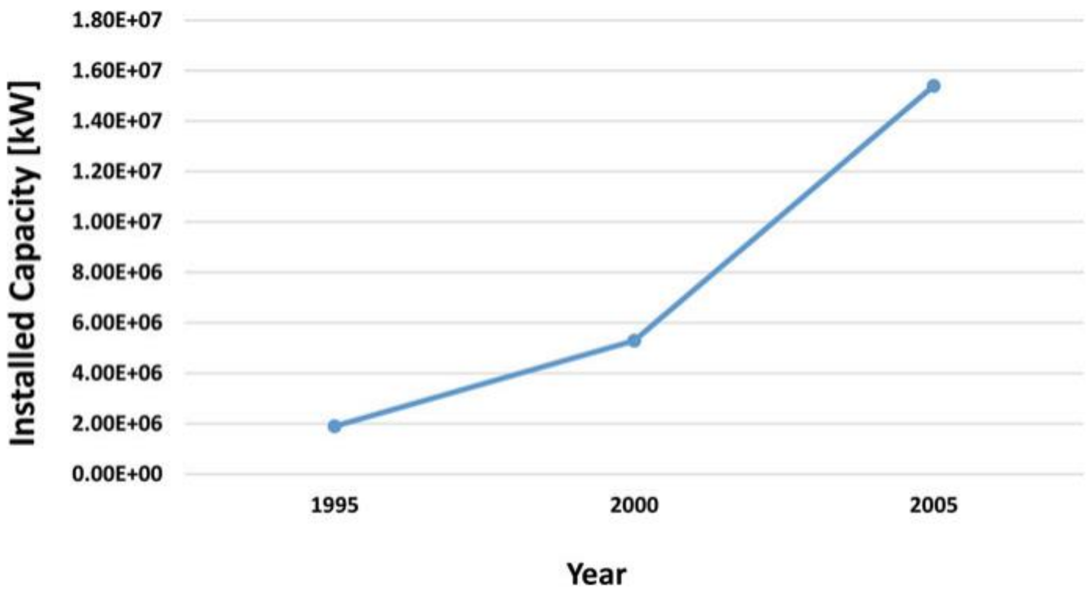

Figure 4.3: GSHP worldwide capacities[4.4]

In Europe, the market for geothermal heat pumps has seen significant growth over the past decade, with a compound annual growth rate of 11.4% between 2014 and 2019 . The leading countries in Europe for geothermal heat pumps are Sweden, France, Germany, and Finland, with Sweden being the largest market for geothermal heat pumps in Europe . The Swedish market has been driven by a combination of government subsidies, awareness-raising campaigns, and strict building codes that require energy-efficient solutions. In 2019, there were approximately 150,000 installed geothermal heat pumps in Sweden, which represents approximately 5% of the country's total heating demand .

In North America, the market for geothermal heat pumps has also been growing, although at a slower pace than in Europe. The United States is the largest market for geothermal heat pumps, with over 1.6 million installed units. The state of Oklahoma is leading the way with over 20% of its households using geothermal heat pumps for heating and cooling . In Canada, the market for geothermal heat pumps is smaller but has seen steady growth over the past decade, with a compound annual growth rate of 5.5% between 2014 and 2019[4.4].

Asia is also emerging as a significant market for geothermal heat pumps, with China being the largest market in the region. In 2018, China had approximately 140 million square meters of geothermal heat pump installations, representing an annual growth rate of 20%. South Korea is also a growing market for geothermal heat pumps, with an annual growth rate of 8.5% between 2014 and 2019.

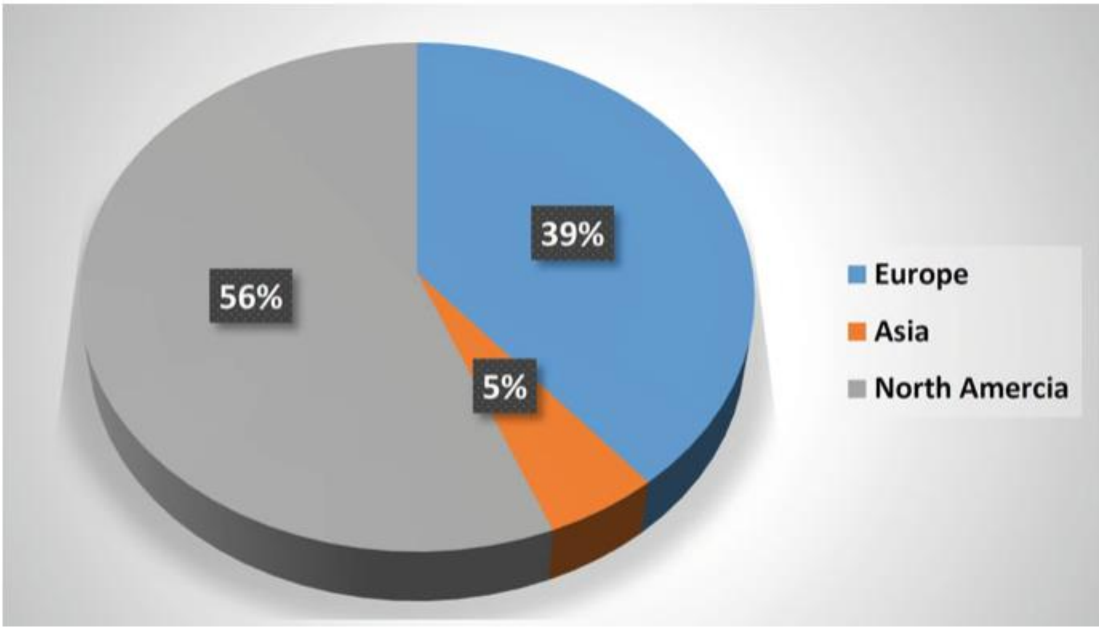

Image 4.10:Chart for GSHP installed capacities of the world in 2005 {4.4]

Geothermal energy is currently only being used for direct purposes in Greece, such as in thermal spas, greenhouses, aquaculture, agriculture, drying, and GSHPs. While there is growing interest in using geothermal energy for seawater space cooling for seaside hotels during the summer, the majority of geothermal applications are found in northern Greece[4.19].

In 2016, the total installed capacity of geothermal applications in Greece was 232 MWth, with GSHPs accounting for 64%, thermal spas for 18%, and greenhouse heating for 14.5%[4.20]. The Greek geothermal market has experienced significant growth due to the increase in GSHP system installations, which can be attributed to a shift in public attitude towards the technology, steady growth in the air-conditioning sector, a campaign promoting the use of GSHPs by the Association of Greek Geothermists, easier licensing processes for well drilling or groundwater usage in open systems, and high oil prices in 2008 combined with relatively stable electricity prices in the country. However, in order to meet the EU's goals for heating/cooling by renewable energy sources, Greece must contribute 50 ktoe capacity to GSHPs by the end of 2020, which is equivalent to 265 MWth installed. Of this total, 45% is expected to come from closed-loop systems, 40% from open-loop systems, and 15% from horizontal systems[4.21].

Despite Greece's significant geothermal potential, its exploitation is severely underdeveloped. Although a substantial number of geothermal fields have been identified in the last 40 years, with proven geothermal electricity generation of 25 MWe on the islands of Milos and Nisyros and estimates indicating potential for up to 250 MWe, the country's utilization of geothermal energy is limited. Probable areas with fluids up to 120 °C, suitable for electricity generation, have been identified in the islands of Lesvos, Chios, and

Samothraki, as well as in the geothermal fields of Aristino, Eratino, and Akropotamos. While water temperatures typically reach up to 100 °C at depths less than 1000 m in promising areas, the conservative estimate of the national total low-enthalpy geothermal potential is 1000 MWt.

The lack of power production through geothermal energy in Greece is mainly attributed to local societies' opposition, which arose from a negative experience with the Milos Island pilot power plant in the 1970s and 1980s. Environmental pollution caused by deficiencies and errors during construction and operation led to strong pushback against this type of power generation, and many local communities and authorities view large-scale exploitation of high-temperature deep geothermal resources negatively, particularly those with temperatures above 90 °C. In contrast, the utilization of low-temperature deep geothermal resources (resources with temperatures between 25 and 90 °C) is viewed more positively, particularly in the volcanic arc of the southern Aegean (Milos, Nisiros, Santorini), where there is great potential for thermal desalination of seawater as a cheaper and more environmentally friendly alternative to supplying these dry coastal areas with freshwater via cargo ships[4.21].

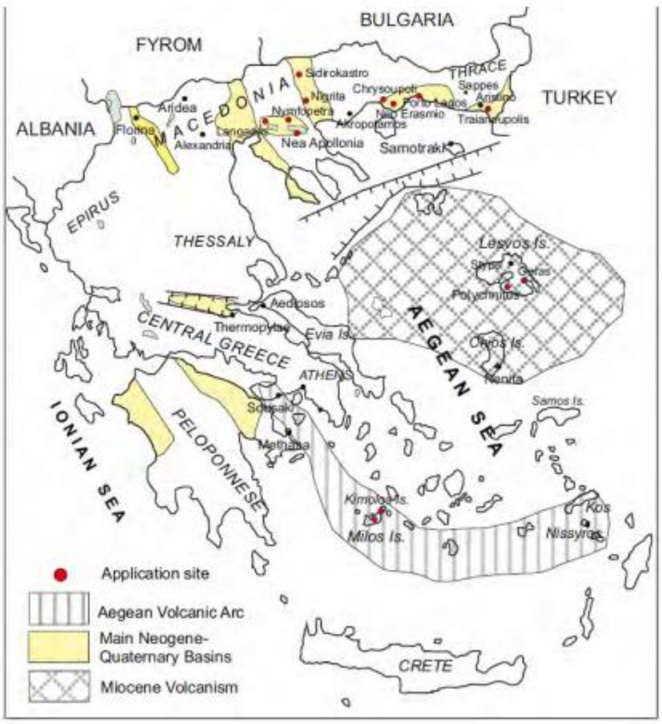

Image 4.11: Map of high potential geothermal areas in Greece[4.20]

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5.TRNSYS 18 SIMULATIONS PROGRAM

5.1 Introduction to TRNSYS

The TRNSYS (Transient System Simulation Program) software is a widely used program for simulating dynamic systems over time, as it can provide accurate results for a wide range of tasks, such as:

- Conventional systems powered by electricity, oil, natural gas

- Renewable energy systems (photovoltaic, solar thermal, wind, geothermal, hydrogen)

- HVAC (Heating, Ventilating, Air Conditioning) systems

- Multi-zone buildings, etc.

The TRNSYS (Transient System Simulation Program) is a widely used simulation program for transient systems, providing reliable results for a large variety of tasks, such as conventional systems using electric power, oil, natural gas, renewable energy systems (photovoltaic, thermal solar, wind, geothermal, hydrogen), HVAC systems (Heating, Ventilating, Air Conditioning), multi-zone buildings, and more.

Universities, researchers, and engineers worldwide use TRNSYS to evaluate the results of various systems, not only because of the large workload it can handle, but also because the program code and its models can be edited by the user according to their needs or even create new models using common programming languages (C, C++, Pascal, Fortran). This allows for the exchange of models between users and continuous software support through new releases. The TRNSYS package includes the Simulation Studio, TRNBuild, TRNEXE, and TRNEdit, and its usefulness is presented below[5.1].

5.2 Simulation Studio - TRNEXE

The simulation studio is the main workspace when opening TRNSYS. It creates a file with the user's simulation program data (*.tpf) and an input file containing all the simulation information. The simulation studio also includes a manager for the program's outputs, allowing the user to determine which variables will be included in the outputs, printed, or used in graphs. Additionally, it includes a recorder and error handler for detailed analysis during simulation. There are also many additional tasks that can be performed within the simulation studio, such as creating new computational models for TRNSYS using the Fortran wizard, reading exported files, editing a model's description by modifying input and output parameters[5.2].

<u>Basic Simulation Studio options</u>

Opening TRNSYS, after creating a new project with the corresponding icon on the top left, we have to choose among the following basic options:

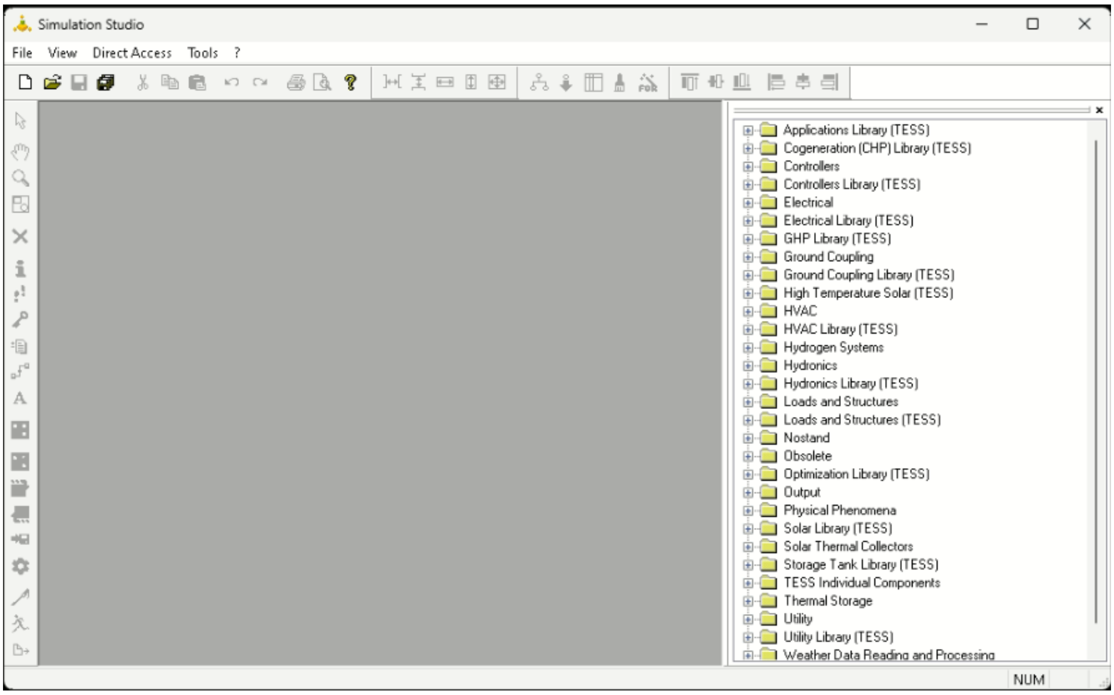

Image 5.1: New task in Simulation Studio

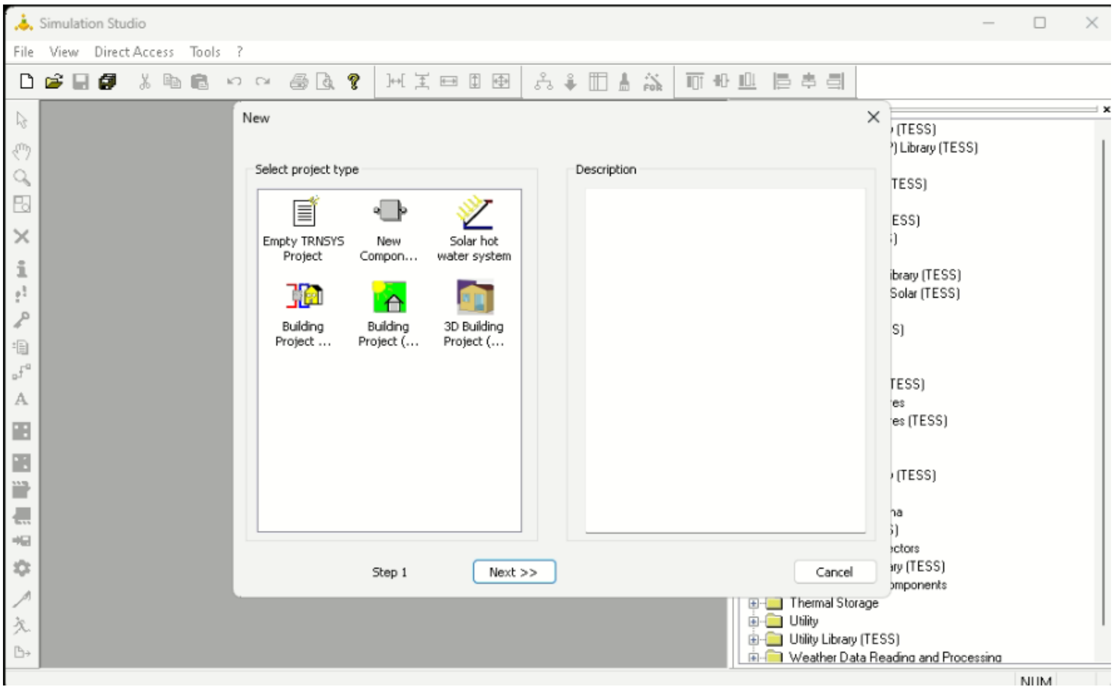

Image 5.2: Basic options of Simulation Studio

- Option to create a new component using a language programming
- Option to create a multi-zone building where it is analyzed in next capital
- Option to create a solar water heating system
- Choosing a blank topic where we will edit it next depending on the task at hand

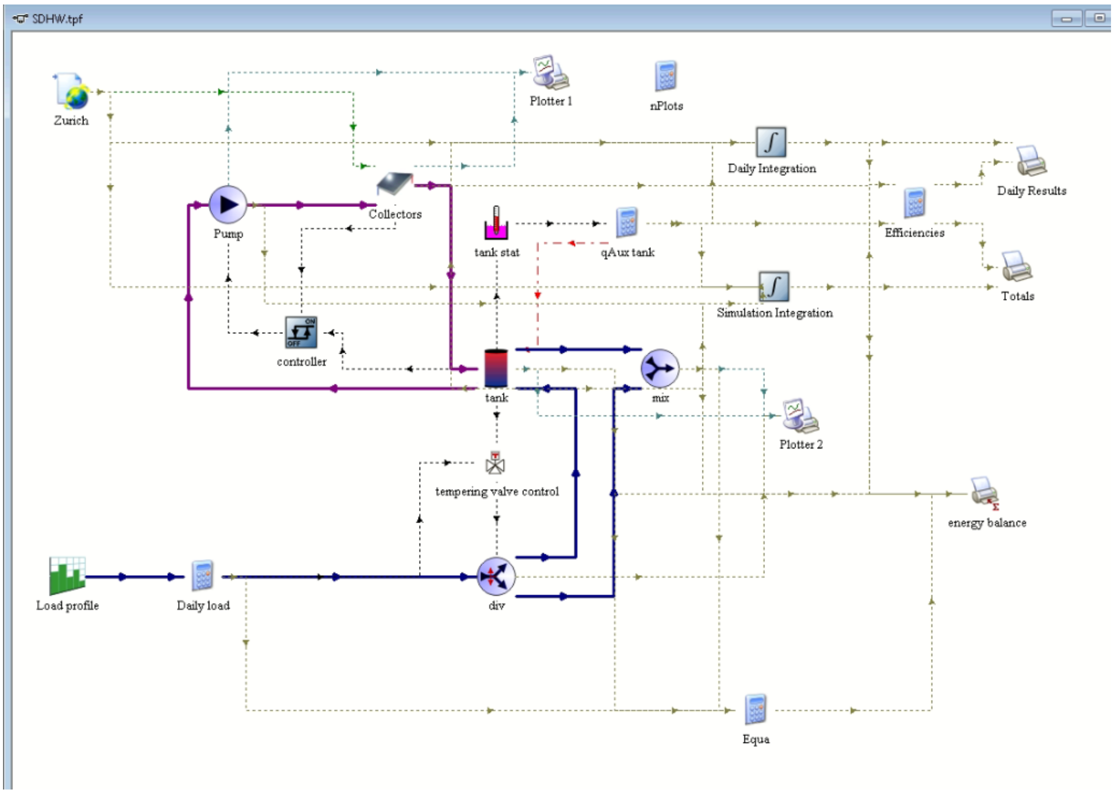

Image 5.3 : Solar water heating system

After choosing to create an empty topic we return to basic working environment. On the right side, all the elements available in tree form.

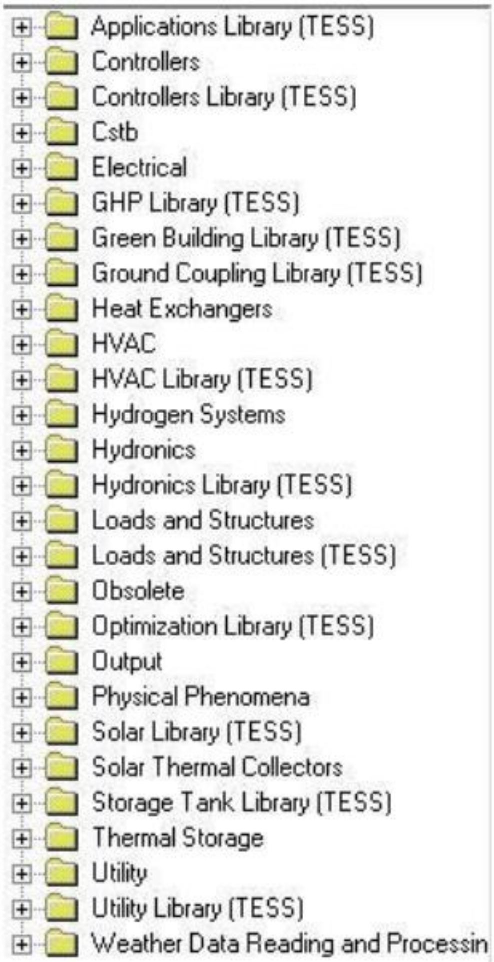

Image 5.4: Model library

The most basic components include:

- Controllers: general-purpose controllers and thermostats

- Electrical: photovoltaic, thermal photovoltaic, batteries, inverter

- Heat exchangers: heat exchangers, heat recovery models

- HVAC: heating, cooling, ventilation models, absorption chillers

- Hydronics: fans, pumps

- Output: printers, online plotters

- Physical Phenomena: psychrometric charts, solar radiation computer

- Solar Thermal Collectors: flat, concentrating solar collectors

- Thermal Storage: tanks with/without stratification, internal heat exchangers

- Utility: unit converters, time programs, data readers

- Weather Data Reading and Processing: meteorological data, solar radiation processors.

5.3 Linking of components

After choosing the component that suits us from the library, we will go to edit its parameters.

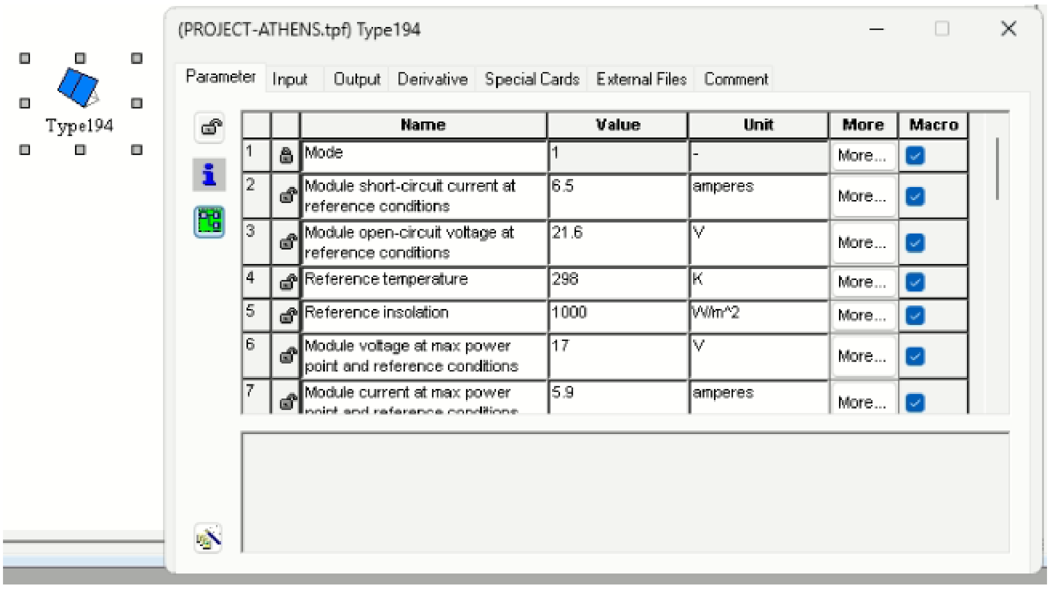

Image 5.5: Processing component parameters

On the left side is the name of the parameter, followed by its value, and finally the units of measurement it has. It's important to note that the parameters we input don't change over time. However, Inputs change over time and take the values provided by the element connected to it. Similarly, Outputs change over time and are the values provided by the element it's connected to. After editing the parameters of the elements, we are ready to connect them to the corresponding icon on the left toolbar. We click on the element we want and drag the mouse to the element it's connected to[5.3].

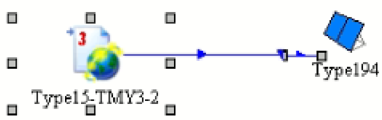

Image 5.6: Connecting Components

Now, by right-clicking on the line, we have the following options:

- Delete: to delete the connection we made

- Connections: to connect the Outputs of the first element with the Inputs of the second element that have a transaction.

- Properties: to edit the connection line (color, dashed, thickness)

We usually choose a red line for hot water or air, a blue line for cold, dashed for information.

5.4 Simulation Studio Tools

Another action worth mentioning is the locking/unlocking of elements. The assembly/Lock-Unlock command allows the creator of a study to "lock" specific elements in the syntax table. Locked elements cannot be deleted or modified. The corresponding icon is located in the left-hand tool column.

Furthermore, TRNSYS allows the insertion of equations via Assembly - Insert new equation. The left column is one member of the equation and the right column is the other. These two members must be properly connected to elements for the equation to be applied. For example, in the left column, the value can be taken from an environmental temperature element (Tamb) and given to the other element as temperature in Kelvin (Tamb_K=Tamb+273)[5.4].

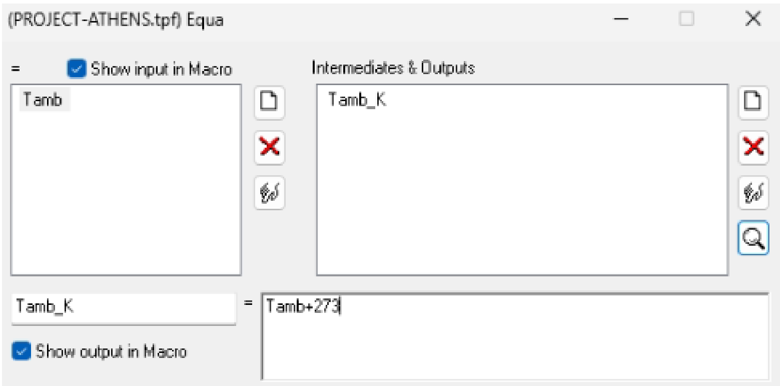

Image 5.7:Introduction of equation

Furthermore, from the left toolbar, we can edit various data for the simulation in the Control Cards tab, with the most important being the start and stop time as well as the simulation step.

Next, if we have selected any component of the plot or printer, we can run the simulation with the Run icon or with Calculate-Run Simulation. At this point, we move to TRNEXE, and after the end of the simulation, we can obtain its results for each time step by going to Calculate - Open - External Files.

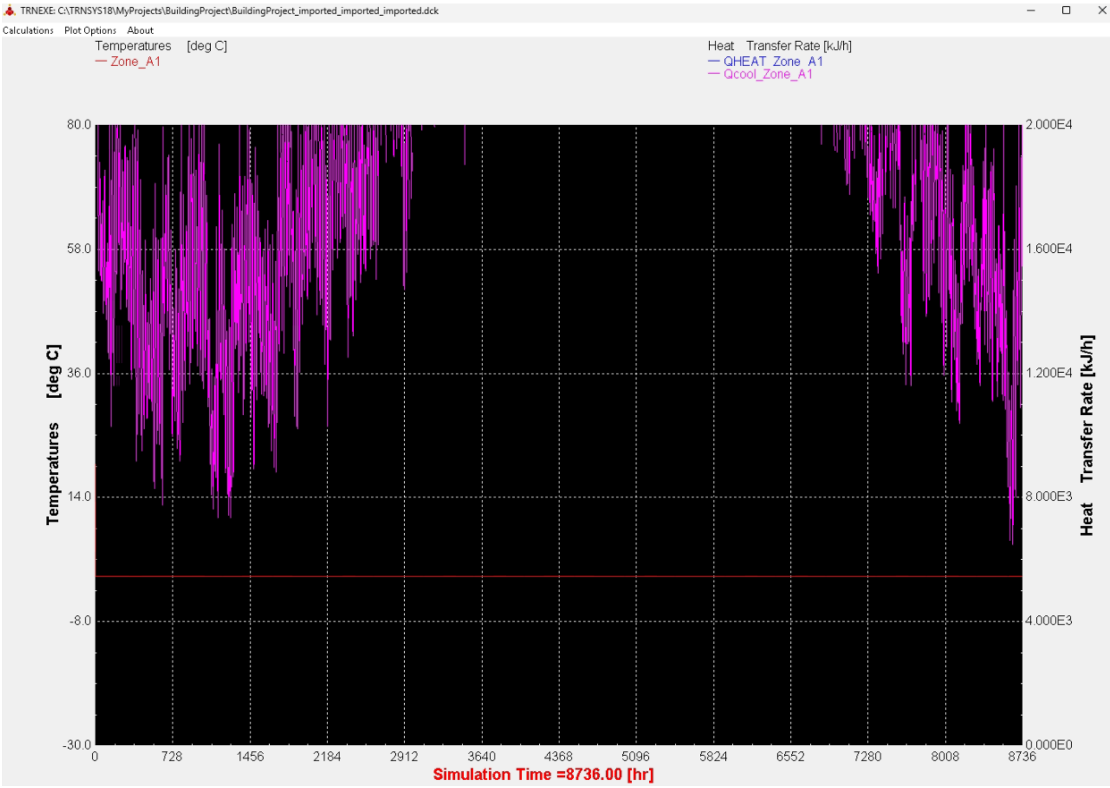

Image 5.8: Transition to TRNEXE

TRNEdit and TRNSED are specialized software applications that can be used to modify input files for TRNSYS. TRNEdit is a graphical editor that allows users to modify input files, add special commands, and create custom TRNSED applications. These applications can be distributed freely among users who do not have a license for TRNSYS, providing them with simplified simulation tools. The TRNEdit environment consists of two tabs, one showing the input file code and the other displaying the graphical output of the TRNSED application[5.5].

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6. Simulating my installation in TRNSYS Simulation Studio

6.1 Building design steps in TRNSYS Studio

After opening the Trnsys Studio program, we select the New icon and then the Building Project (multizone) icon.

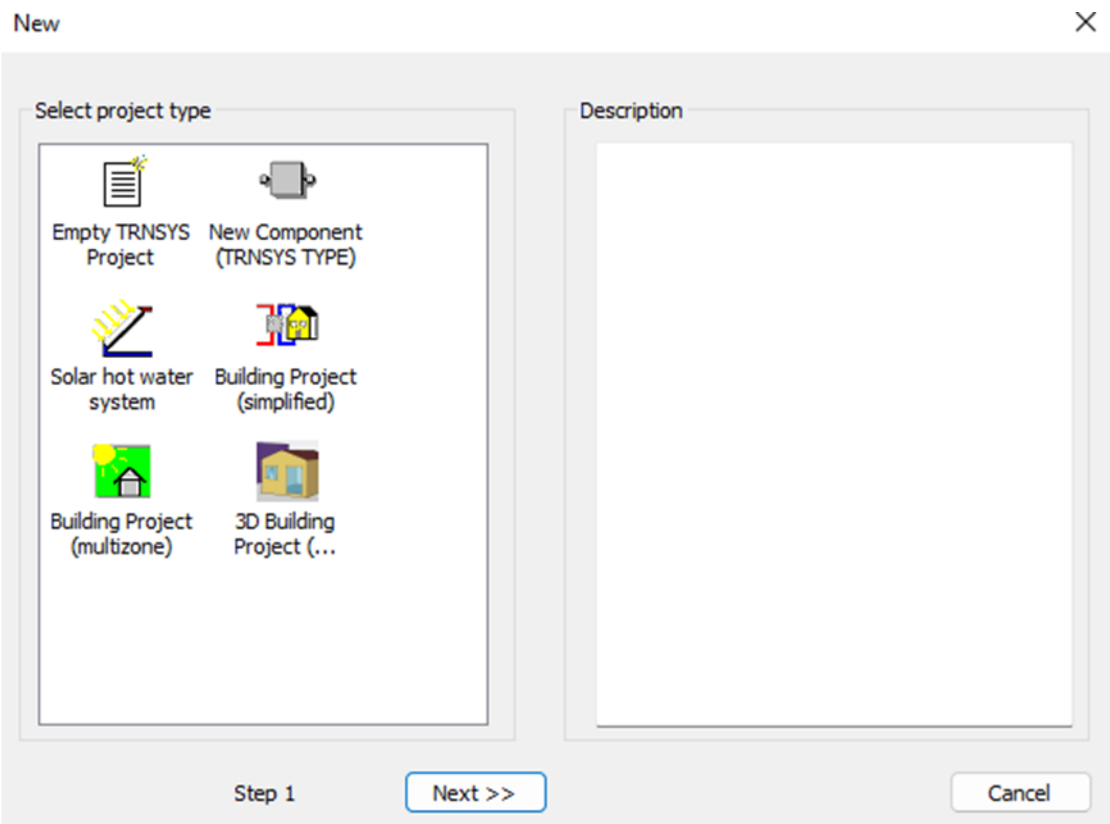


Image 6.1: Creating a multi-zone building model

At this point we have to select the number of zones of our building. In our study we used one energy zone.

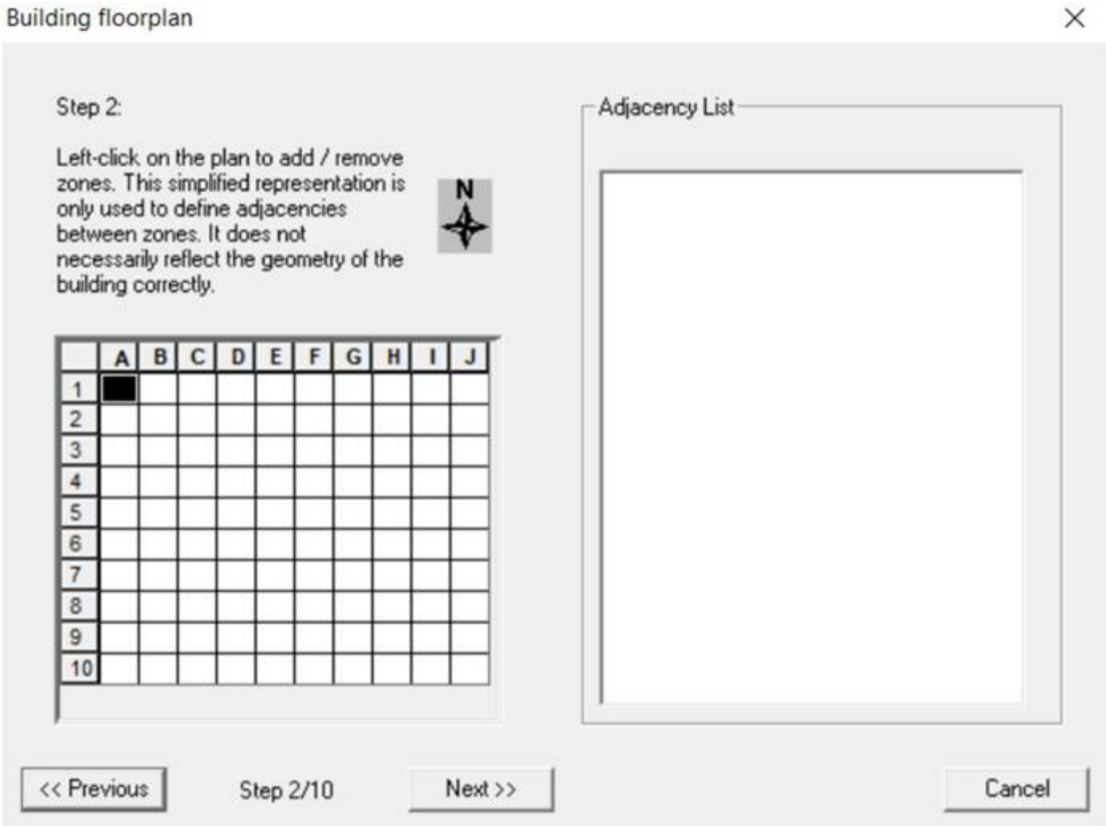


Image 6.2: Selection of number of building zones

In this point, the dimensions for each zone of our building are selected.We will use a zone, with the dimensions of a typical building of 200 m^2.

Specifically:

-Length: 10 m

-Width: 20 m

-Height: 3 m

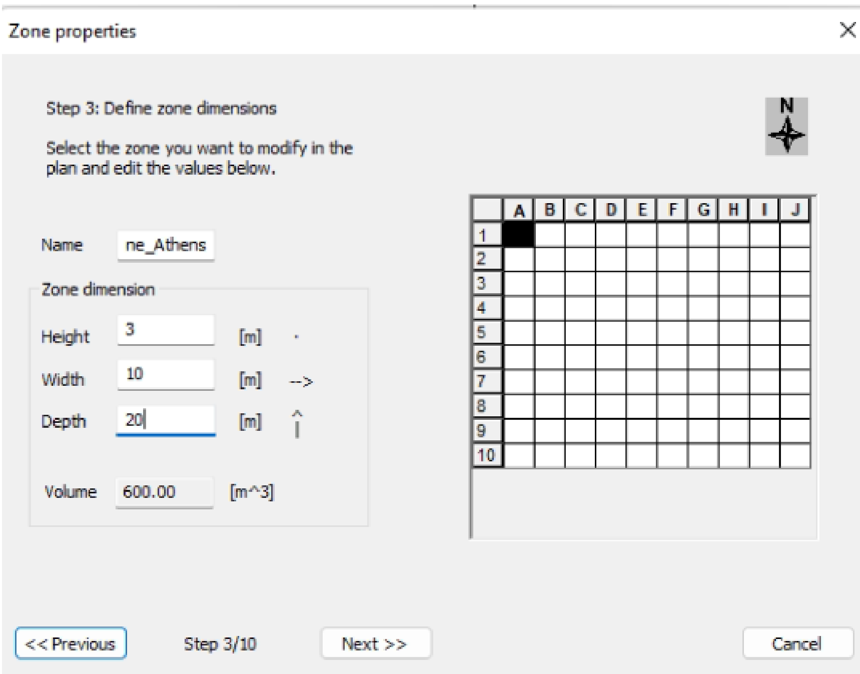


Image 6.3:Selection of building zone dimensions

The next setting concerns the percentage of windows on each of the four directions (North, South, West, East) of the wall. However, we determined this setting in a second phase and not from this step. Also, the location of the building is selected, for which we chose Athens, while there is the possibility of specifying the exact orientation of the building, but this setting was not used and the default value of 0 degrees remained.

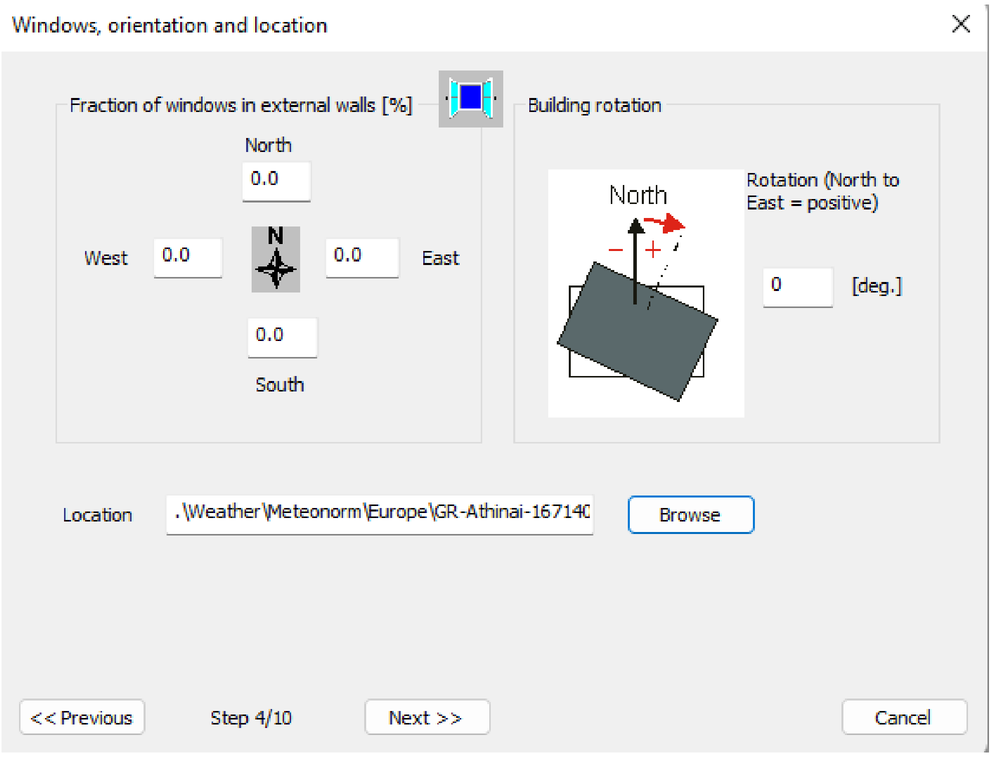


Image 6.4: Selection of openings, orientation, meteorological data.

From now on , this is where air infiltration and ventilation are determined. While we did not activate ventilation, either natural or mechanical.

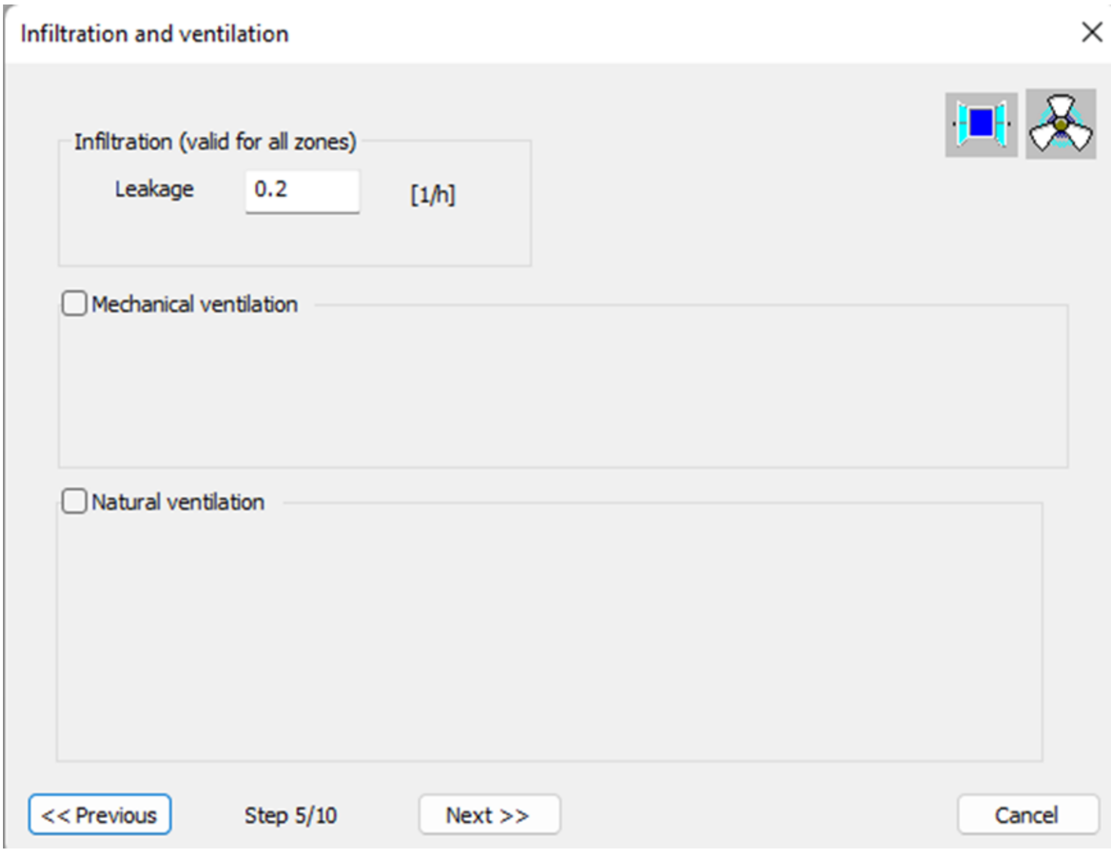


Image 6.5: Selection of space ventilation parameters.

The next step is to select the heating and cooling options for our building. No action was taken here, as a specific heating and cooling system will be used later on.

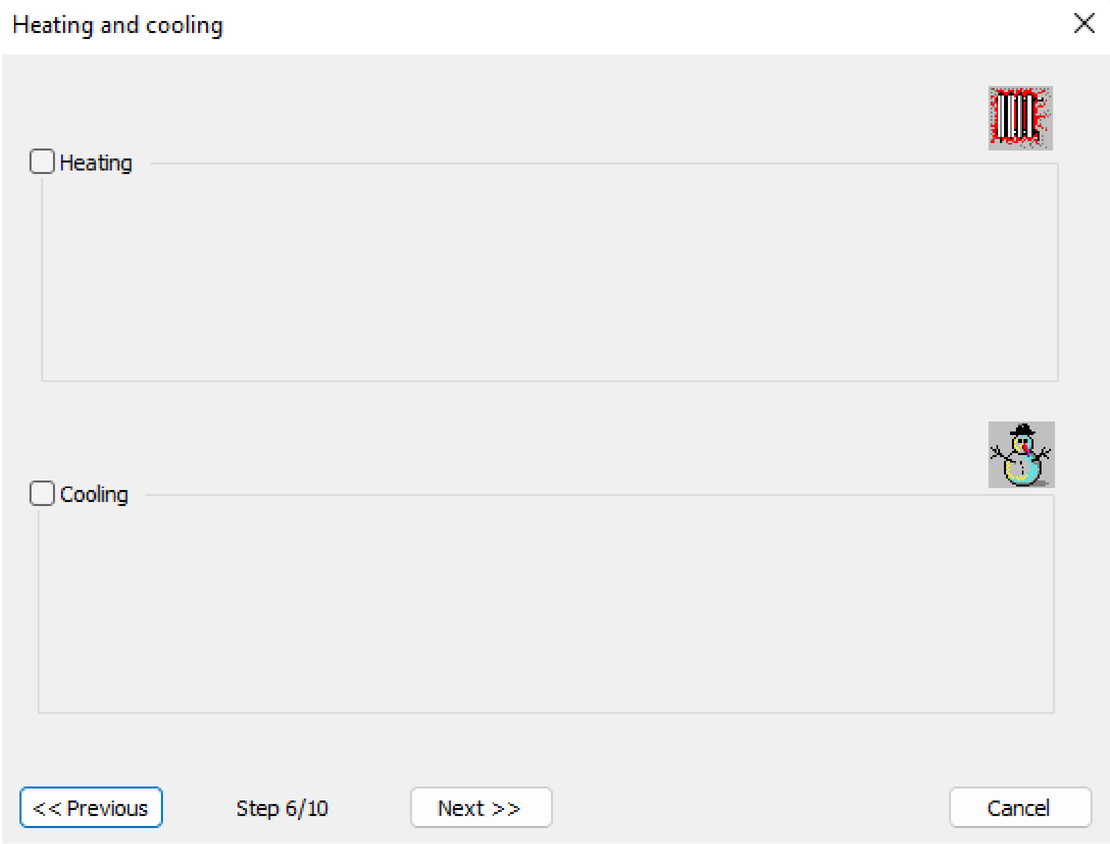


Image 6.6:Selection of building heating and cooling.

At this point, it is possible to determine the internal loads of the building that arise from the presence of people inside the space, the use of electronic devices, and lighting. However, it was decided to adjust these parameters in a second phase using TRNBuild, where they can be adjusted in more detail and with greater accuracy. Therefore, at this step, we did not change the default values.

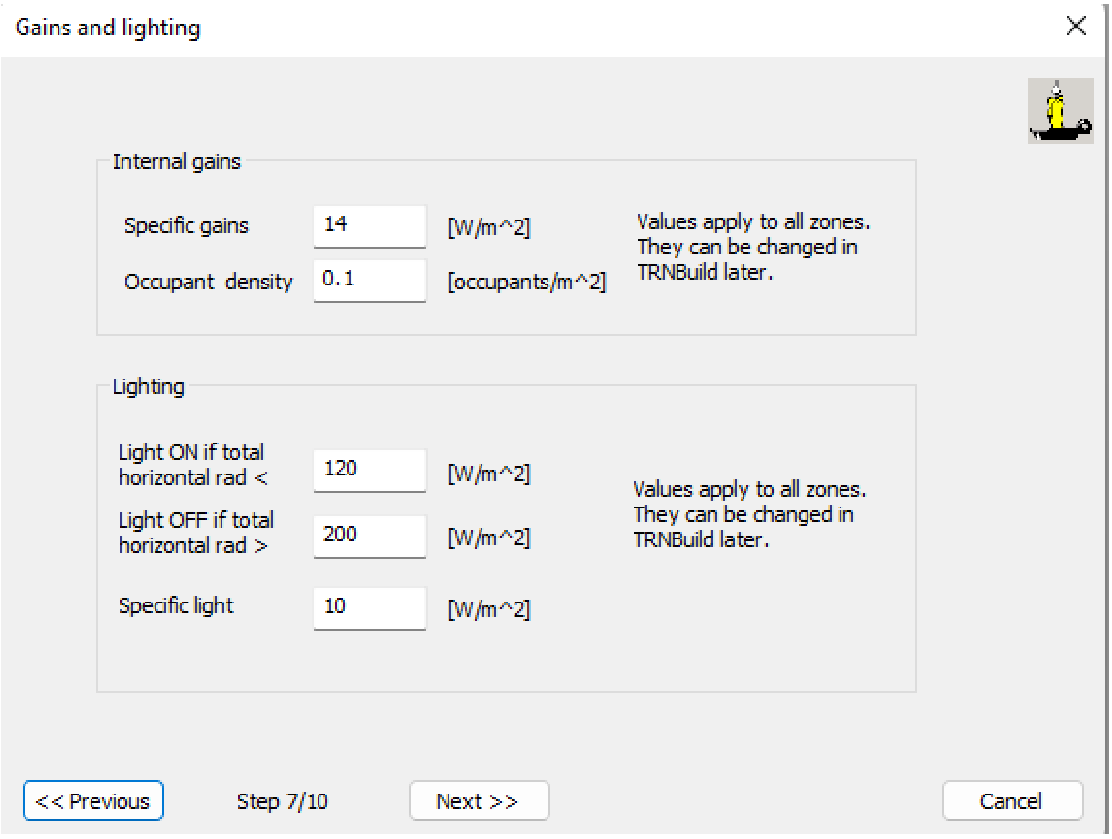


Image 6.7: Selection of building thermal gains from people, lighting and devices.

During the next steps, the shading (Fixed and Movable) as well as the orientation are adjustable. The default values were not changed here and the shading coefficient will be selected in a subsequent phase.

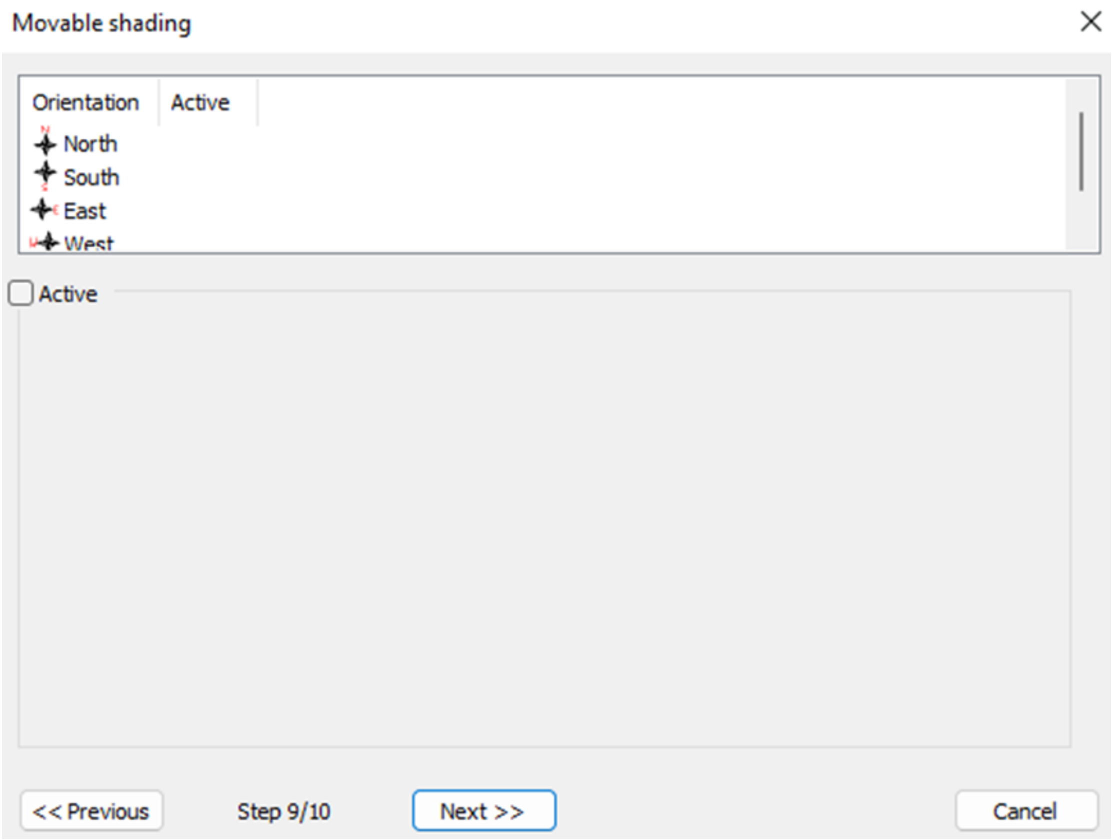


Image 6.8: Building shading option

We choose the icon Create Project and we complete the design of our building as for the last step.

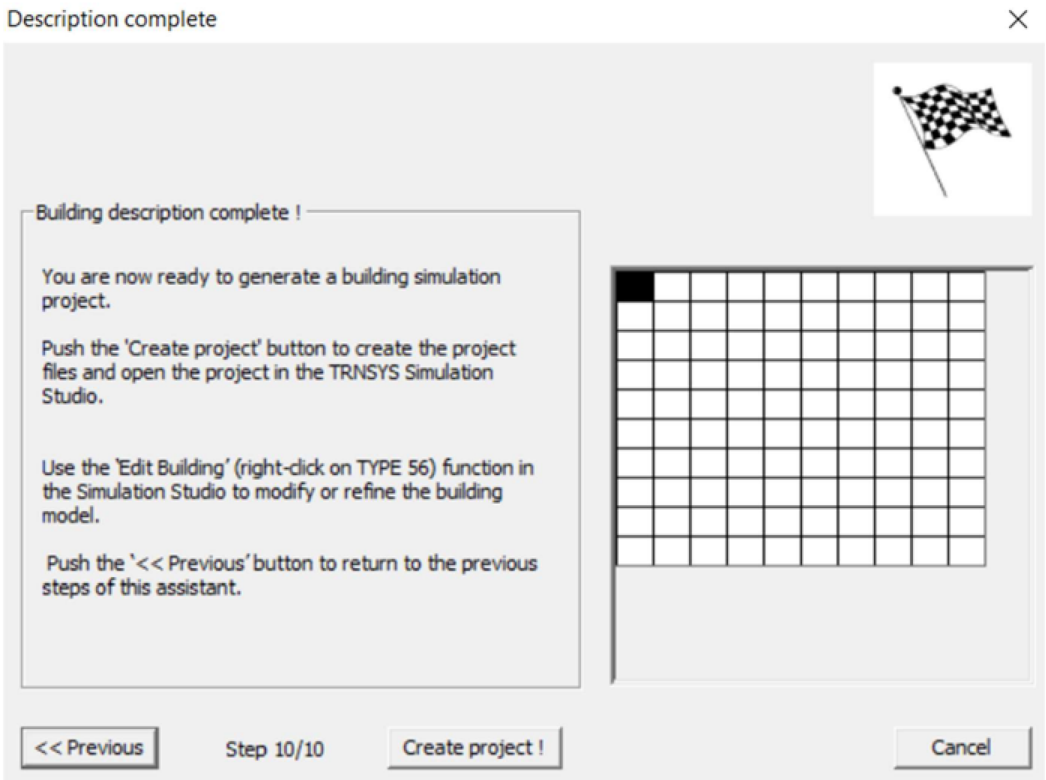


Image 6.9: Completion of building design

Simulation Studio then displays the building installation that we will study:

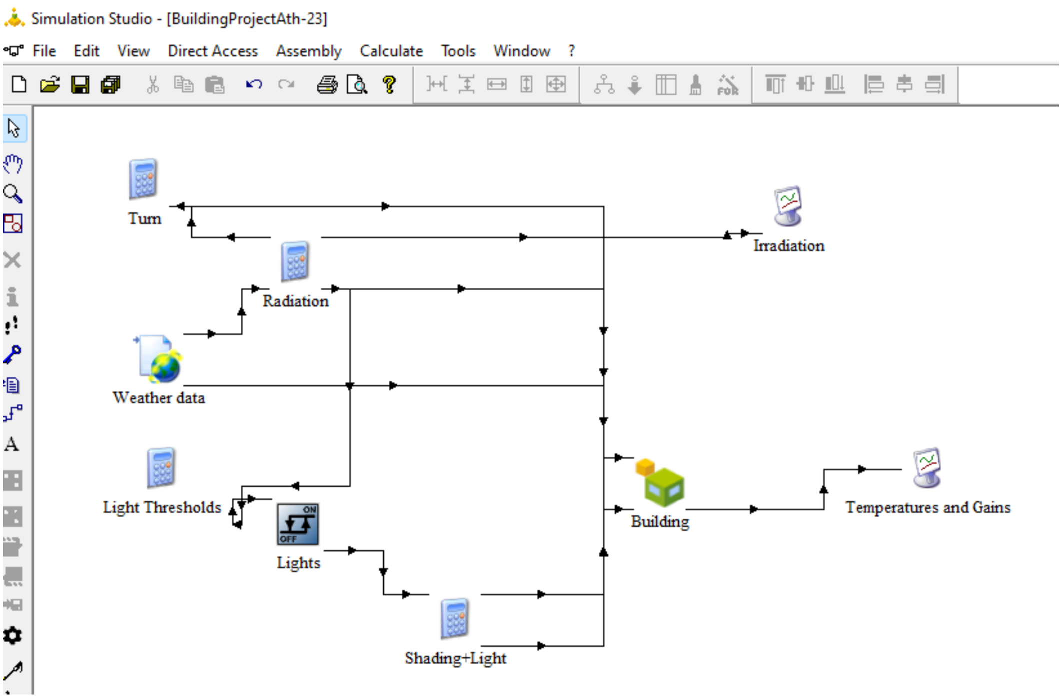


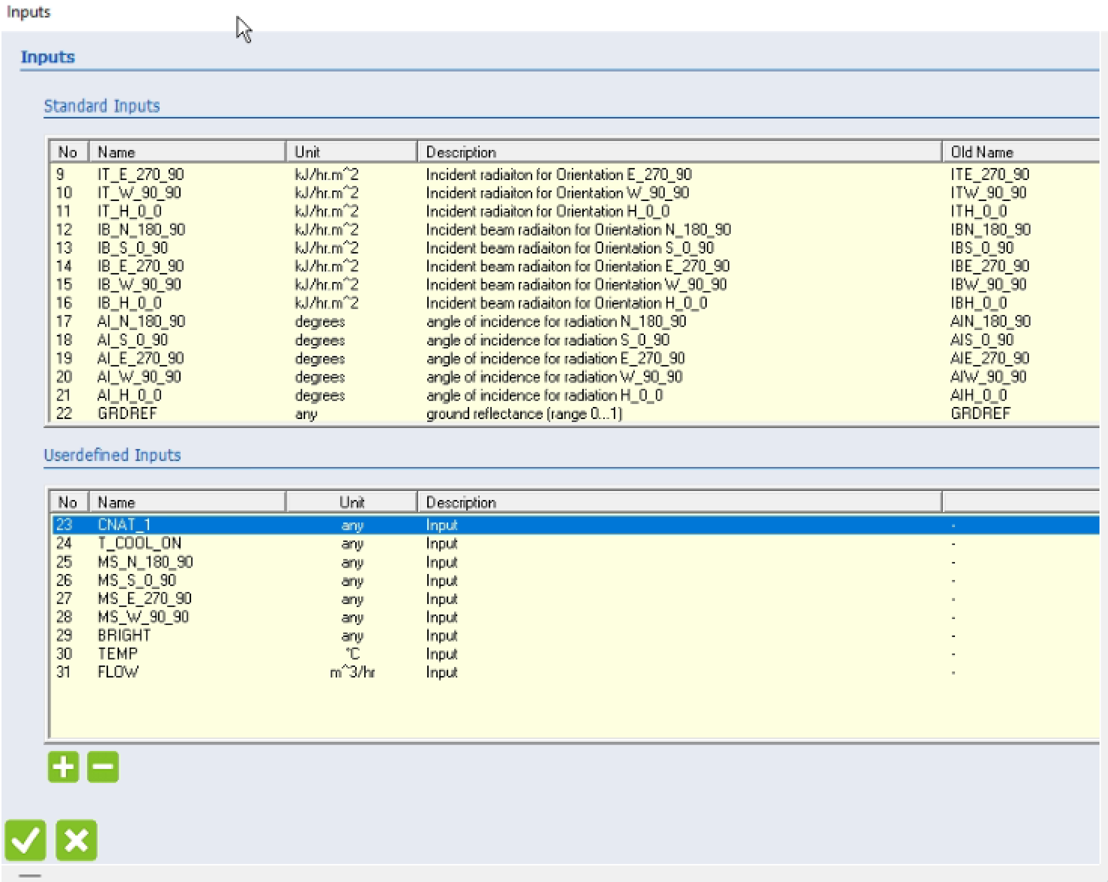
Image 6.10: The building connected to the Simulation Studio components

6.2 Configuration of the building

Having created the model of our building, we are able to edit it according to the needs of our study. To do so, we select the Building icon, right-click and choose Edit Building. This will automatically take us to the TRNBuild environment.

Input data for the building

We select the Project icon and then Inputs, in order to specify the variables that will be as inputs to our building. These variables will be the TEMP variable referring to the temperature of the air of the heating system to be used, and the FLOW variable referring to the supply of air of the heating system. In our case, the heating system will consist of a heat pump, as we will see in more detail later on.


Inputs

Inputs

Standard Inputs

No	Name	Unit	Description	Old Name
9	IT_E_270_90	kJ/hr.m^2	Incident radiaiton for Orientation E_270_90	ITE_270_90
10	IT_W_90_90	kJ/hr.m^2	Incident radiaiton for Orientation W_90_90	ITW_90_90
11	IT_H_0_0	kJ/hr.m^2	Incident radiaiton for Orientation H_0_0	ITH_0_0
12	IB_N_180_90	kJ/hr.m^2	Incident beam radiaiton for Orientation N_180_90	IBN_180_90
13	IB_S_0_90	kJ/hr.m^2	Incident beam radiaiton for Orientation S_0_90	IBS_0_90
14	IB_E_270_90	kJ/hr.m^2	Incident beam radiaiton for Orientation E_270_90	IBE_270_90
15	IB_W_90_90	kJ/hr.m^2	Incident beam radiaiton for Orientation W_90_90	IBW_90_90
16	IB_H_0_0	kJ/hr.m^2	Incident beam radiaiton for Orientation H_0_0	IBH_0_0
17	AI_N_180_90	degrees	angle of incidence for radiation N_180_90	AIN_180_90
18	AI_S_0_90	degrees	angle of incidence for radiation S_0_90	AIS_0_90
19	AI_E_270_90	degrees	angle of incidence for radiation E_270_90	AIE_270_90
20	AI_W_90_90	degrees	angle of incidence for radiation W_90_90	AIW_90_90
21	AI_H_0_0	degrees	angle of incidence for radiation H_0_0	AIH_0_0
22	GRDREF	any	ground reflectance (range 0...1)	GRDREF

Userdefined Inputs

No	Name	Unit	Description	
23	CNAT_1	any	Input	-
24	T_COOL_ON	any	Input	-
25	MS_N_180_90	any	Input	-
26	MS_S_0_90	any	Input	-
27	MS_E_270_90	any	Input	-
28	MS_W_90_90	any	Input	-
29	BRIGHT	any	Input	-
30	TEMP	°C	Input	-
31	FLOW	m^3/hr	Input	-

Image 6.11:Introduction of input variables to the building.

Structural elements of the building

The next step is to edit the structural elements of the building, including the floor, roof, and external walls. We are currently in the TRNBuild environment, so we select the Wall type manager icon to specify the materials from which each wall will be made, as well as the thickness of each wall.

External Walls

The 4 external walls of our building will consist of 5 different layers of materials, which are listed below, and will have a total thickness of 0.37 m. The value of the thermal transmittance coefficient(u-value) is 0.338 W/m^{2}K.

- Plaster: 0.015 m

- Brick: 0.12 m

- Insulation: 0.1 m

- Brick: 0.12 m

- Plaster: 0.015 m

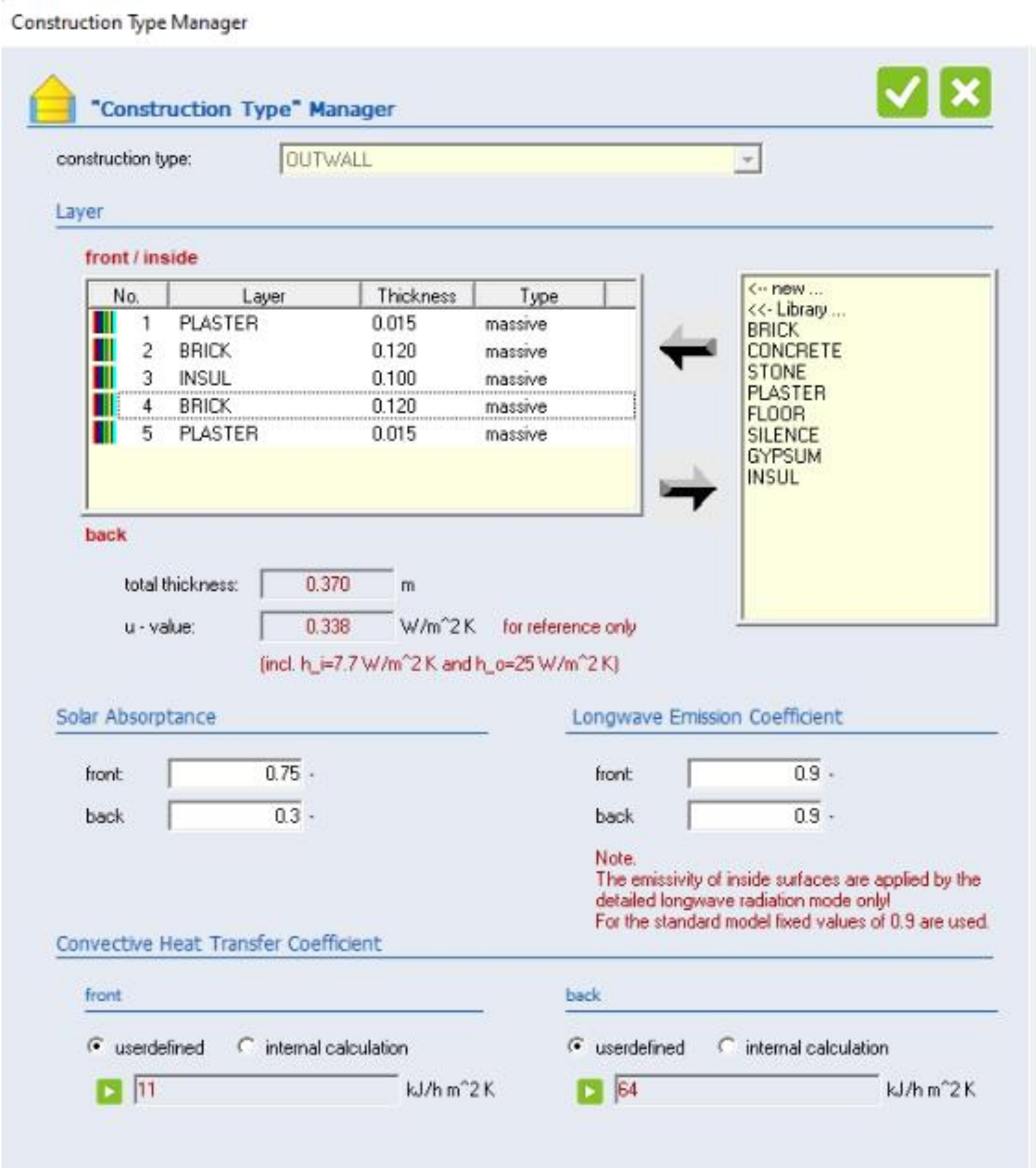


Image 6.12: Selection of materials for the external walls of the building.

<u>Roof</u>

The roof of our building will consist of 3 different layers , which are listed below, while it will have a total thickness of 0.365 m. The value of the thermal transmittance coefficient(u-value) will be 0.357 W/m²K.

- Concrete: 0.25 m

- Insulation: 0.1 m

- Plaster: 0.015 m

Construction Type Manager

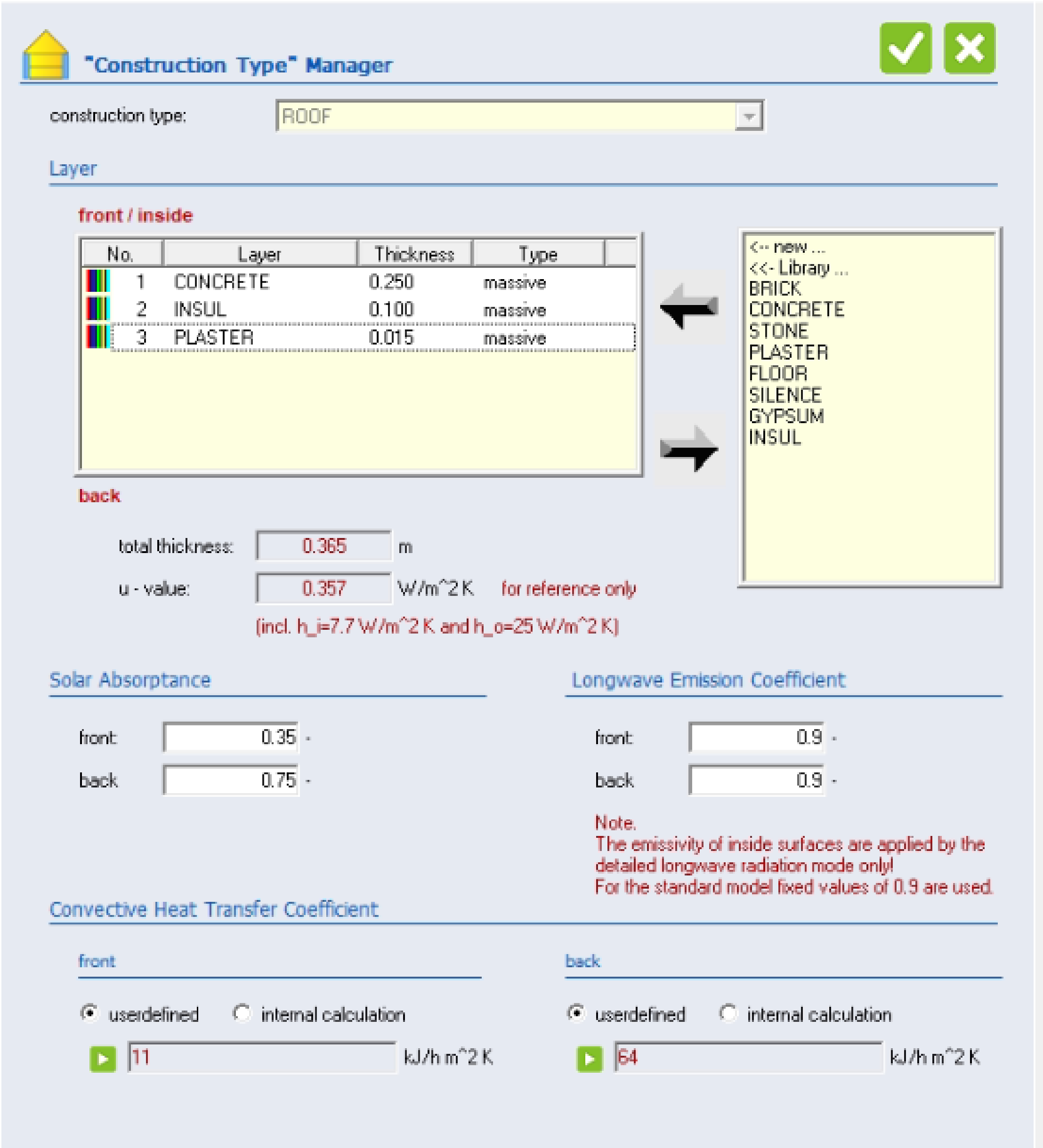


Image 6.13:Selection of materials for the roof of the building.

<u>Building windows</u>

-North side: 0 m^2

-South side: 8 m^2

-East side: 4 m^2

-West side: 4 m^2

To input these values, we select the “Ath-23” icon and work on the right Windows column. We have chosen for all 3 windows to be double glazed, using the DOUBLE option.

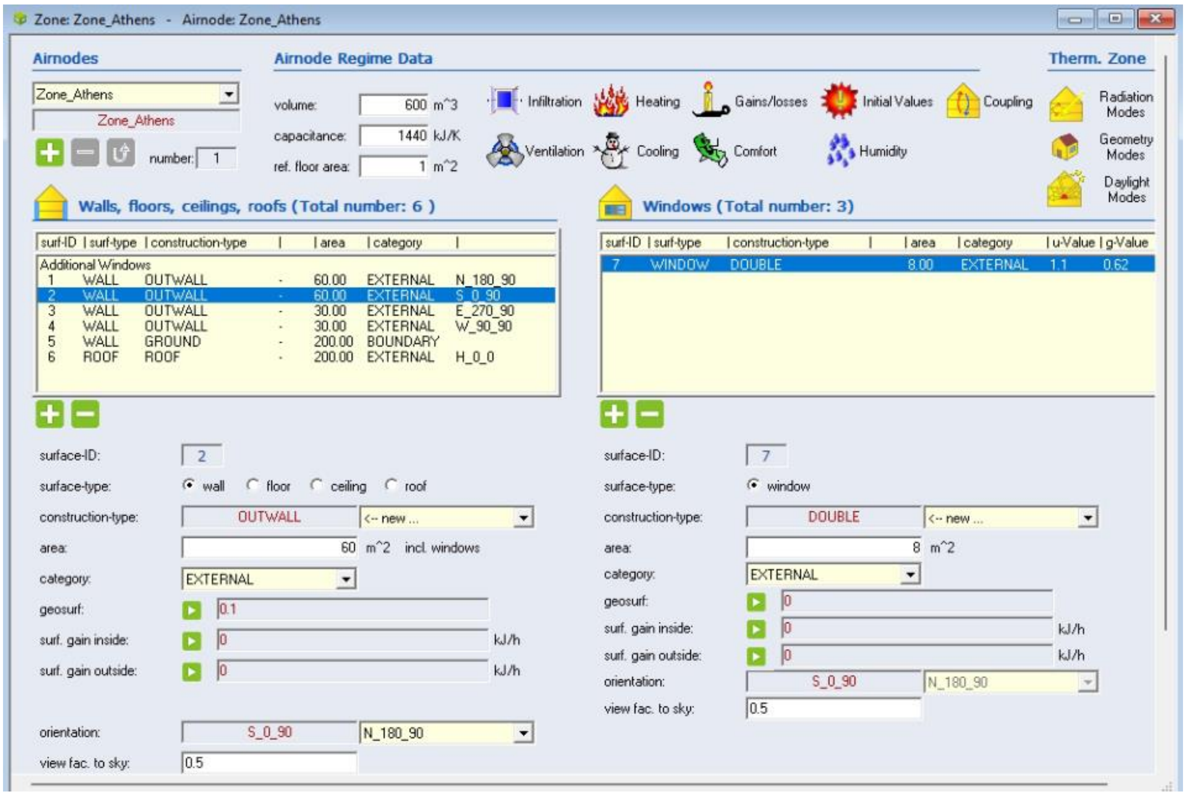


Image 6.14: Editing glass double window

The next stage is the regulation of the room ventilation. For this purpose, we will use the Ventilation type manager icon. The parameters that need to be defined here to activate the ventilation system are the number of air changes, the air supply, and the relative humidity. The FLOW variable defined previously will be used for the air changes.

$$\frac{airchange}{hr} = \frac{\dot{m}}{\rho V} = \frac{\dot{m}}{1.18[\frac{kg}{m^3}]*600[m^3]} = 0.0014 * \dot{m} \quad (6.1)$$

Where the value 1.18 kg/m^3 refers to the density of air, while the value 600 m^3 refers to the volume of our building. The variable $\dot{m}$ obviously refers to the air supply of the heat pump and will be replaced by the variable FLOW, which will be connected as an input to the building. Therefore, in the Airchange of Ventilation window, we will define the function 0.0014×FLOW.

Next, the temperature will be equal to the variable TEMP, which refers to the temperature of the air of the heat pump, so the function 1×TEMP is defined in the Temperature of Air Flow window, while for the relative humidity, a typical value of around 50% is selected in the Relative Humidity of Air Flow window.

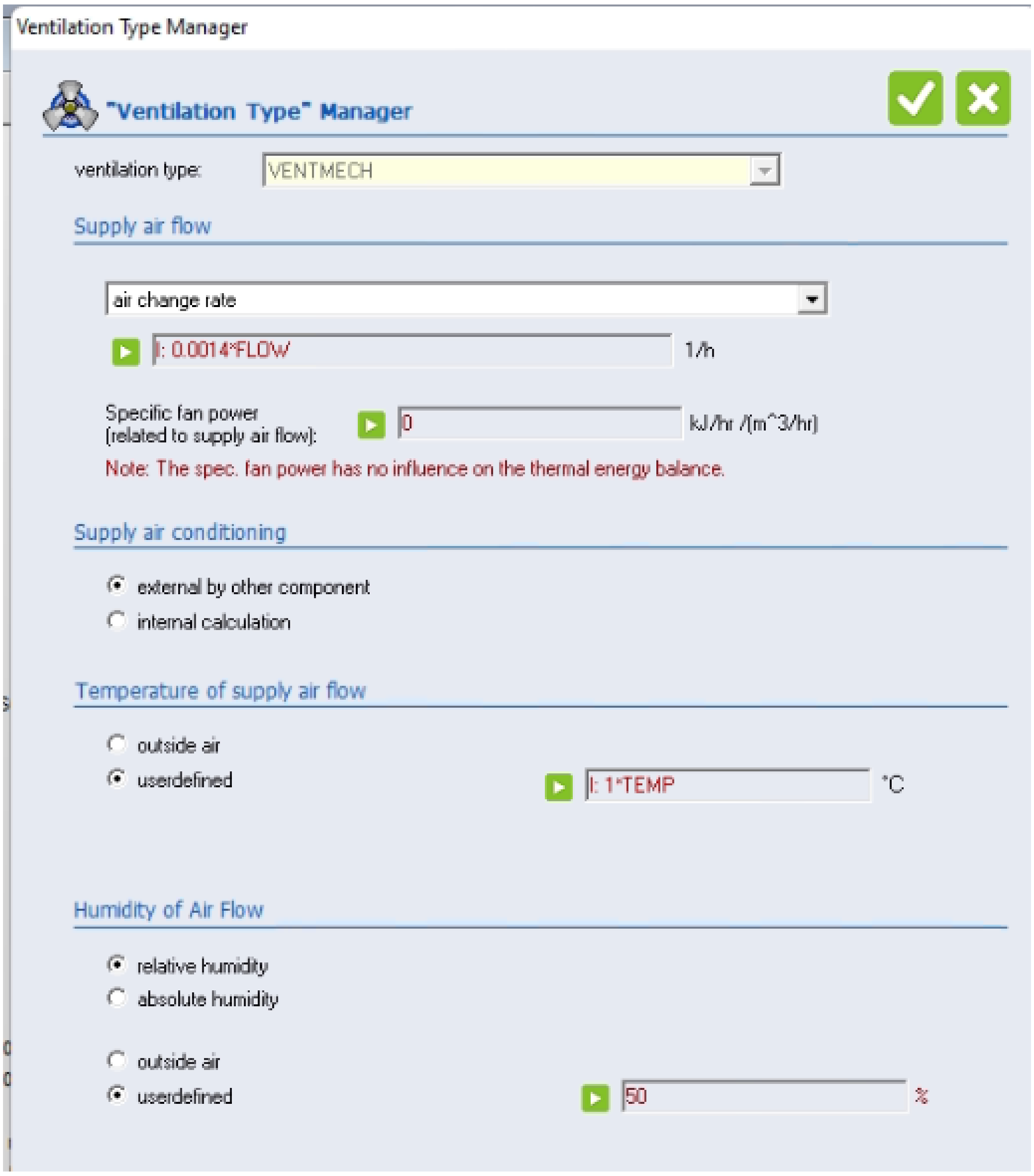


Image 6.15: Building Ventilation Processing

To set the operating hours of our building, we use the Schedule type manager icon. Since our building is a private residence, we define the schedule as 24 hour operation.

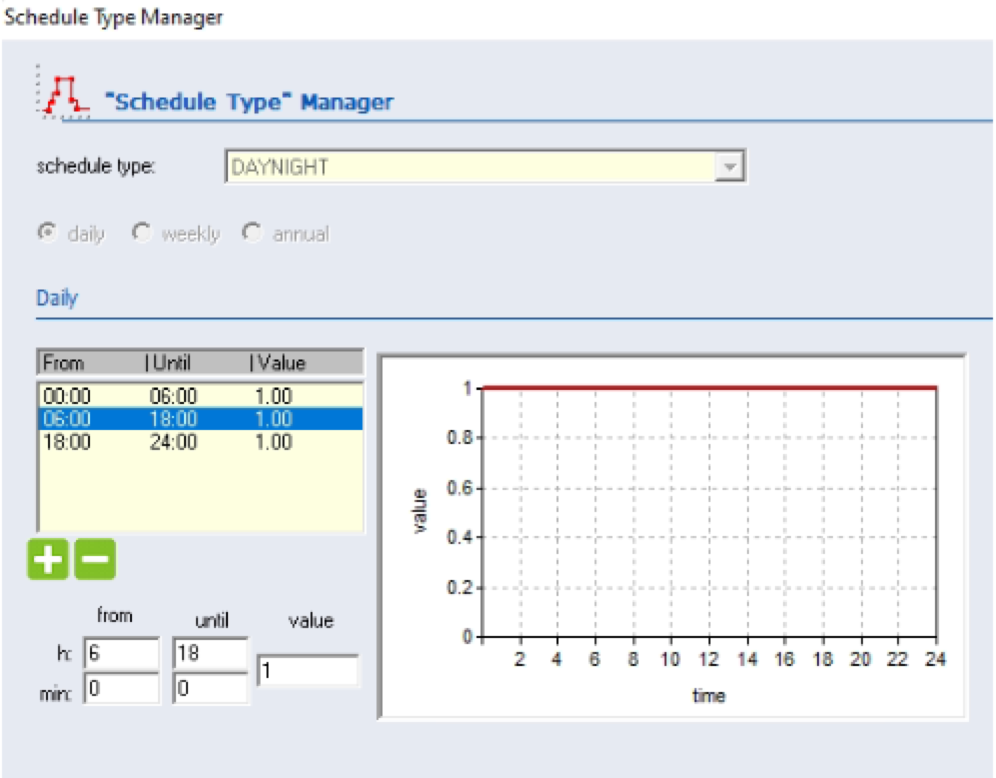


Image 6.16: Setting the building's operating hours

At this point, we have finished editing the building. After saving the changes, we close TRNBuild and move back to Simulation Studio.

6.3 Basic simulation models

Combined model for reading meteorological data and processing solar radiation

This model serves the general purpose of reading meteorological data at regular time intervals from a data file, converting them to the desired unit system, and calculating the direct and diffuse radiation for an arbitrary number of surfaces with arbitrary orientation and slope. Model 109 reads certain files with known formatting as well as files with formatting determined by the user.

Observations:

- Up to 5 109 models can be used in one simulation.

- Data from line to line must have a constant time interval.

- In operation 0, where the data formatting is determined by the user, the data is exported in the same order as it appears in the data file. In all data management operations, the output has the same default output order to facilitate the process.

- In operation 0, there can be up to 20 lines of comments before the data lines. Comment lines should not start with a number.

- Interpolation may or may not be applied between time steps depending on the specified parameters.

- If the simulation ends with data giving radiation ≠ 0, the radiation value is set to 0 for the last hour of the simulation.

Image 6.17: Combined model for reading meteorological data and processing solar radiation type 109.

<u>Creating Direct Plots</u>

This model is used to display selected variables on the screen at specific time steps simultaneously with the simulation execution. This model is very useful as it allows the user to directly control the variables under study during the simulation process. Additionally, the plots of different variables are displayed in different windows on the screen.

With this model, it is also possible to create a file with all the variable values that are being printed. This can be done by setting parameter 10 of the model to a positive number. Additionally, the printer can be turned off without deleting the model from the simulation program by setting parameter 9 to -1. If all online plotters have been turned off, the default progress bar of the simulation is displayed instead of the plots. If output file generation has been selected, it is created even if the printer is turned off.

Observations:

• In a simulation, there can be up to 5 online plotters.

• Each printer can have 1 to 20 inputs (10 on the left axis and 10 on the right).

• Label cards are required to define the units of variables and the titles of graphs. Specifically, three labels must be defined. The first refers to the title of the left y-axis, the second to the title of the x-axis, and the third to the title of the graph.

• The number of inputs is equal to the sum of the first two parameters.

Image 6.18: Creating direct type 65 plots.

Building

The multi-zone building is simulated using model 56 of the TRNSYS program. In this model, each zone is described by its thermal capacitance, the volume of air it encloses, and the thermal capacitance of the elements within it (e.g. furniture). Each zone is a separate computational node in which the thermal capacitance and volume of the zone are separate inputs.

Image 6.19: Building type 56

6.4 Analysis of the interconnection of the components of the basic installation

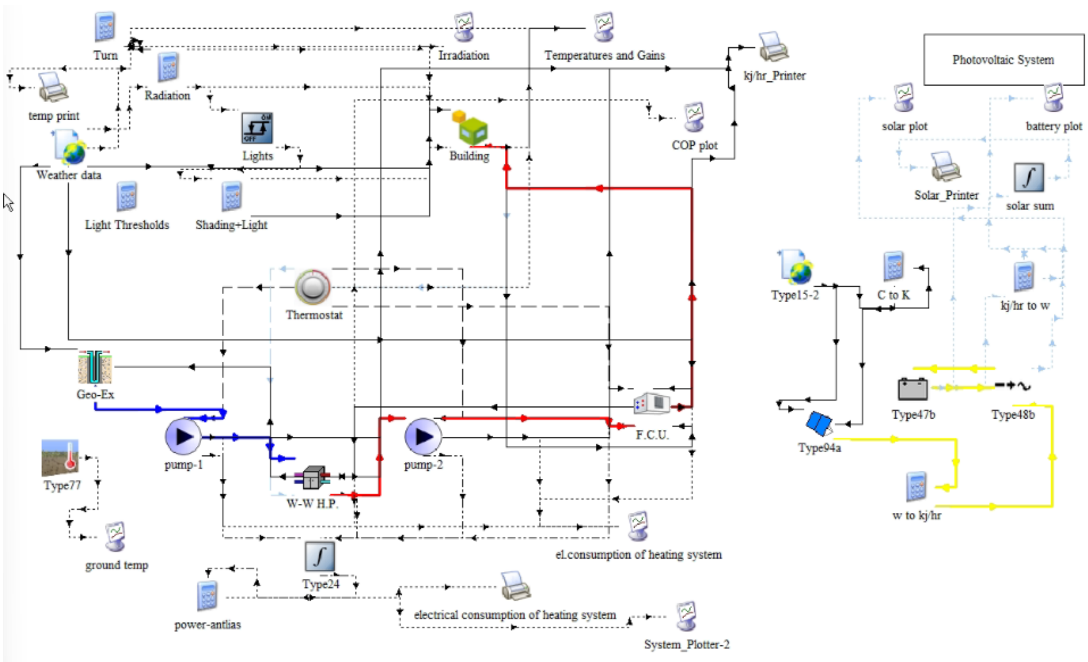


Image 6.20: The whole installation in Transys

In our installation, we will use a water to water heat pump to heat our building. A thermostat will determine the temperature of the air in the building.

First of all we select the weather data file of Athens form the External Files.

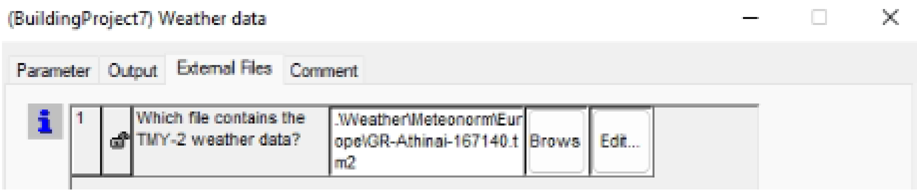


Image 6.21: Selection of weather data file

The building has the default inputs of a multizone building project.

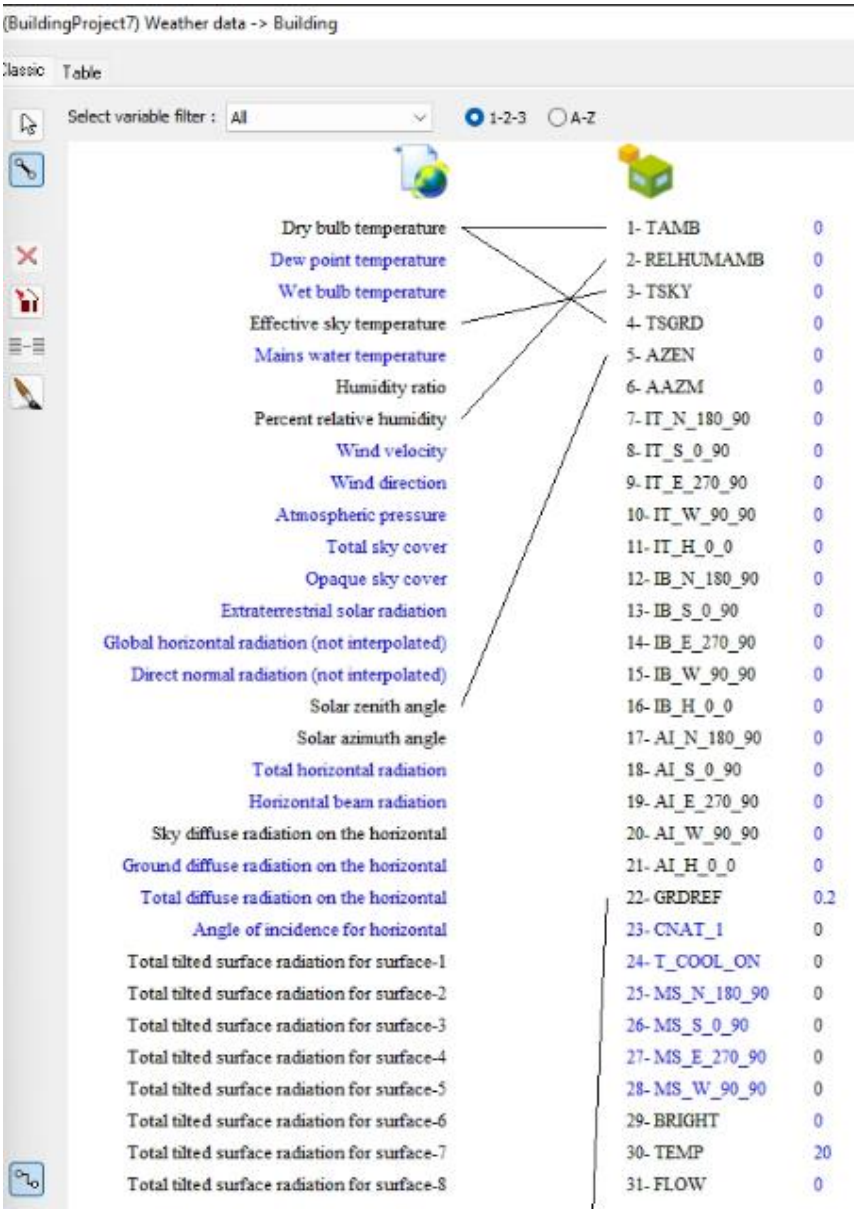


Image 6.22 : Weather data and building connection

Geothermal heat exchanger- Water to water heat pump - Fan coil unit system

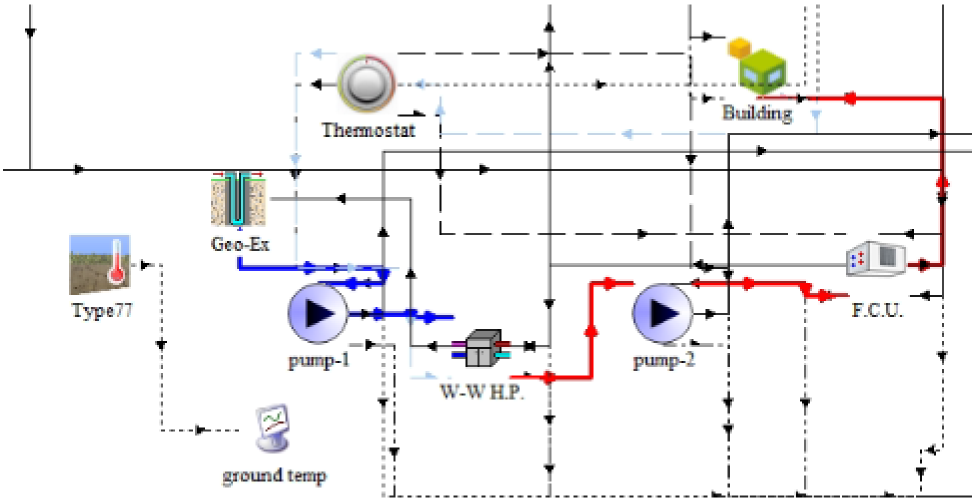


Image 6.23: Components connection of heating system

We used Type 77 to find the temperature of the ground in different depths in order to see what's the optimal depth for our ground heat exchanger.

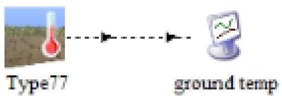
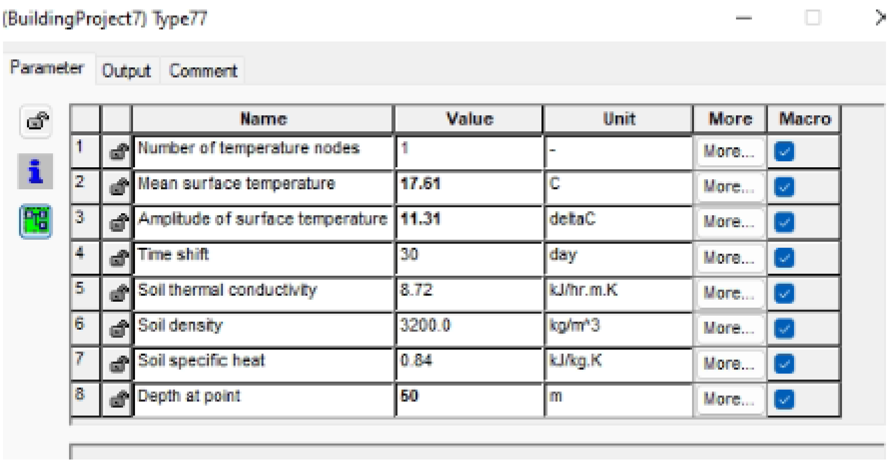


Image 6.24: Connection of type 77 with a plot output manager


(BuildingProject7) Type77

Parameter Output Comment

	Name	Value	Unit	More	Macro
1	Number of temperature nodes	1	-	More...	☑
2	Mean surface temperature	17.61	C	More...	☑
3	Amplitude of surface temperature	11.31	deltaC	More...	☑
4	Time shift	30	day	More...	☑
5	Soil thermal conductivity	8.72	kJ/hr.m.K	More...	☑
6	Soil density	3200.0	kg/m^3	More...	☑
7	Soil specific heat	0.84	kJ/kg.K	More...	☑
8	Depth at point	50	m	More...	☑

Image 6.25: Parameters of type 77

After plotting the dry bulb temperature from the weather data file of Athens, we calculated the Mean surface temperature and amplitude of surface temperature. The temperature of the ground is stable as deeper as we go and in 50m deep the temperature is 17 ^{o}C.

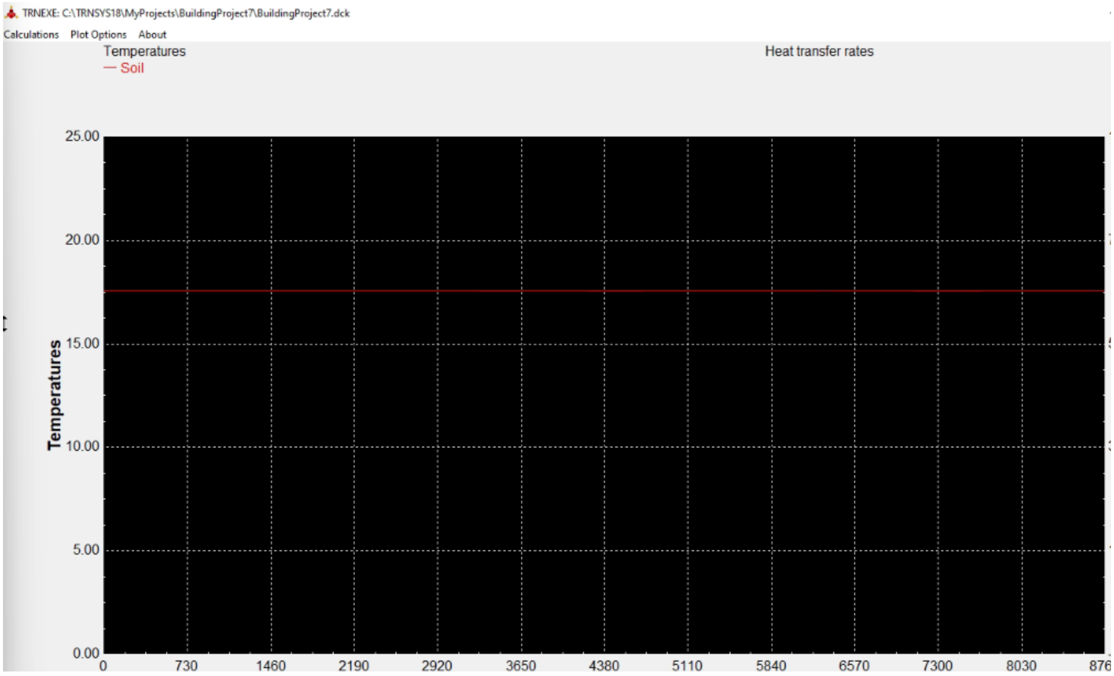


Image 6.26: Soil temperature depiction

Then we edit the parameters of the type 557 of a vertical U tube ground heat exchanger. This subroutine models a vertical ground heat exchanger that interacts thermally with the ground. A heat carrier fluid is circulated through the ground heat exchangers and either rejects heat to, or absorbs heat from the ground depending on the temperatures of the heat carrier fluid and the ground.

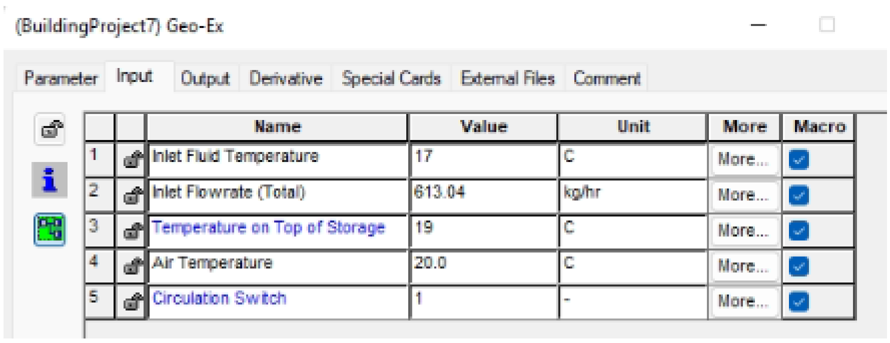


Image 6.27: Parameters of ground heat exchanger component

This component is linked with the weather data, a pump , the water to water heat pump and as shown in the next images.

Image 6.27: Connection of ground heat exchanger with the pump

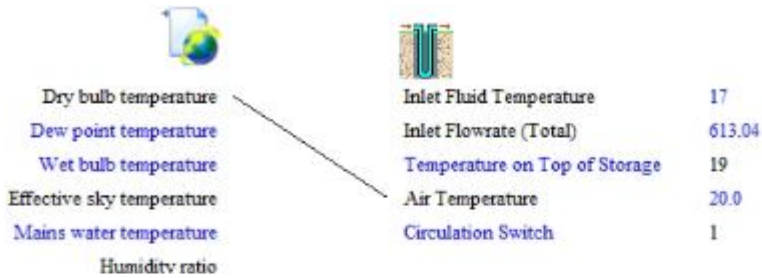
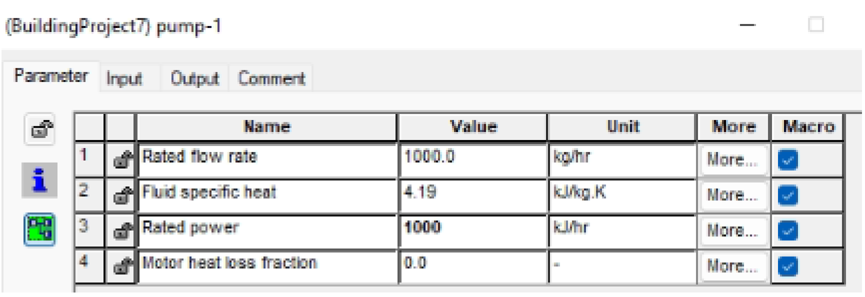


Image 6.28: Connection of weather data with ground heat exchanger

The first Pump is between the geothermal heat exchanger and our heat pump.This pump and the other one between the heat pump and the fan coil unit are very important to our simulation because they need an important amount of energy as we will see in the next chapter and moreover due to their power efficiency ,they make our simulation more realistic.The linking of the first pump and it's parameters is shown in the next images.


(BuildingProject7) pump-1

Parameter Input Output Comment

	Name	Value	Unit	More	Macro
1	Rated flow rate	1000.0	kg/hr	More...	☑
2	Fluid specific heat	4.19	kJ/kg.K	More...	☑
3	Rated power	1000	kJ/hr	More...	☑
4	Motor heat loss fraction	0.0	-	More...	☑

Image 6.29: Parameters of single speed pump component

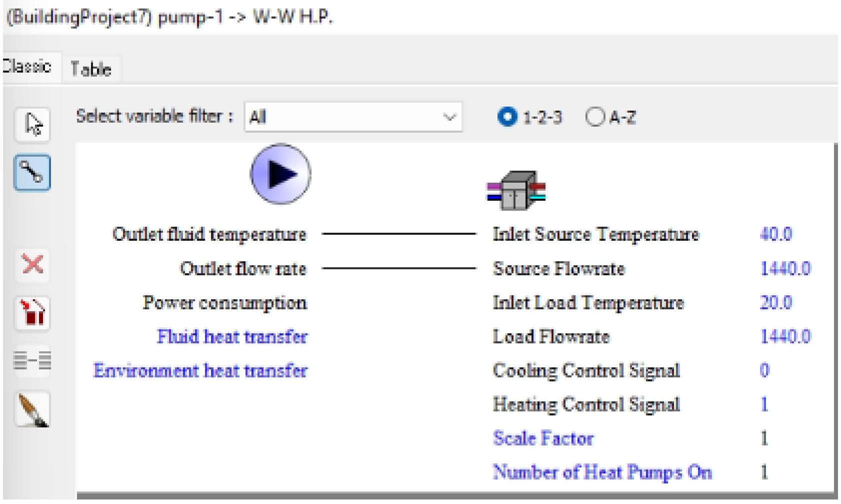
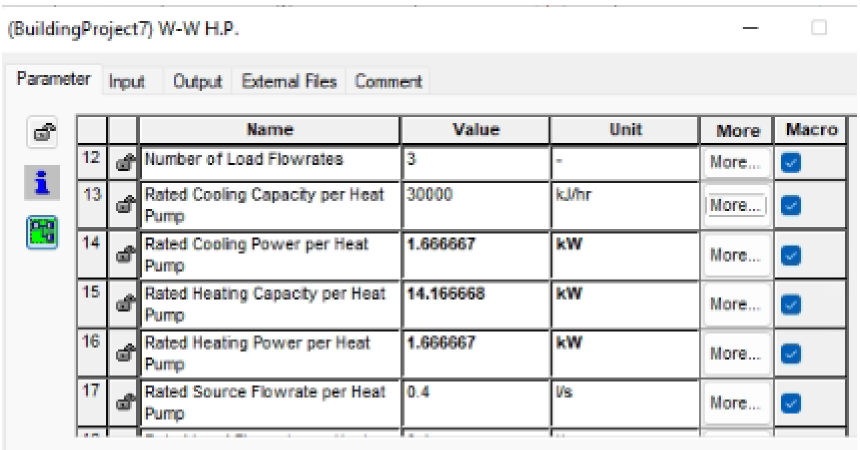


Image 6.30: Connection of single speed pump with the water to water heat pump

The type 927 is a normalized single stage water to water heat pump .This type contains a catalog of capacity and power draw based on the inputs such as the load and temperature. The way we operated on the parameters modification of this component was to provide the most efficient variables in order to never let the temperature of the building get lower from the heating se point. If that happened in any moment of the year, it would mean that we should provide a more powerful or efficient heat pump parameters. This method will be discussed more in the next chapter.



	Name	Value	Unit	More
12	Number of Load Flowrates	3	-	More...
13	Rated Cooling Capacity per Heat Pump	30000	kJ/hr	More...
14	Rated Cooling Power per Heat Pump	1.666667	kW	More...
15	Rated Heating Capacity per Heat Pump	14.166668	kW	More...
16	Rated Heating Power per Heat Pump	1.666667	kW	More...
17	Rated Source Flowrate per Heat Pump	0.4	l/s	More...

Image 6.31: Parameters of water to water heat pump component

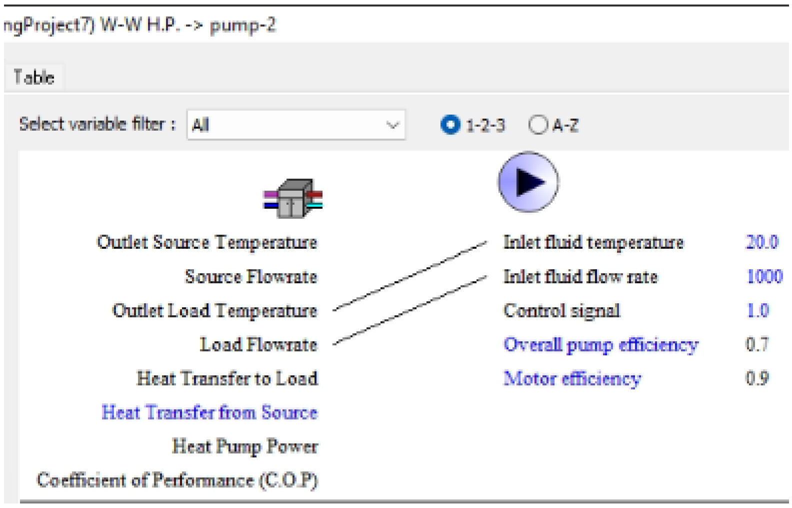


Image 6.32: Connection of water to water heat pump with the single speed pump.

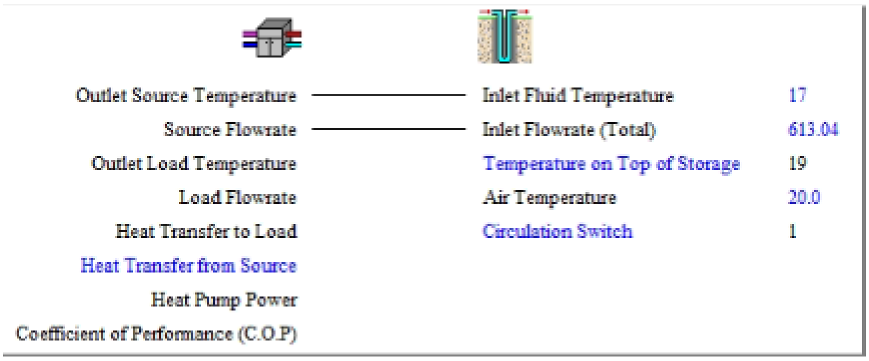


Image 6.33: Connection of W-W H.P with the ground heat exchanger

After the water source heat pump the fluid goes on another pump and after that to a fan coil unit. There, the heat is transferred from the fluid to the air and then to the building.

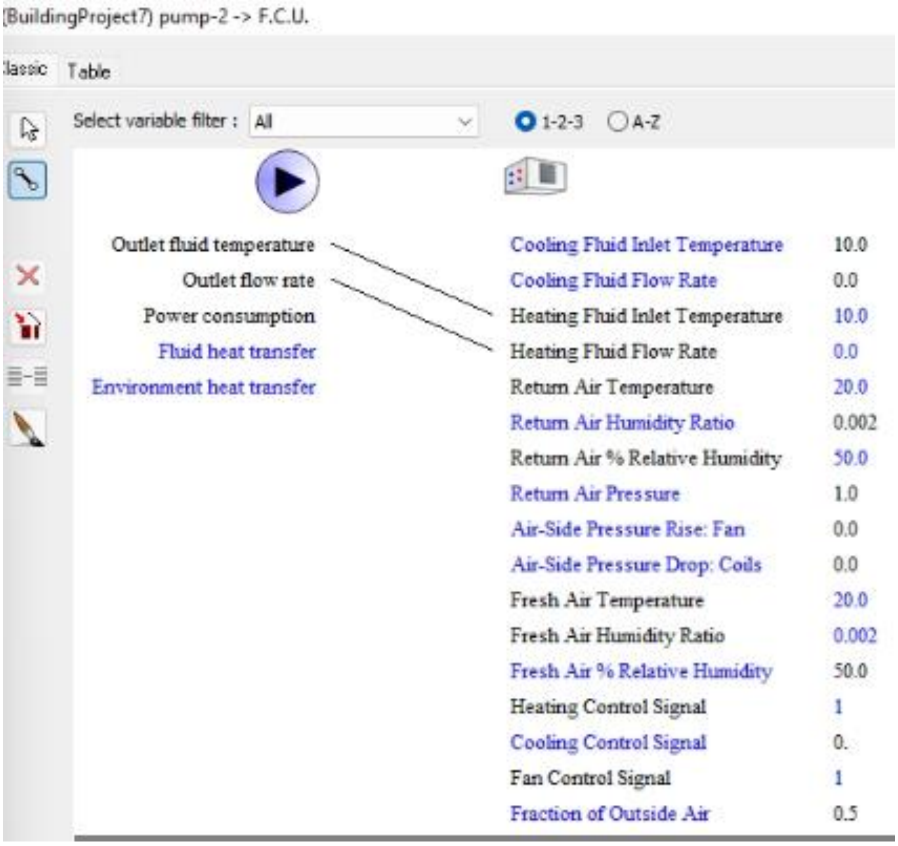


Image 6.34: Connection of single speed pump with the Fan Coil Unit

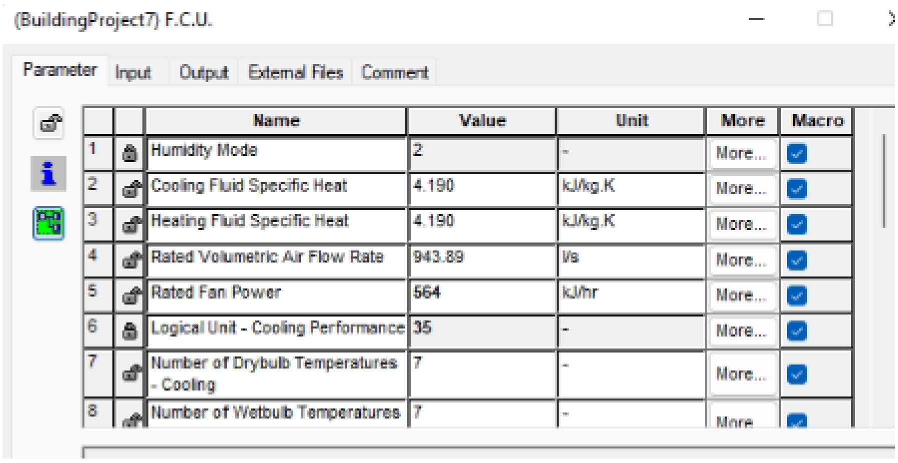


Image 6.35: Fan Coil Unit component parameters

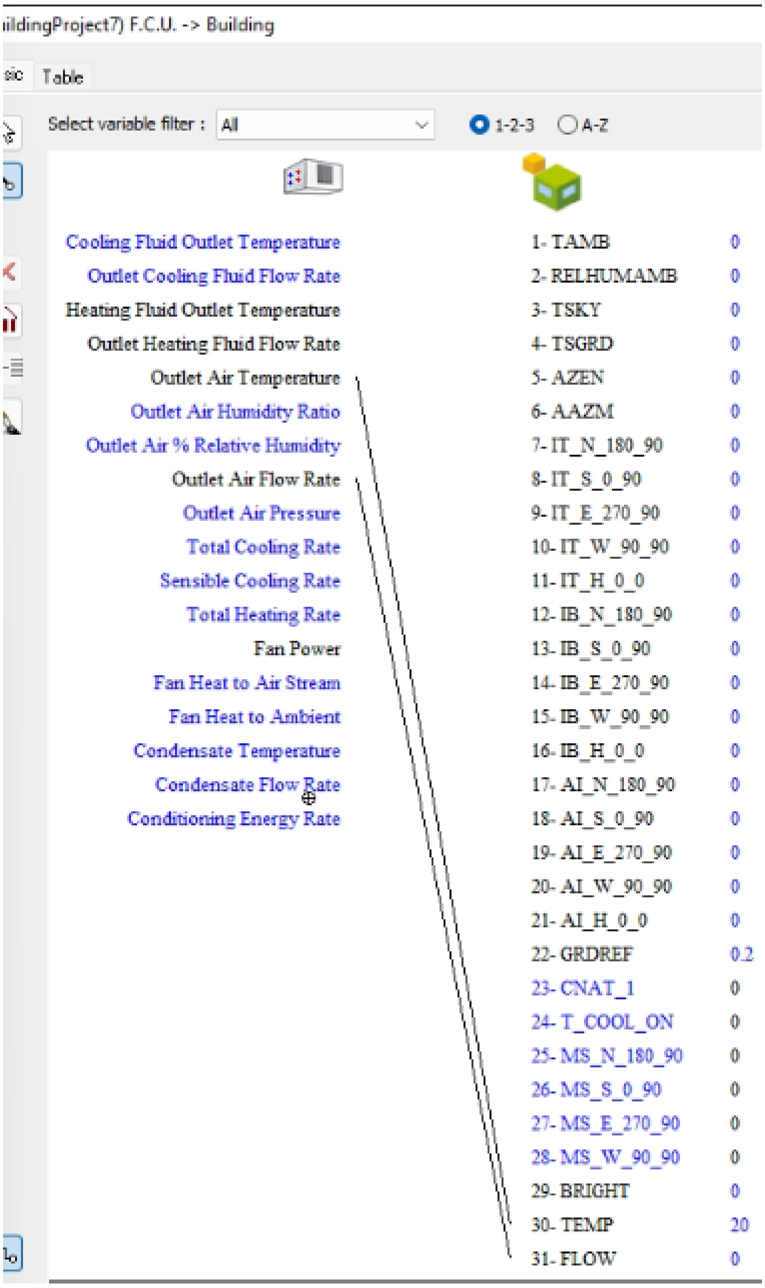


Image 6.36: Connection of F.C.U. with the Building

Except from the output temperature of the fan coil unit we should also take into account the relative humidity of the air. After the fan coil, the fluid returns to the water source heat pump and then in the geothermal heat exchanger.

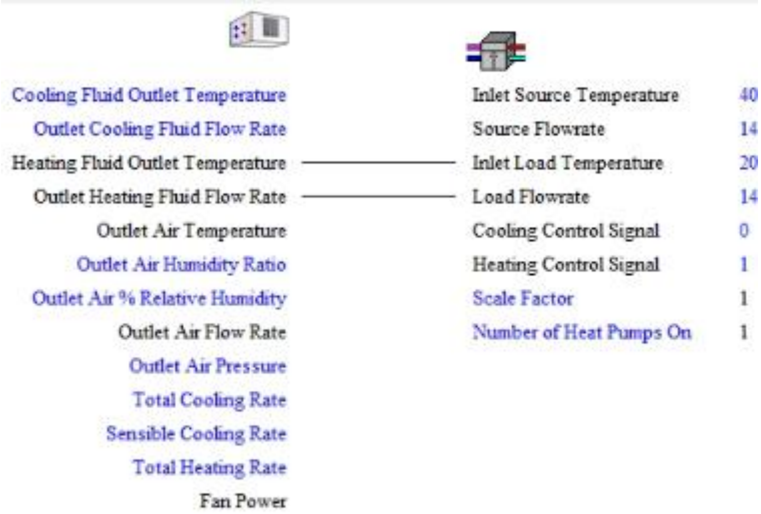


Image 6.37: Connection of the F.C.U. with the W.W.H.P.

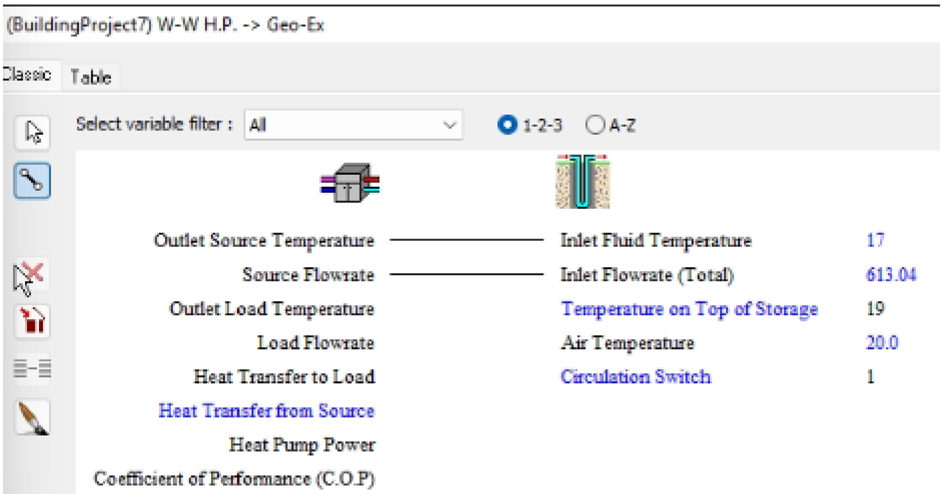


Image 6.38: Connection of the W.W.H.P. with the ground heat exchanger component

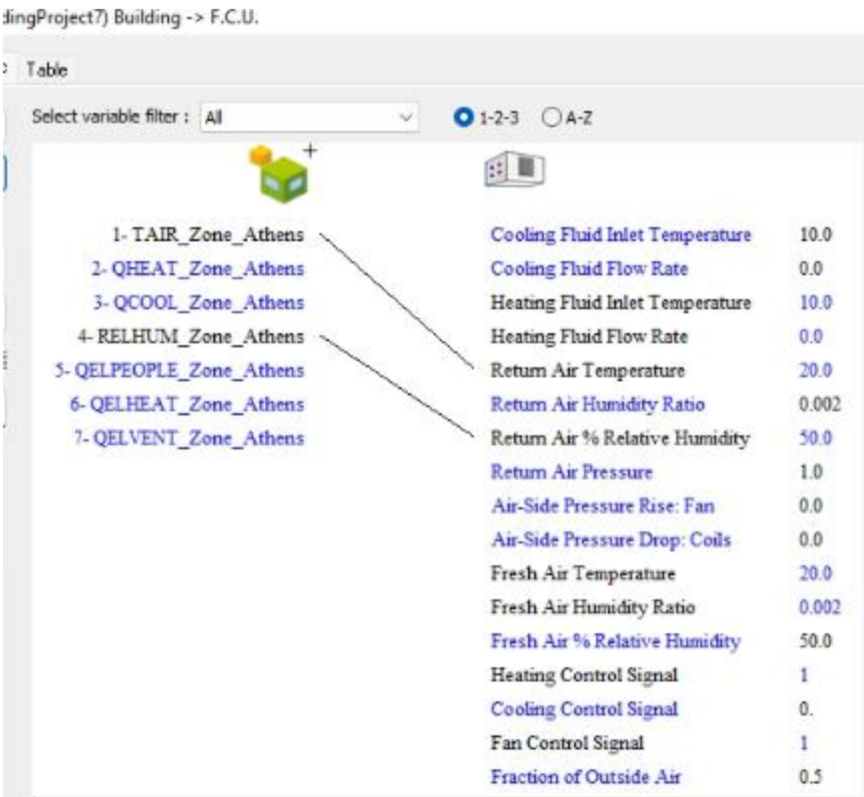
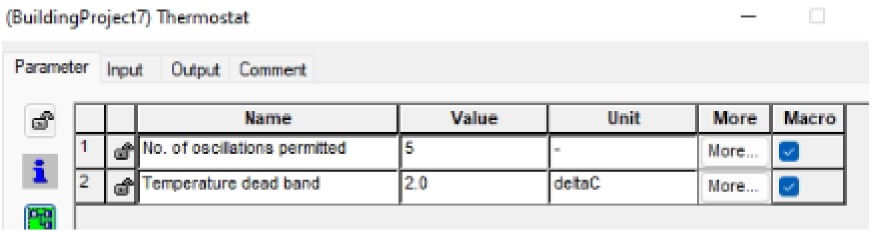


Image 6.39:Connection of the building with the F.C.U.

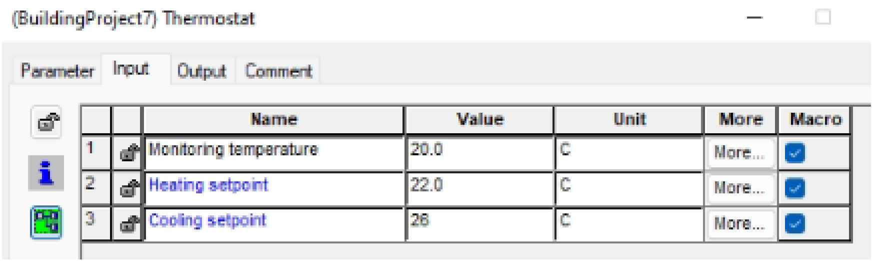
All this components are under operation after a thermostat sends a heating signal. We set the heating signal in 22°C. When the temperature of the house goes under of that limit the heat pump, the fan coil and the two pumps start to operate.


(BuildingProject7) Thermostat

Parameter Input Output Comment

	Name	Value	Unit	More	Macro
1	No. of oscillations permitted	5	-	More...	☑
2	Temperature dead band	2.0	deltaC	More...	☑

Image 6.40: Parameters of the Thermostat component


(BuildingProject7) Thermostat

Parameter Input Output Comment

	Name	Value	Unit	More	Macro
1	Monitoring temperature	20.0	C	More...	☑
2	Heating setpoint	22.0	C	More...	☑
3	Cooling setpoint	26	C	More...	☑

Image 6.41: Input values of the thermostat components.

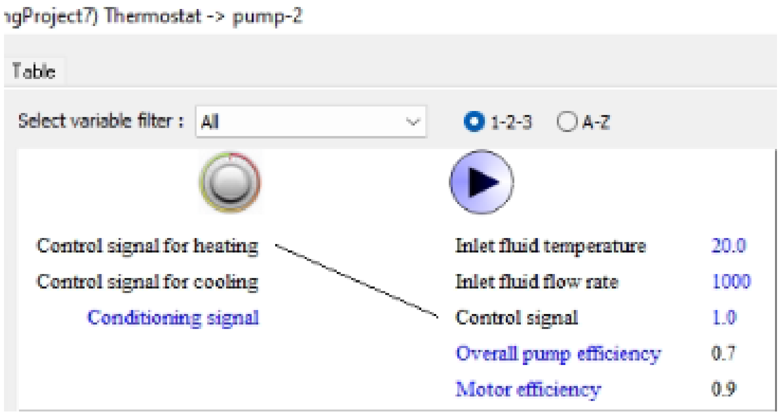


Image 6.42: Connection of the thermostat with the single speed heat pump

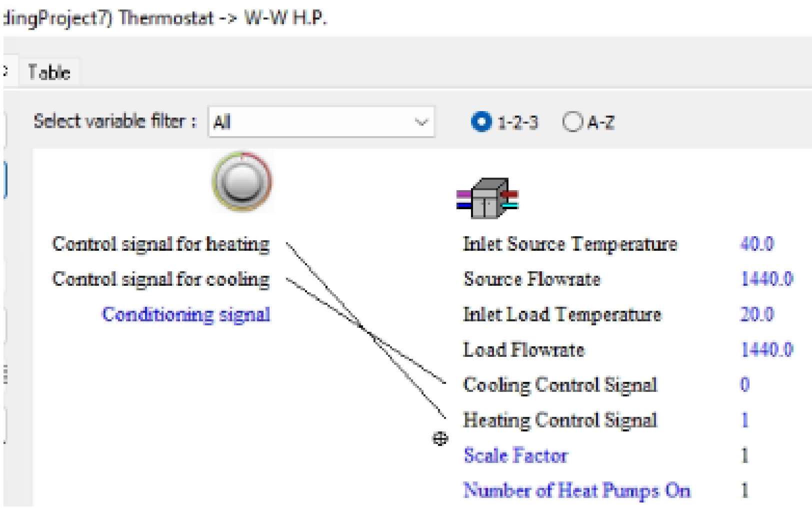


Image 6.43: Connection of the thermostat with the W.W.H.P.

Image 6.44:Connection of the thermostat with the F.C.U.

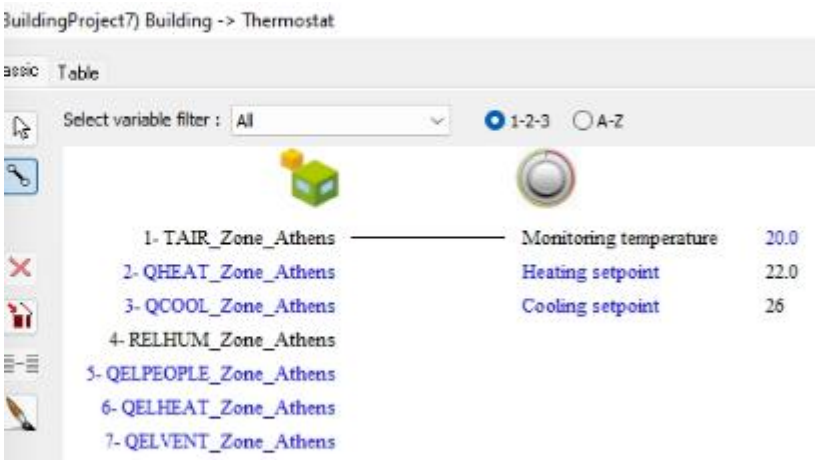


Image 6.45:Connection of the building with the thermostat component

Phtovoltaic panels – inverter – battery

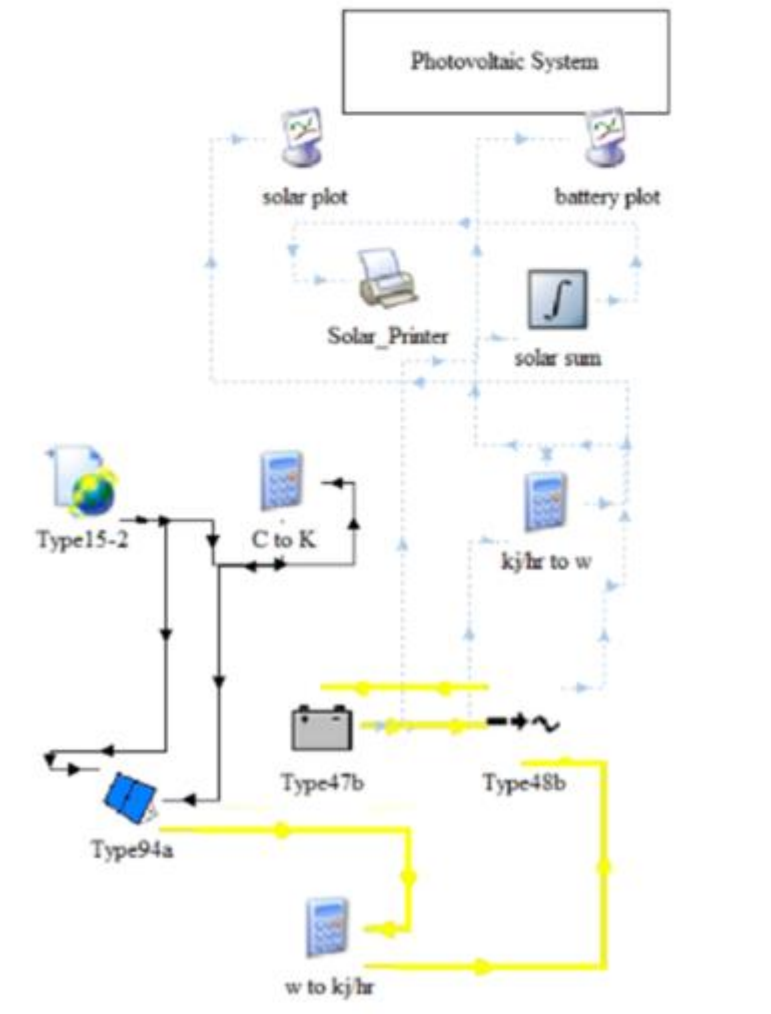
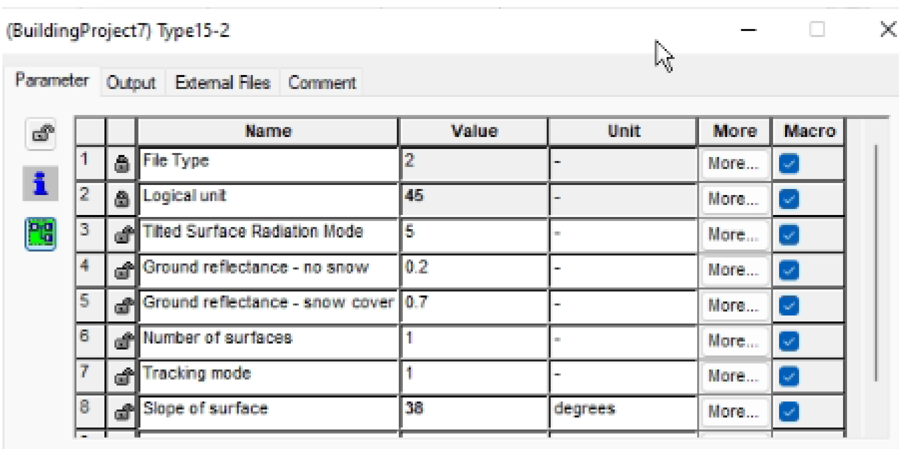


Image 6.46: Photovoltaic system

First, we connect the weather data with the p/v panels. We put 38 degrees tilt of p/v panel in the input of weather data.



	Name	Value	Unit	More	Macro
1	File Type	2	-	More...	
2	Logical unit	45	-	More...	
3	Tilted Surface Radiation Mode	5	-	More...	
4	Ground reflectance - no snow	0.2	-	More...	
5	Ground reflectance - snow cover	0.7	-	More...	
6	Number of surfaces	1	-	More...	
7	Tracking mode	1	-	More...	
8	Slope of surface	38	degrees	More...	

Image 6.47: Parameters of the weather data component in the photovoltaic system

Then we insert a calculator in ordet to convert the ambient temperature from Celsius to Kelvin.

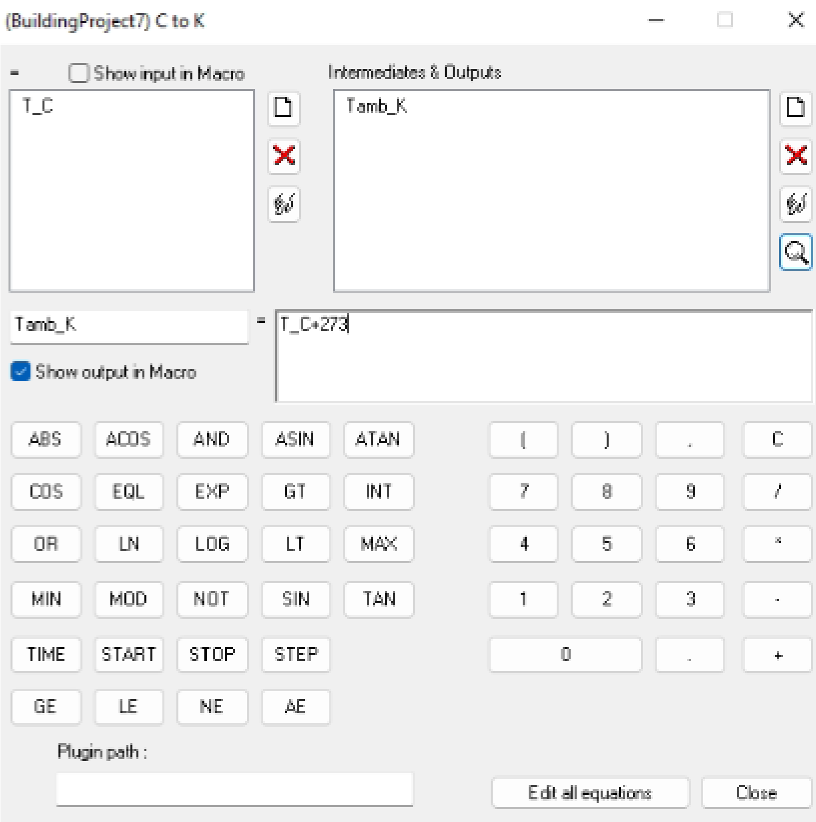


Image 6.48: Convergence from C to K

The type 94a needs the total incident radiation and the ambient temperature as an input from the weather data.

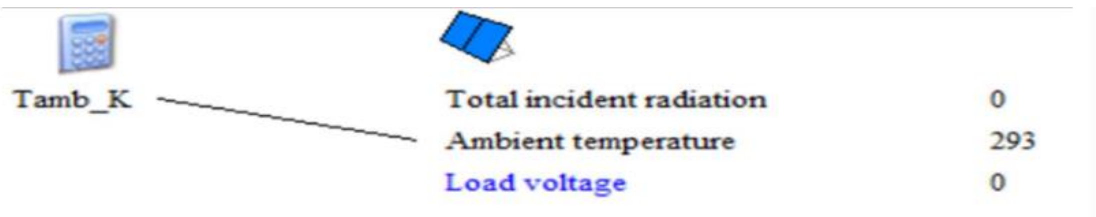


Image 6.49: Connection of the equation component with the P/V panel

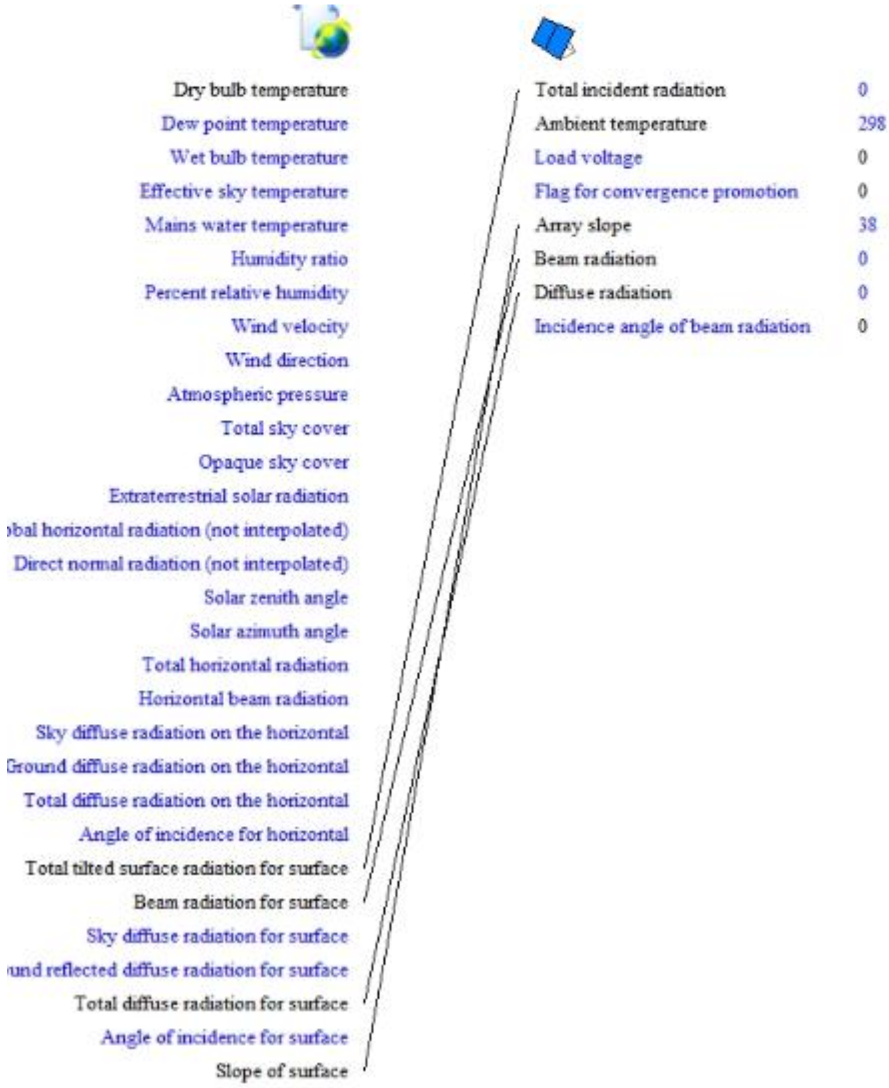
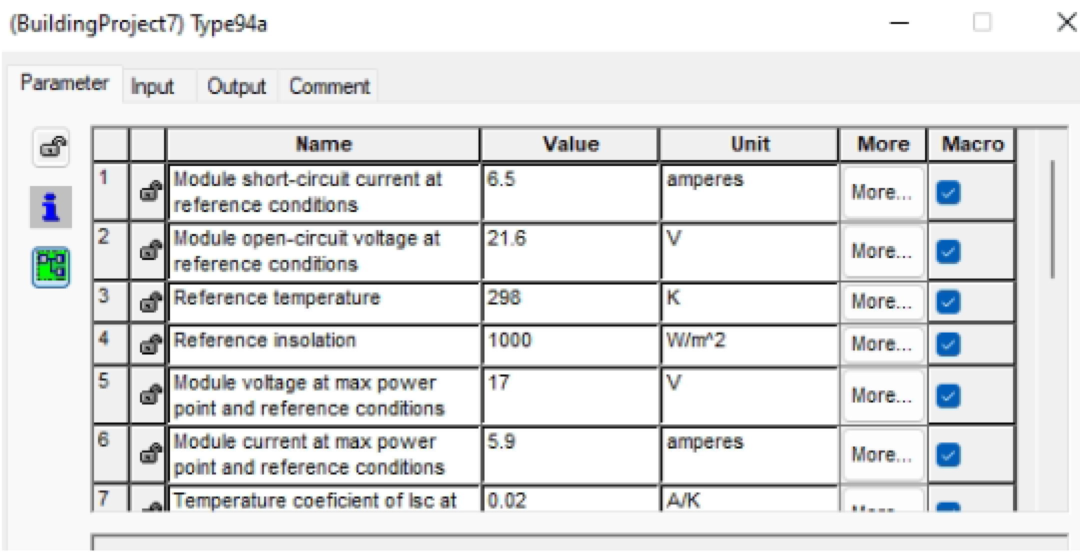


Image 6.50: Connection of weather data with the p/v panels

For sizing of the photovoltaic panels and their parameters, we use 36 panels (6 parallel and 6 series). Each panel is 0.89 m^2, so we have 32.04 m^2 of panel area. This measurement was chosen because of the assistance factor of the solar energy to the heat pump. More details will be discussed on the next chapter.



	Name	Value	Unit	More	Macro
1	Module short-circuit current at reference conditions	6.5	amperes	More...	☑
2	Module open-circuit voltage at reference conditions	21.6	V	More...	☑
3	Reference temperature	298	K	More...	☑
4	Reference insolation	1000	W/m^2	More...	☑
5	Module voltage at max power point and reference conditions	17	V	More...	☑
6	Module current at max power point and reference conditions	5.9	amperes	More...	☑
7	Temperature coeficient of Isc at	0.02	A/K		

Image 6.51: Parameters of the Photovoltaic panel component

For the battery- inverter connection we use the type 47b for the battery and type 48b for the inverter. The battery is lead-acid storage .The inverter provides the data to the battery for the power it absorbs or gives. The battery informs the inverter for the state of charge every moment. As for the parameters of them, we chose the inverter output power capacity to 2kW after tests and the battery capacity to 150 Ah because of the efficiency and economic factors that will be discussed in the next chapter. With 4*6*150Ah (3600) battery we will have a capacity of 43.2 kWh. The battery has a charging efficiency 90% and the inverter efficiency 95%. The inverter power capacity was chosen after defining the maximum power that the system will demand which will be discussed in the results.

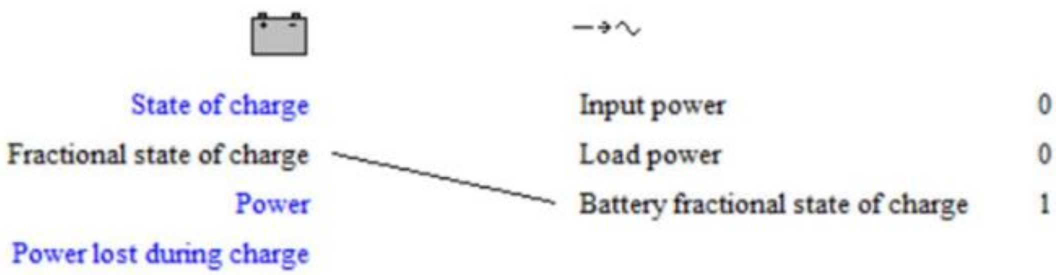


Image 6.52: Connection of the Battery with the Inverter component

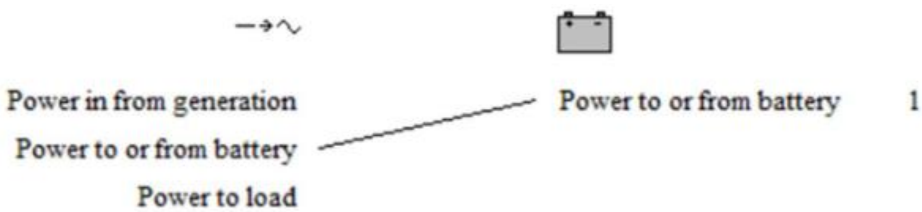


Image 6.53: Connection of the Inverter with the Battery component

(BuildingProject7) Type47b

Parameter | Input | Output | Derivative | Comment

		Name	Value	Unit	More	Macro
1		Mode	2	-	More...	☑
2		Cell energy capacity	**150**	Ah	More...	☑
3		Cells in parallel	**4**	-	More...	☑
4		Cells in series	6	-	More...	☑
5		Charging efficiency	0.9	-	More...	☑
6		Max. current per cell charging	3.33	amperes	More...	☑
7		Max. current per cell discharge	-3.33	amperes	More...	☑
8		Max. charge voltage per cell	2.5	V	More...	☑

Image 6.54:Parameters of battery component

(BuildingProject7) Type48b

Parameter | Input | Output | Comment

		Name	Value	Unit	More	Macro
1		Mode	1	-	More...	☑
2		Regulator efficiency	**0.85**	-	More...	☑
3		Inverter efficiency	0.96	-	More...	☑
4		High limit on fractional state of charge (FSOC)	1	-	More...	☑
5		Low limit on FSOC	0	-	More...	☑
6		Charge to discharge limit on FSOC	0.85	-	More...	☑
7		Inverter output power capacity	**2**	**kW**	More...	☑

Image 6.55: Parameters of Inverter component

For the connection of photovoltaic panels with the battery-inverter system , the p/v panels should send the DC electrical power they generate to the inverter in order to convert it to AC that could be used by the heat pump or the house energy consumption. A calculator is used to convert Watt to kJ/hr.

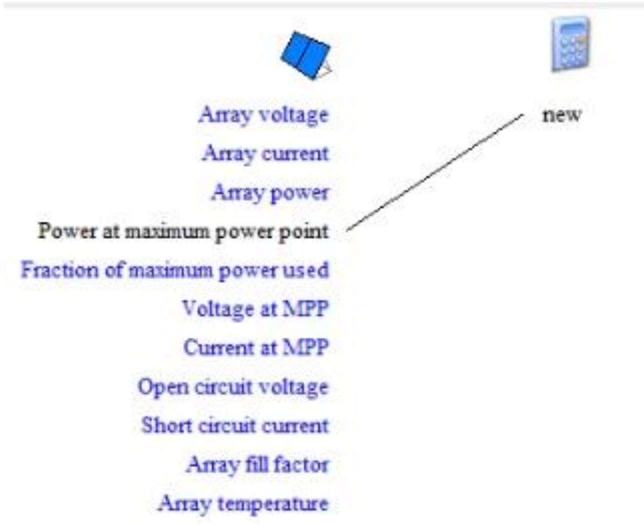


Image 6.56: Connection of the P/V component with the equation component

The variable “Power at maximum power point” is the output of the photovoltaic panels and is the power that becomes the input to the inverter that connects to the “input power”.

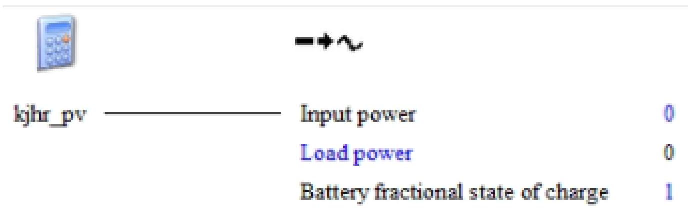


Image 6.57: Connection of the equation component with the Inverter

BIBLIOGRAPHY OF CHAPTER 6

[6.1]TRNSYS. "TESS Libraries 17: General Descriptions." Available online: http://www.trnsys.com/tess-libraries/TESSLibs17_General_Descriptions.pdf.

[6.2]"TRNSYS Documentation: Tutorials." Available online: http://www.ptuchiasiakishionline.com/trnsys%20documentation/09-Tutorials.pdf.

7. Study Results

7.1 Introduction

This section presents the results obtained from the evaluation of a solar-assisted ground source heat pump system implemented in a building located in Athens and the same building in Helsinki from the TRNSYS simulation. The simulation was conducted for one year period,aimed to provide a more realistic and unbiased evaluation.

First, we describe the building's structural components and the heating loads. A water to water heat pump was chosen to achieve the heating for the studied space. The primary focus was on analyzing the indoor temperature profiles and the corresponding heating loads required for both cases. Additionally, the energy production from the photovoltaic panel system was examined to maximize its efficiency. Furthermore, a comprehensive comparison of key performance indicators, such as the Coefficient of Performance (COP) and heating needs, was conducted to assess the system's effectiveness in each location. For this reason, photovoltaic panels and a battery were used. As for the photovoltaic panels sizing, we chose 36 panels of 32 m^2 after careful parameterization for Athens and 225 panels of 200.25m^2 for Helsinki.

Finally, an in-depth economic analysis was carried out to determine the financial viability of implementing the solar-assisted ground source heat pump system in both scenarios by demonstrating values like the payback periods and the installation costs.

The objective of this study was to investigate the performance and potential advantages of utilizing renewable energy sources, specifically solar-assisted ground source heat pumps, for space heating purposes in contrasting climates. The comparison between Athens and Helsinki allows for a comprehensive understanding of how different climatic conditions impact the system's performance and energy efficiency.

The results obtained in this study will provide valuable insights into the operational characteristics of the solar-assisted ground source heat pump system and its potential for energy savings, greenhouse gas emissions reduction, and cost-effectiveness. Moreover, these findings will contribute to the broader field of sustainable building technologies and aid in the decision-making process for implementing renewable energy solutions in diverse geographical regions.

7.2 Building's description and structural components

After conducting the building in TRNSYS , it provides information about the materials we used on the walls of the building. We have 4 external walls (OUTWALL), the ground and the roof. On the first table we see the thermal and physical properties of the materials.On the second table we see the values of the thickness and thermal transmittance of each wall that are calculated from TRNSYS.

Material	Cp (kJ/kg*k)	ρ (kg/m^3)	k (W/m*K)
Brick	1	1800	0.89
Plaster	1	2000	1.39
Concrete	0.8	2400	2.1
Insulation	0.8	40	0.04
Floor	1	800	0.07
Silence	1.44	80	0.05
Stone	1	1800	0.07

Table 7.1: Building Material Properties

Wall type	Width(m)	U(W*k/m^2)
Outwall	0.37	0.338
Ground	0.43	0.313
Roof	0.365	0.357

Table 7.2: Thickness and Thermal Transmittance of Walls

By having a wall with a thermal transmittance value of 0.338, the heat generated inside the building can be better retained, creating a more comfortable and thermally efficient indoor environment during the heating period. As we will see when we demonstrate the heating needs of the building, due to the heating efficient thermal transmittance values of the external walls, the heating needs are smaller than an average building. This happened due to the parameterization of the insulation which reduces the thermal bridging effect, preventing significant heat loss or gain.

On the next table the sizing of the overall building is presented.

Building parameter	Units
Length	10 m
Width	20 m
Height	3 m
Area	200 m^2
Volume	600 m^3
East /West window	4/4m^2
South window	8 m^2

Table 7.3: Construction parameters of the building

The next step of our simulation was to calculate the annual heating loads of the building. In this case , there were two ways to work using “Calculations “ option in TRNSYS.

First, after setting the ventilation, heating, cooling and gains/loss option of the TRNBuild and running the simulation, TRNSYS provides the theoretical heating and cooling needs of the building after setting the ideal heating and cooling temperatures.

The second way was to close the heating and cooling option of the TRNBuild and after setting the heat pump system , to ensure from the temperature of the air in the building that it never exceeds the temperature of the thermostat.

From the first way, after setting the thermostat temperature to 20^o for heating gave us the following calculations.

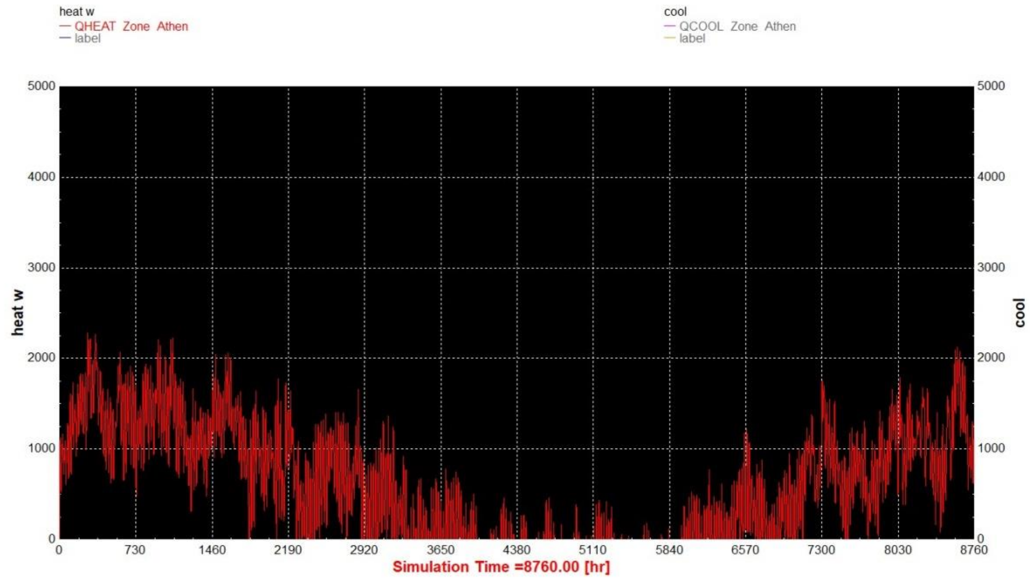


Figure 7.1: TRNSYS calculation on heating needs of the building

By viewing this, we had a first view of what our heating system should provide. A maximum heating load 2.28 kW and an annual heating of 5376 kWh.

This measurement was used as initialization of the heat pump heating system of the second way that was described. The advantage of this way was that by setting an ideal thermostat temperature , we could easily change the parameters of our components and as long as the temperature was bigger than the one we set , it meant that our system was efficient. So by operating like this, the maximum heating load would be automatically into account and with a “integrator” component, we could calculate the annual heating load and the electrical consumption of the pump and the whole system.

We set the thermostat to send heating signal when the temperature of the air in the building becomes 21 ^oC. After the water to water heat pump system was set, we run the simulation and the following results occurred.

- Qheating=4480 kWh
- Qel,heating =1106 kWh

Those results are valid and reasonable after comparing them with the first calculation of the TRNSYS simulation. They are a little lower but this is obvious because of the different temperature of the thermostat we had set for the heating system to operate. This happened to begin changing the parameters of the system from the upscale values to the optimal of an ideal system of a building in Athens.

The following diagram of the integrator illustrates the upper values.

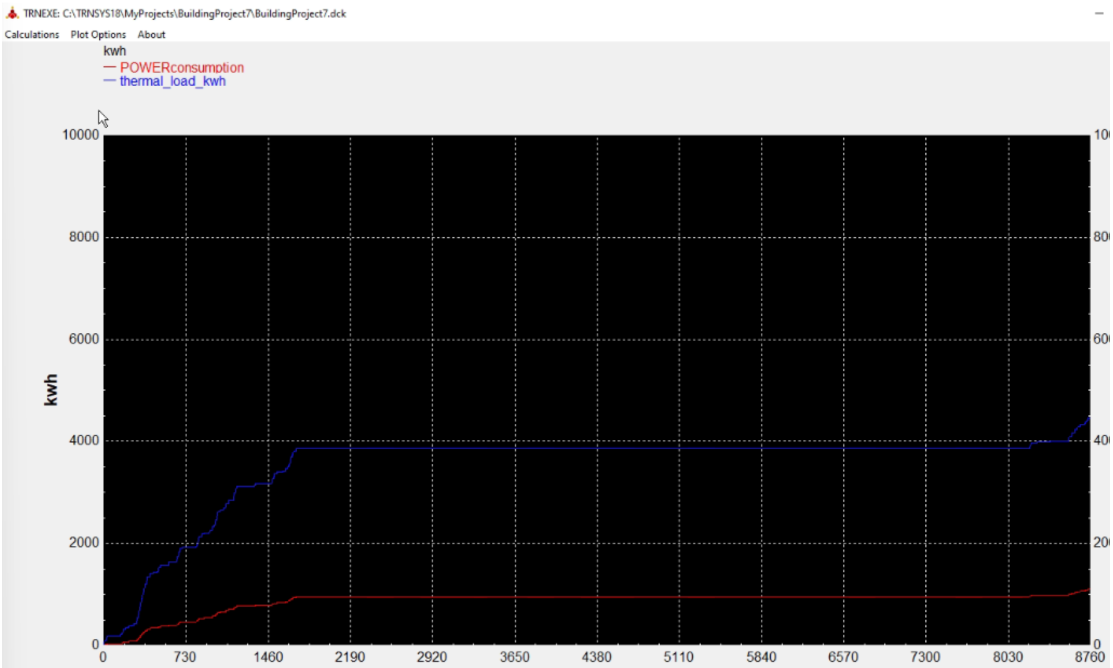


Figure 7.2: Calculation of the thermal load and the power consumption of the heating system

We should also note that this electrical consumption is only form the heat pump. After this section , the consumption of the other systems of the heating system will be considered. Now we demonstrate the results of our heat pump.

The performance coefficient of a heat pump for heating is:

$$\text{COP heating} = \frac{Qheating}{Qel,heating} = 4.05 \qquad (7.1)$$

A COP of 4.05 indicates that for every unit of electricity consumed, the heat pump produces approximately 4.05 units of heat energy. This signifies a high level of efficiency and implies that the heat pump is able to generate a significant amount of heat while minimizing electricity consumption.

This COP value is valid and reasonable for a water to water heat pump. In some cases the COP becomes bigger as we can see in the next diagram that demonstrates the COP every hour of the simulated year.

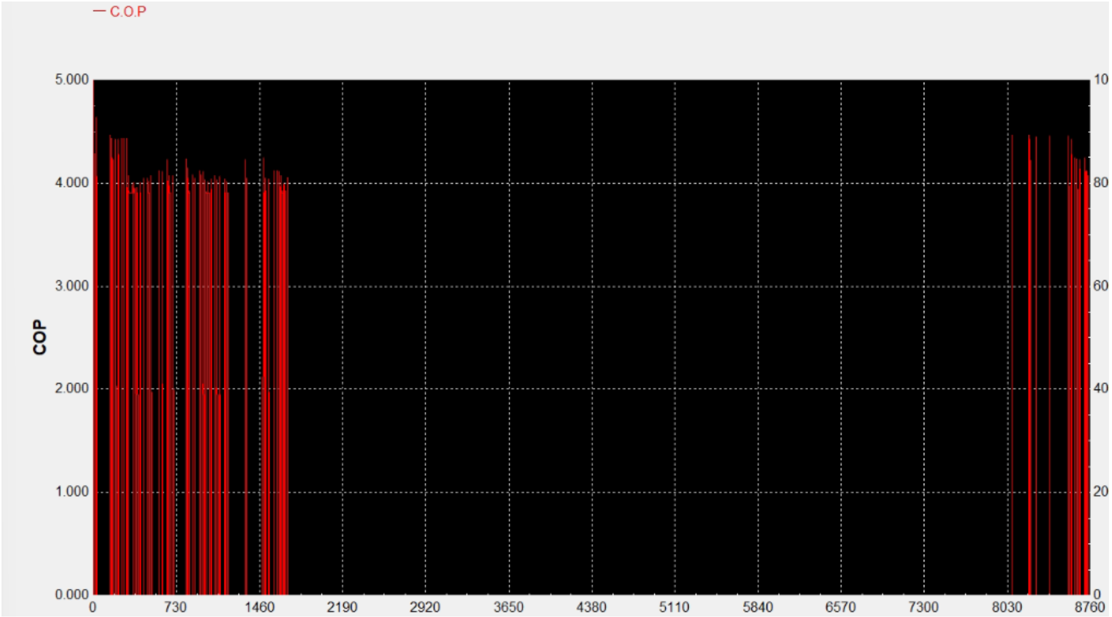


Figure 7.3: C.O.P. factor

The calculations will also be performed on a monthly basis to determine the variations in the building's heating demands throughout the year. The heating and loads for each month of the year are presented in detail in the following table.

Month	Heating Load (kWh)
December	585.8
January	1938
February	1296.1
March	683

Table 7.4: Monthly heating load

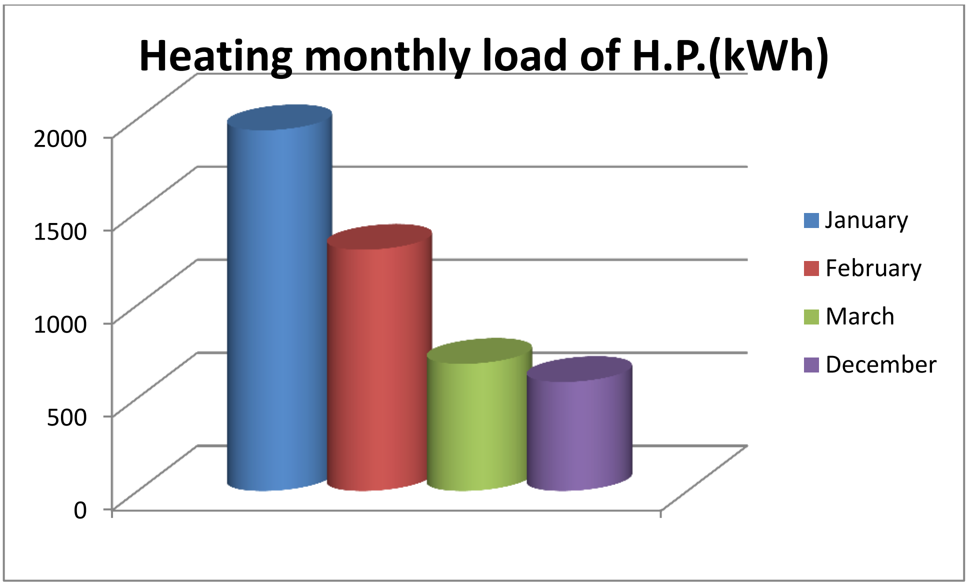


Figure 7.4: Heating monthly load of H.P.

After the first observations on this results , we could see that November didn't required heating load .This is because of the good insulation of the building and Athens's hot climate. As we will see on the next diagram, although the average temperature on November is lower than 21 ^{o}C the air temperature of the building is not lower. This can also be seen by the previews diagram that represents the integration of the heat pump consumption and load, which shows that on November, our pump doesn't operate.

So, the heating annual load is distributed on January which requires the bigger load, February with an important amount of heating load and March with December having the lower heating needs.

Next step is to calculate the electrical consumption of the two pumps that help our system to operate and the fan coil unit.

The water to water heat pump system gets the water from the ground, this source is the geo thermal heat exchanger. In order to pump the fluid from there and to circulate it from the pump to the fan coil unit we used two pumps to model the system. Those pumps had their first parameters and we optimized them by changing their values. As long as the whole system was running correctly (the air temperature of the building was higher than 21 ^{o}C) we kept changing the parameters of the pumps in order to be more energy efficient.

With the same way, we work for the Fan Coil Unit .Those components made the simulation more realistic not only for their extra electric power they demand in a real system, but for the heat loss and non ideal energy efficiency of the components .The electrical power that those components demand is illustrated on the next diagram.

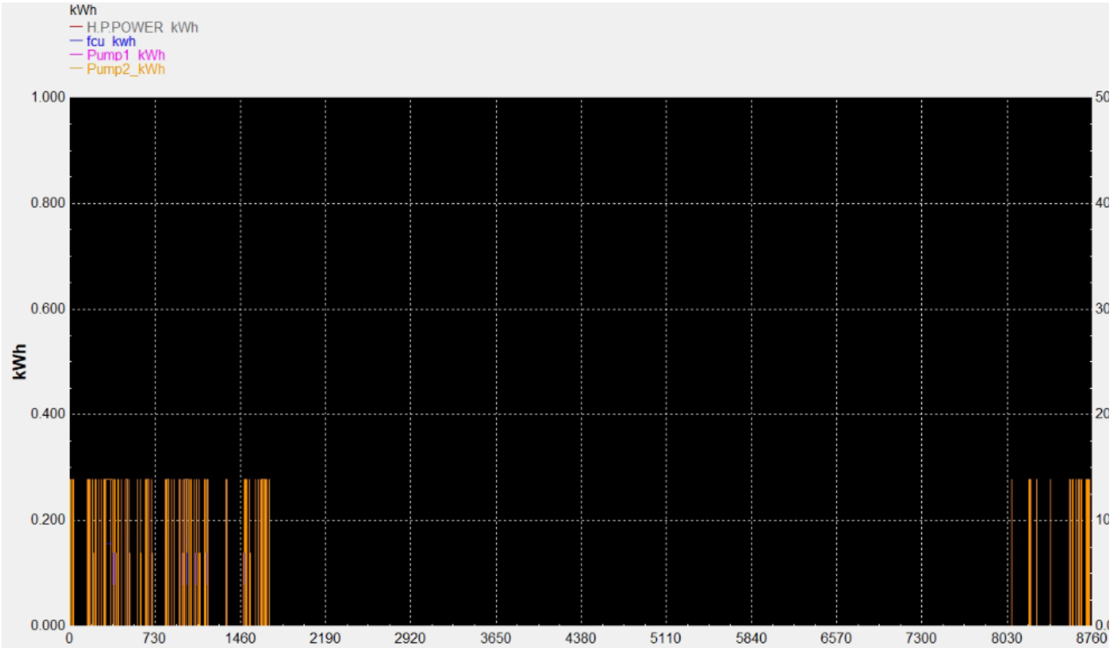


Figure 7.5: Power consumption of the F.C.U. and the two single speed pumps

On the next table we will see how the electrical consumption of the system is distributed.

Month	Power consumption (kWh)
December	184.5
January	595.6
February	398.3
March	215.2

Table 7.5: Monthly electrical consumption of the heating system

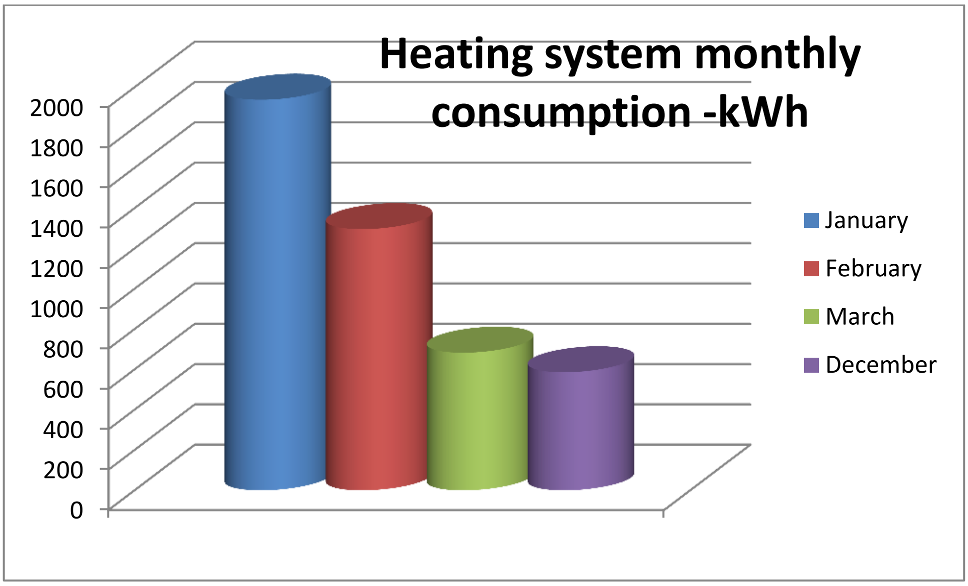


Figure 7.6: Heating system monthly consumption

The heating system consumption is 1393.8 kWh per year. So the whole system is 1.26 times bigger than the heat pumps energy consumption which is 1106.2 kWh per year. The aim of this thesis is to cover the electricity consumption of the heat pump, as much as possible from renewable energy sources, and to minimize the use of the grid.

7.3 Use of a Ground Source Heat Pump for Heating

The water to water heat pump takes advantage of the fluid temperature of the ground source heat exchanger. We had to calculate the temperature of the ground in different depths. As we will see, the temperature of the ground was more stable annually as deeper as we were going on our simulation. A basic ground loop is between 50 and 150 meters. For the most economical solution we have chosen 50 m deep as long as the result was stable (17^{o}C).

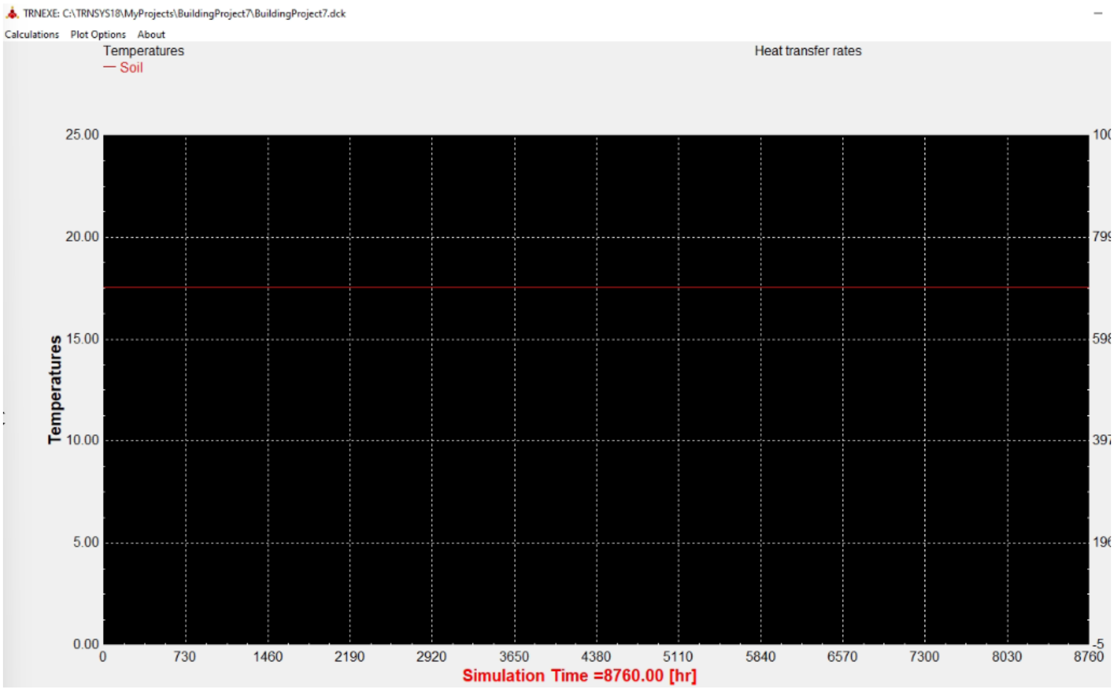


Figure 7.7: Ground temperature at 50 m deep

Next, the temperature profile inside the building is presented throughout the year, with the heating system of the building now in operation. The purpose of this depiction is to illustrate the extent of the heat pump's influence on the temperature profile during both winter months. The temperature of the environment is also demonstrated.

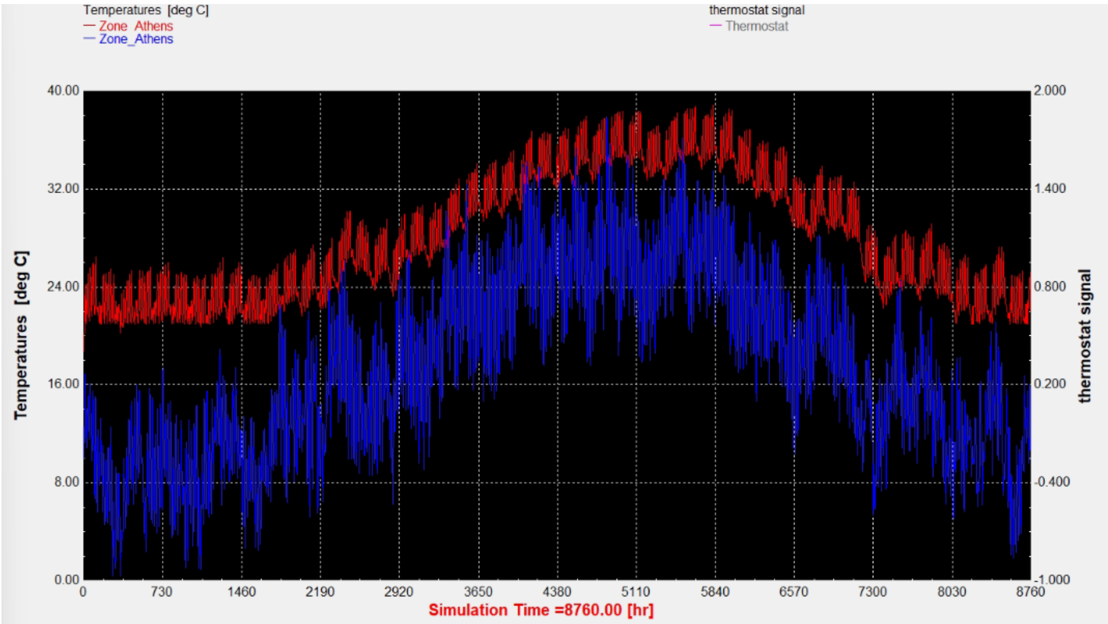


Figure 7.8: Contrast of the outlet and inlet temperature of the building in the city of Athens

The maintenance of thermal comfort conditions inside is evident, despite the extreme temperature conditions of the surrounding environment during the winter months. This temperature profile shows that our heating system keeps the temperatures of the air of the building always higher than 21^{o}C. Moreover we observe that there isn't a time interval of the year that our system can't respond on the highest heating loads. We have to pinpoint this, because we could design our system differently if we could let some occasions the temperature to be a little lower but still acceptable for the inner building's air (e.g. 19^{o}C).

Next we see our thermostat heating operation signal depending on the outlet air temperature.

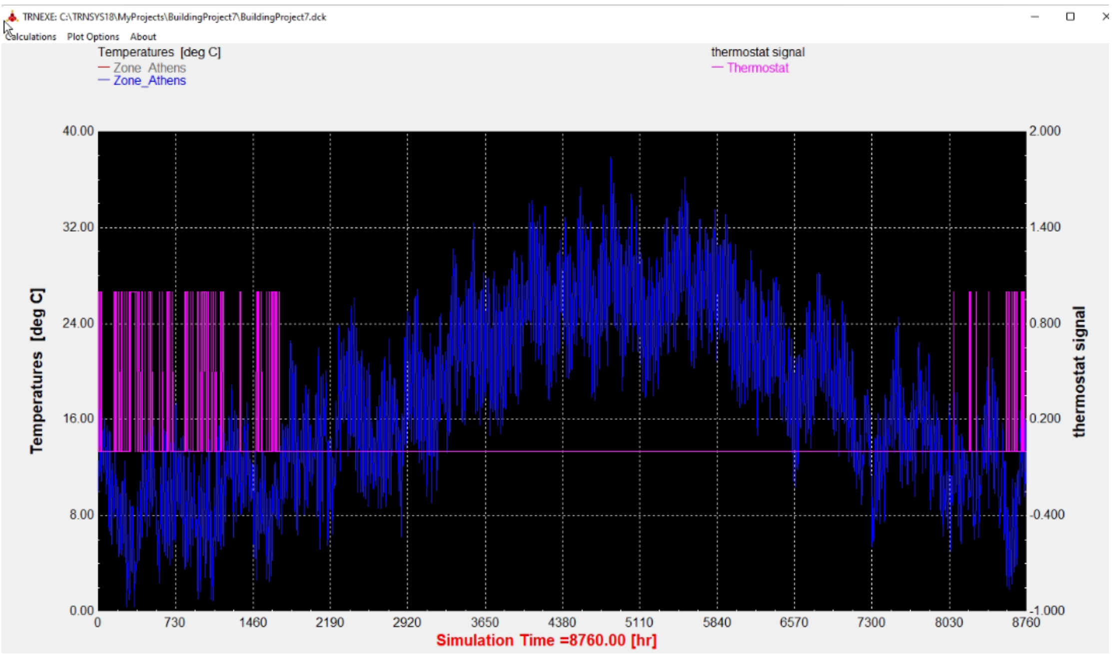


Figure 7.9: Thermostat signal and outlet air temperature of the building

After observing those two upper temperature profiles someone could be concerned about the high building's inlet air temperature on the summer months that exceed 30^{o}C. Our heat pump can also operate on cooling mode and can keep the temperature of the air in the building under 26^{o}C. We demonstrate the summer temperature profile to ensure that our heat pump can operate properly all the year, but this will be the only point that we will make on the cooling mode of our simulation's pump because this thesis is about solar assisted ground source hat pumps for heating.

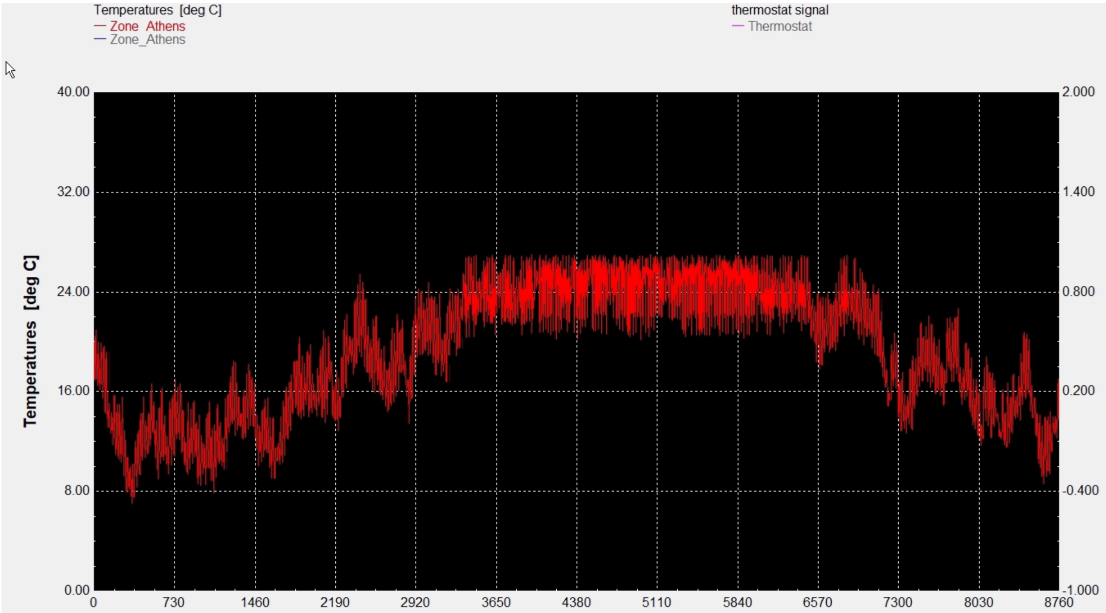


Figure 7.10: Inlet air temperature profile of the building when the H.P. is on cooling mode

7.4 Use of a PV system for heating of the building

This installation is considered an investment that is evaluated from both energy and economic perspectives to determine the best solution. From an energy standpoint, the goal is to cover a large percentage (approximately 90% and above) of the annual electricity consumption of 1393 kWh using photovoltaic panels. Increasing the collector area of the panels leads to more electricity generation, which initially seems favorable as it reduces reliance on the grid. However, expanding the collector area without limits is impractical and costly due to the panels themselves, as well as additional components like the battery and inverter. Therefore, finding the optimal balance between energy efficiency and cost is crucial.

On the following table we see the annual power that the photovoltaic system produces and that it produces on the months that our heat pump operates for heating.

The power that refers to heating is symbolized “Qwinter” and the annual electric energy that is produces is symbolized “Qannual”.

Ac(m^2)	Qannual (kWh)	Qwinter(kWh)
15	2939.4	718.4
20	3919.2	957.8
25	4899	1197.3
30	5878.8	1436.7
35	6858.6	1676.2
40	7838.4	1915.6
45	8818.2	2155.1

Table 7.6: Electrical energy from photovoltaic system for various collector areas during the winter season and annually.

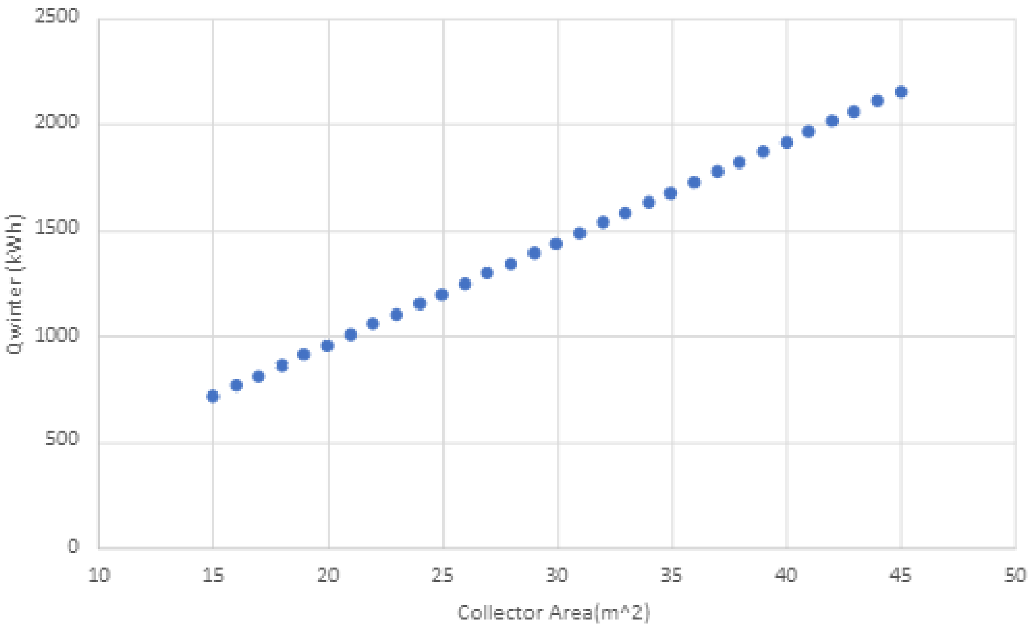


Figure 7.11: Electrical energy obtained from solar panels as a function of collector area during the winter season.

We observe that the electrical energy obtained from PV systems is higher during the summer period, and it increases as the collector surface area increases, which is very logical.

When a PV panel system is equipped with a battery, there may be instances where the system draws power from the grid. This occurs when the electricity generated by the PV panels is insufficient to meet the immediate energy demands of the connected loads or to charge the battery. In such cases, the system utilizes grid power to supplement the shortfall and ensure a continuous and reliable electricity supply. This helps prevent the battery from being completely depleted and allows for uninterrupted power supply even when solar generation is limited, such as during periods of low sunlight or high energy consumption.

Except from the energy that the system retrieves from the grid to keep the battery healthy, it retrieves the proper electricity power that the photovoltaic system can't provide to the heat pump system.

We see the power needed from the grid on the following table and the following diagram.

Ac(m^2)	Qgrid-winter(kWh)
15	675.7
20	436.2
25	196.8
30	0
35	0
40	0
45	0

Table 7.7: Electrical energy from the grid for various collector surface areas during the winter.

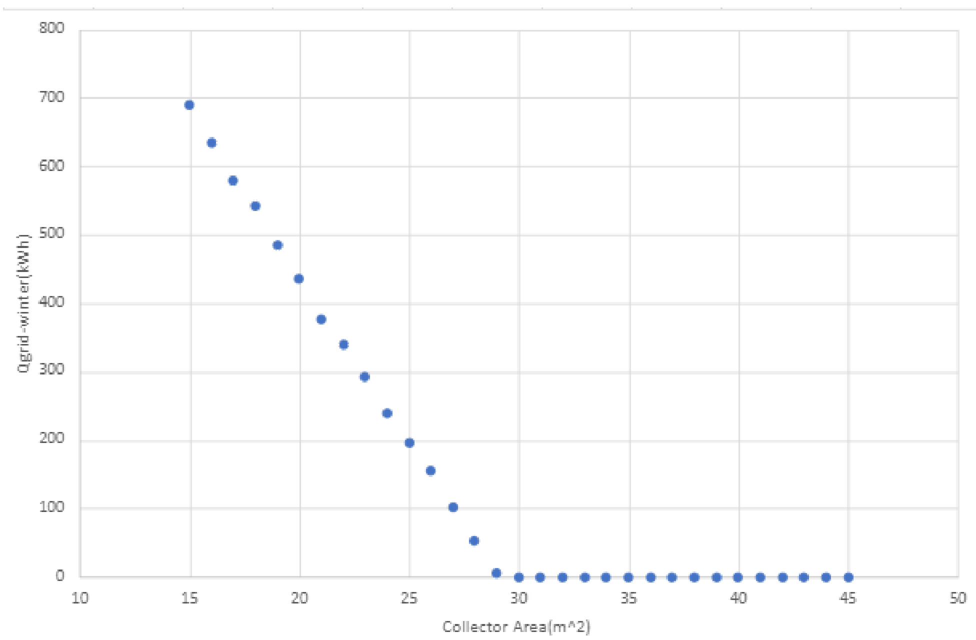


Figure 7.12: Electrical energy obtained from the grid based on the collector surface area during the winter period.

The next parameter that is going to concern us is the coverage ratio of the installation's needs from the photovoltaic system, represented by "f".

$$f = \frac{Qtotal - Qgrid}{Qtotal} * 100\% \quad (7.2)$$

$$Qtotal = Qgrid + Qwinter \quad (7.3)$$

Ac (m^2)	f (%)
15	51.5
20	68.7
25	85.8
30	100
35	100
40	100
45	100

Table 7.8: Energy Coverage from PV as a function of Collecting Area .

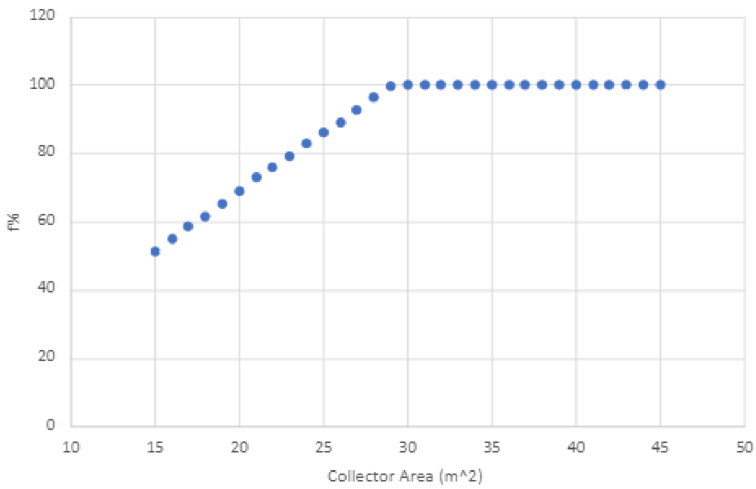


Figure 7.13: Percentage of Energy Coverage from PV as a function of Collecting Area.

So, by observing this diagram, we choose the proper collector area which is 30 m^2. We see that more collector area will provide us more electricity power but for the heat pump system, 30 m^2 is suitable. This way, no electricity power is taken from the grid and the heating system is using power from renewable energy sources. With 36 panels of 0.89 m^2 we have 32.04 m^2 of collector area used in this simulation.

The next table shows how much power in generated on each month.

Month	Power generated (kWh)
January	385.3
February	385
March	458.6
December	305.8

Table 7.9: Monthly P/V system power production on winter for 32 m^2 of collector area.

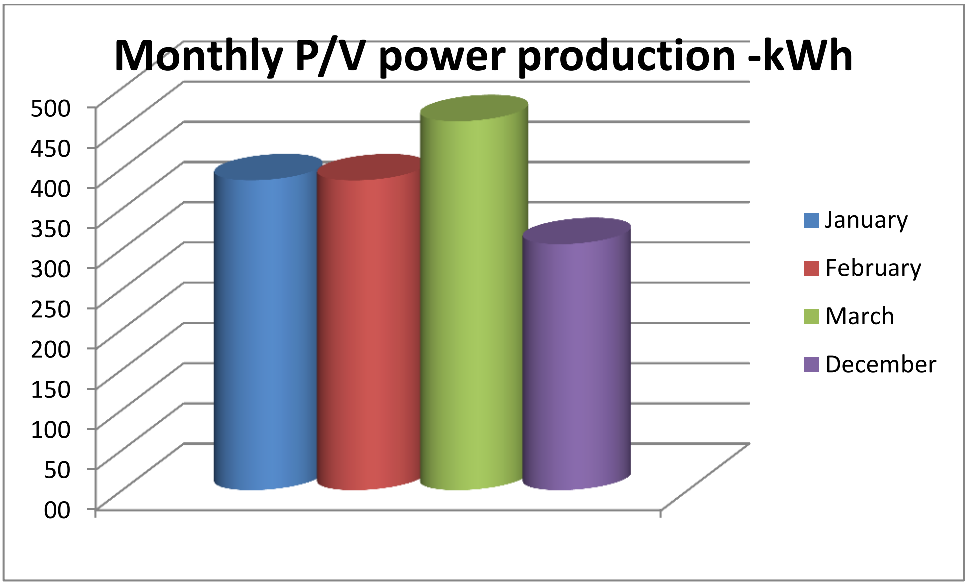


Figure 7.14: Monthly P/V system power production on winter for 32 m^2 of collector area.

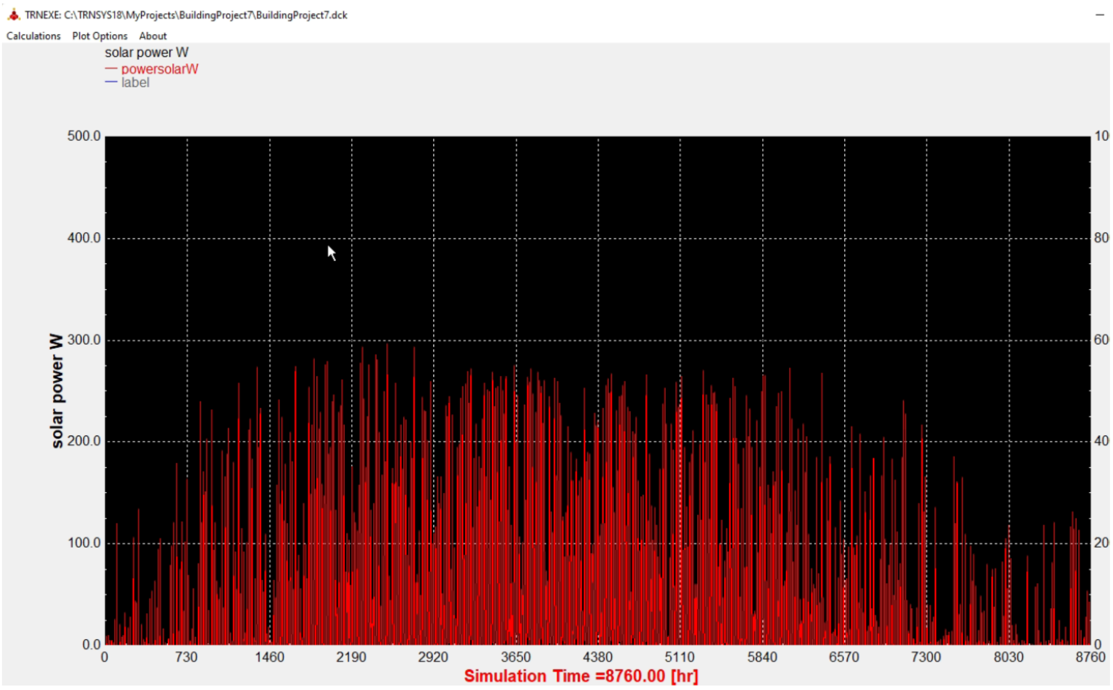


Figure 7.15: Annually solar power production the photovoltaic system

On March our system produces the biggest amount of power which is logical as in this month we have more sunshine days. January and February are the next ones with almost the same production. Then December comes last, as everyone could expect due to the less sunshine month. This observations are logical if we take consider of the radiation plot received from the TRNSYS calculations.

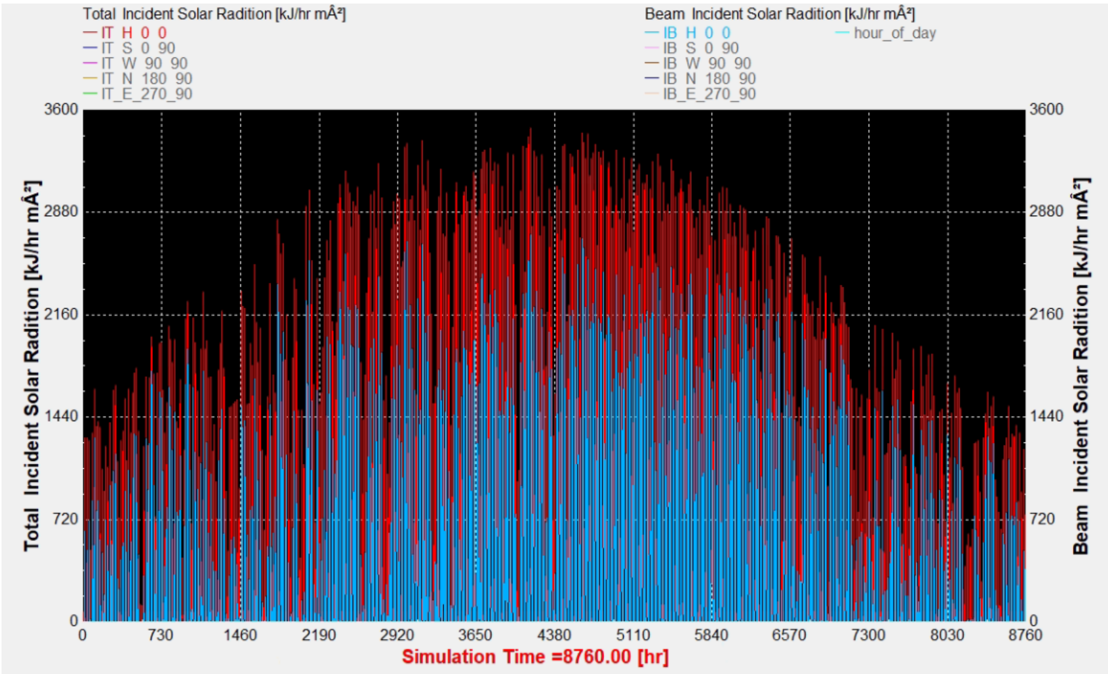


Figure 7.16: Total and Beam incident solar radiation in the city of Athens.

There are some months that the heating power demand is bigger than the power generated from the photovoltaic system. Nowadays, there are many ways to give the extra power of the p/v system and exchange it when needed. This is called ”Net Metering”. By having a battery of 24 hour autonomy, and an excess power of 4744.8 kWh during the other months of the year, our heating system could definitely be considered as green energy operated system.

The only reason that we don’t design a p/v system that could immediate provide all the maximum electrical load that the heating system will need is because this occurs rarely and we don’t want to hyper-dimensionalize the system because it would be extremely expensive.

7.5 Second study case of Solar Assisted Ground Source Heat Pump System in a cold climate city

Now on the same way we designed a SAGSHPS for Athens, we will design another one in a cold climate city to observe the differences and designing issues that need different methods. We will try to provide its energy power from a photovoltaic system like we did in Athens and in the end we will compare those methods based on its sufficient, economic and environmental needs. The city that we will choose in Helsinki in Finland .Helsinki experiences long, cold winters with a significant demand for heating. The average annual temperature is around 5.9°C , and the heating season typically lasts for several months. This makes Helsinki a good candidate for utilizing ground source heat pumps, as they can efficiently provide heating during cold periods.

Although Helsinki is located in the northern latitudes, it still receives a substantial amount of sunlight during the summer months. The longer daylight hours and relatively high solar irradiance make it possible to generate solar energy that can supplement the heat pump's operation during the heating season.

Finland, including Helsinki, has been actively promoting renewable energy and sustainable solutions. The country aims to be carbon neutral by 2035, and Helsinki has implemented various initiatives to reduce carbon emissions and increase the use of renewable energy sources. This environment of sustainability could provide interesting opportunities for implementing solar-assisted ground source heat pump systems. Helsinki has a strong focus on technology and innovation, with a well-developed infrastructure and expertise in the renewable energy sector. This can facilitate the adoption and integration of advanced energy systems like solar-assisted ground source heat pumps.

By choosing Helsinki, we can explore the potential of solar-assisted ground source heat pumps in a city with a genuine need for heating, abundant sunlight during the summer, and a supportive environment for renewable energy solutions.

So, the basic point of those two cities contrast is that in Athens there is no big need of heating and positive solar influence on the system and in Helsinki there is a major need of heating and not too much solar capabilities.

On this point we will not show in detail the connections and the parameters that we made in TRNSYS to adjust the simulation in order to be valid for Helsinki, but we will mention some of the basic changes.

TRNSYS components modifications and results

First of all, because of the cold climate of the city we set the heating point of the thermostat to 20^oC.

The temperature of the city can be from -24^oC to 26^oC. The Mean surface temperature is 4.69^oC and the amplitude of surface temperature is 7.75^oC. Those numbers where derived from the temperature profile of the city and the soil component plot which shows the temperature of the ground.

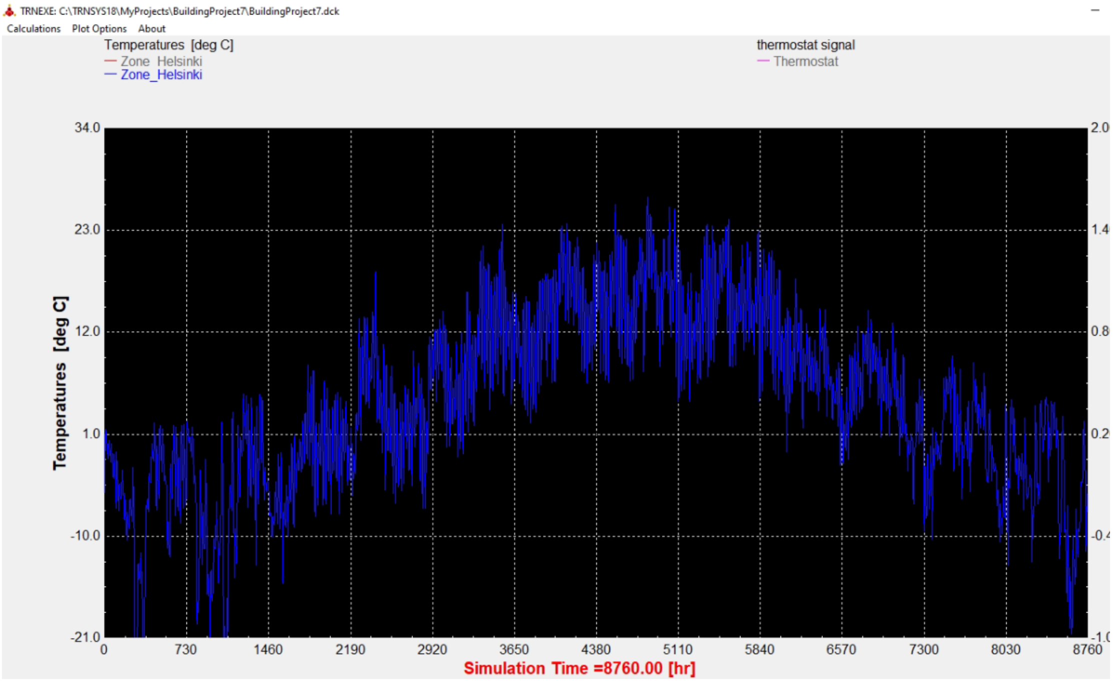


Figure 7.17: Temperature profile of Helsinki

On this image we see that on December, January and February there is a big heating load need as the heating system must be able to keep the building from those cold temperatures to the heating set point. This is a temperature gap of 40°C in many cases. So, the rated heating capacity of the water to water heat pump is 28kW.

Changes were also made in the geothermal heat exchanger. There, we used two boreholes in 80m depth with storage volume of 4000m^3.

In this depth we see the temperature of the ground in the following image.

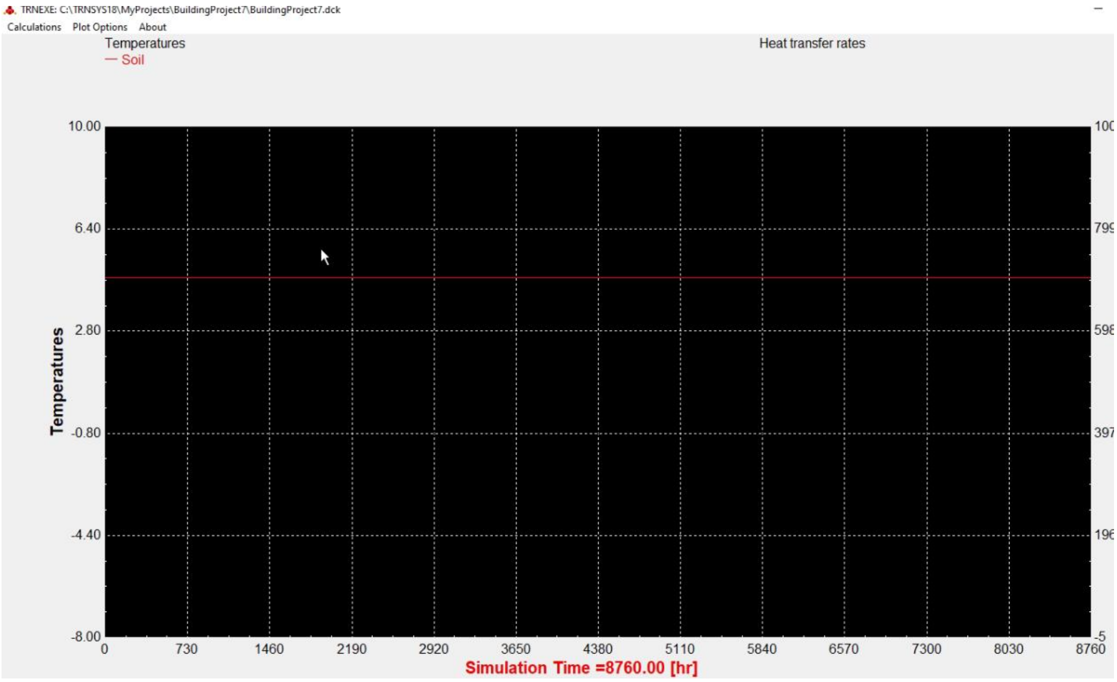


Figure 7.18: Ground temperature 80m deep.

We also used the two pumps with rated power of 1150 kJ/hr and a Fan Coil Unit with Fan rated power of 630kJ/hr. In the following diagram we see the power consumption of those components.

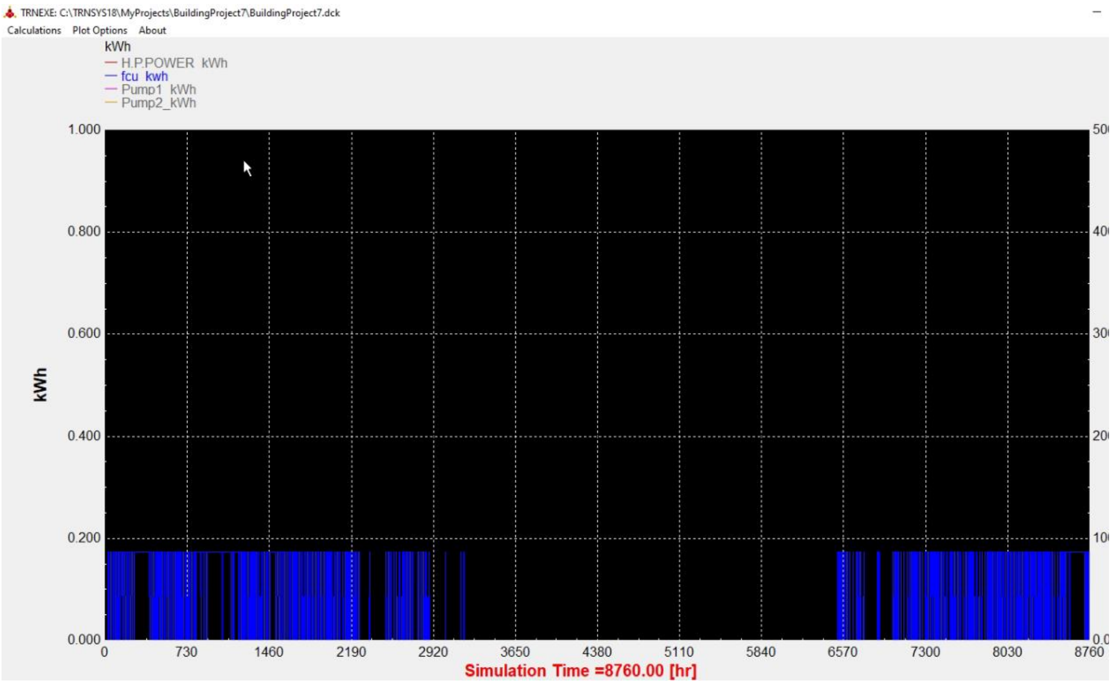


Figure 7.19: Fan Coil Unit annual power consumption.

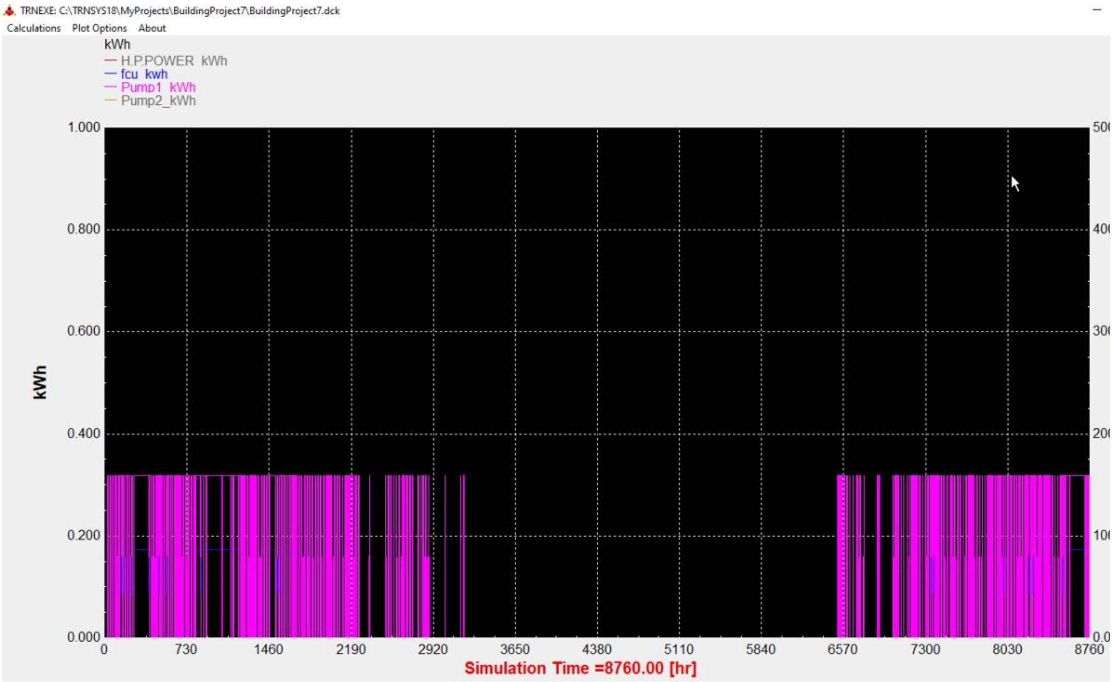


Figure 7.20: Pump's annual power consumption.

The water to water heat pump provides thermal heating load to the building as it shows on the next table and the next image.

Month	Heating Load (kWh)
January	9780.73
February	10469.83
March	6661.48
April	1787.32
May	94.91
September	145.21
October	1911.19
November	4485.08
December	9810.89

Table 7.10: Monthly heating Load of the heat pump.

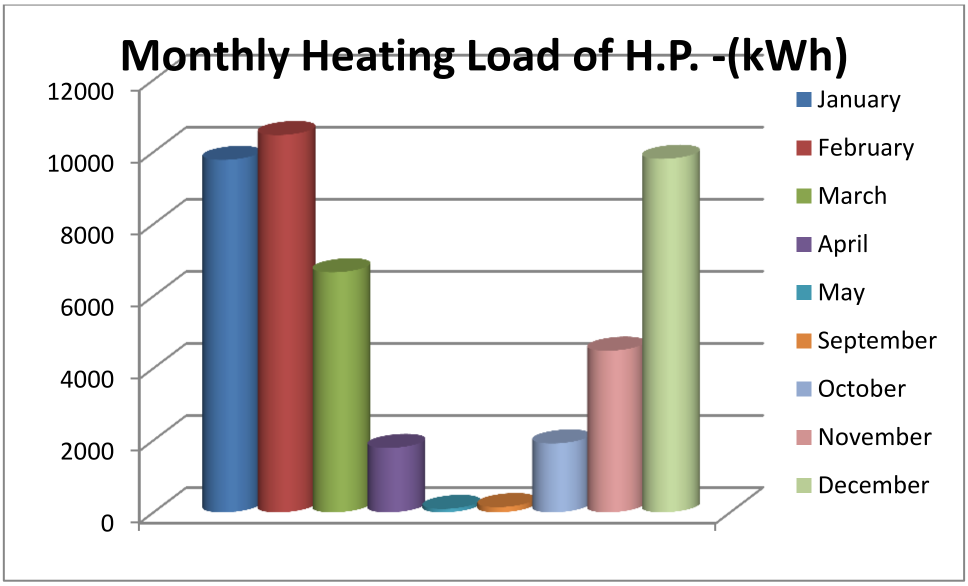


Figure 7.21: Monthly heating load of the Heat pump.

As we can observe from the diagram, our heat pump produces the biggest heating load on February, then on December and January. Only on summer the system doesn't operate where the ambient temperature is more than 20^{o}C. All the other months, except May and September the system provides important amount of heating load.

After we presented the heating load of the system, now the following table and diagram show the consumption of the whole system.

Month	System power consumption (kWh)
January	2814
February	3029
March	1913
April	495
May	27
September	47
October	531
November	1371
December	2738

Table 7.11: System monthly power consumption.

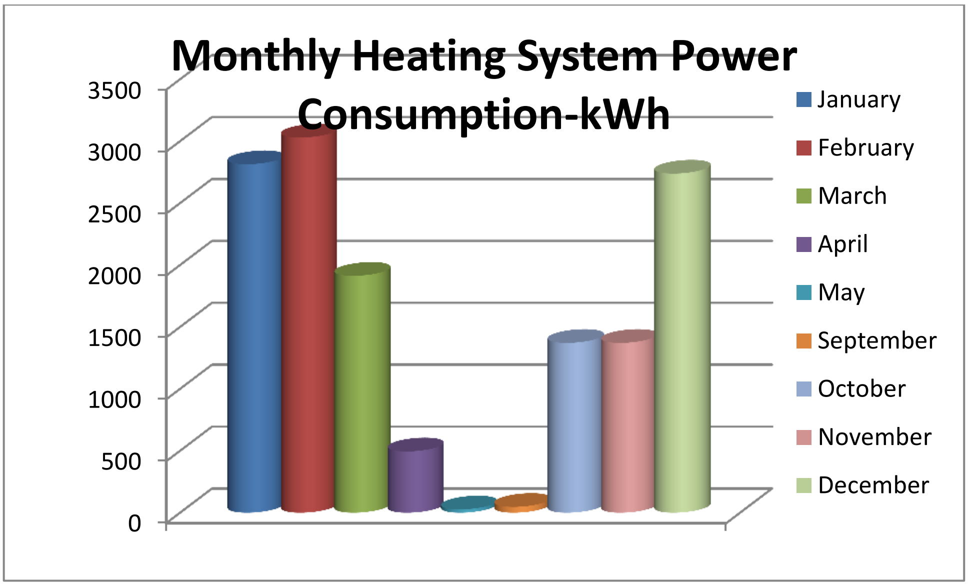


Figure 7.22: System monthly power consumption.

As we expected, on the winter we have the biggest amount of electrical power needs. The other months have also important electrical energy needs except from summer.

When designing the whole system we need to see how much power the system provides and uses. With the component of integrator the following plot shows an overall performance of our pump.

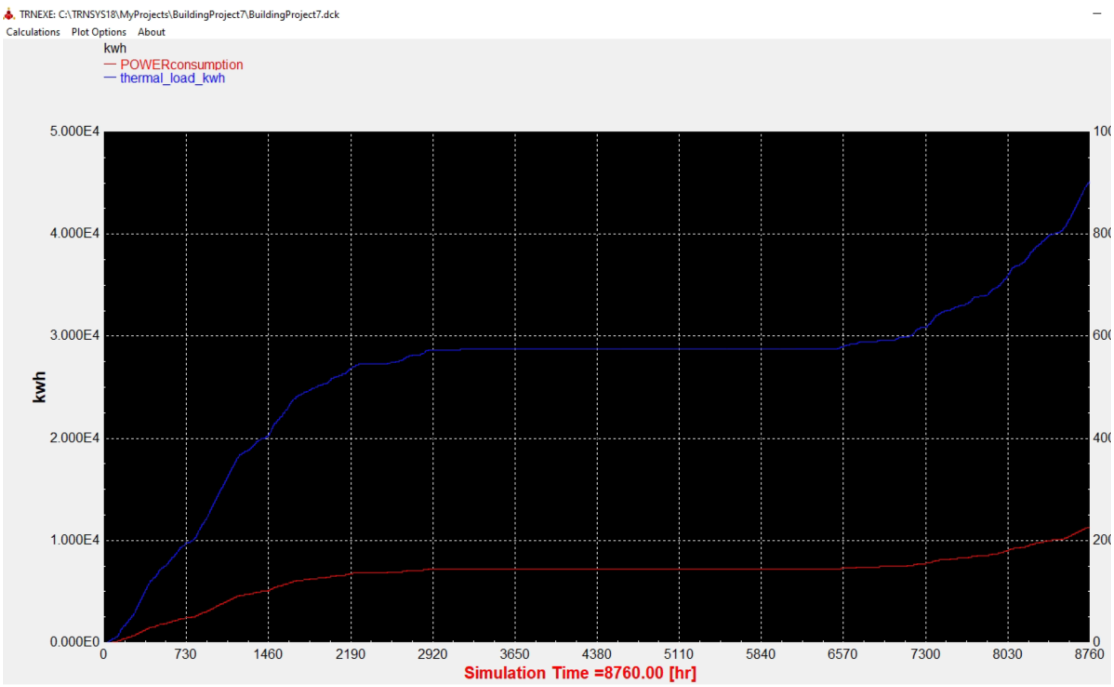


Figure 7.23: Contrast of total power consumption and pump's heating load.

In this diagram it's obvious to understand the efficiency of our heat pump which produces significantly more power than it consumes. Overall, it provides 45100 kWh annually and it consumes 11359 kWh as a heat pump and 12966 kWh as a whole heating system.

This efficiency is illustrated from the C.O.P. factor that is shown from the following plot.

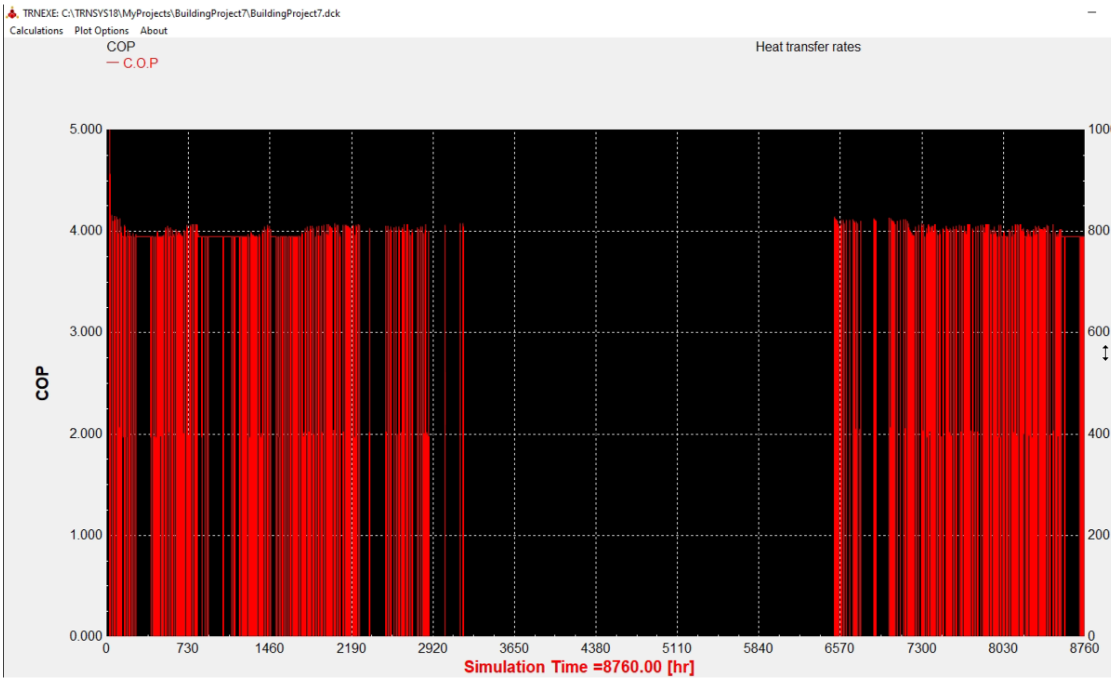


Figure 7.24: C.O.P. factor of the heat pump.

The C.O.P. of our system has an average value of 4 .This makes our system valid for a water to water ground source heat pump and also makes it efficient for use.

With this results being demonstrated, we achieved to heat a building in Helsinki. As we will see on the next diagram, there are several times when our system can't provide the heating load that it needs. Our design couldn't provide a more powerful and also logical heat pump but in this case we used the same building parameters as in Athens. With more insulation on the walls our heat pump could provide more stable temperatures on the inlet temperature of the building when the outlet temperature gets below 20^{o}C. In this thesis our point is to operate a ground source heat pump for heating so there was no need to study the cell of the building further more.

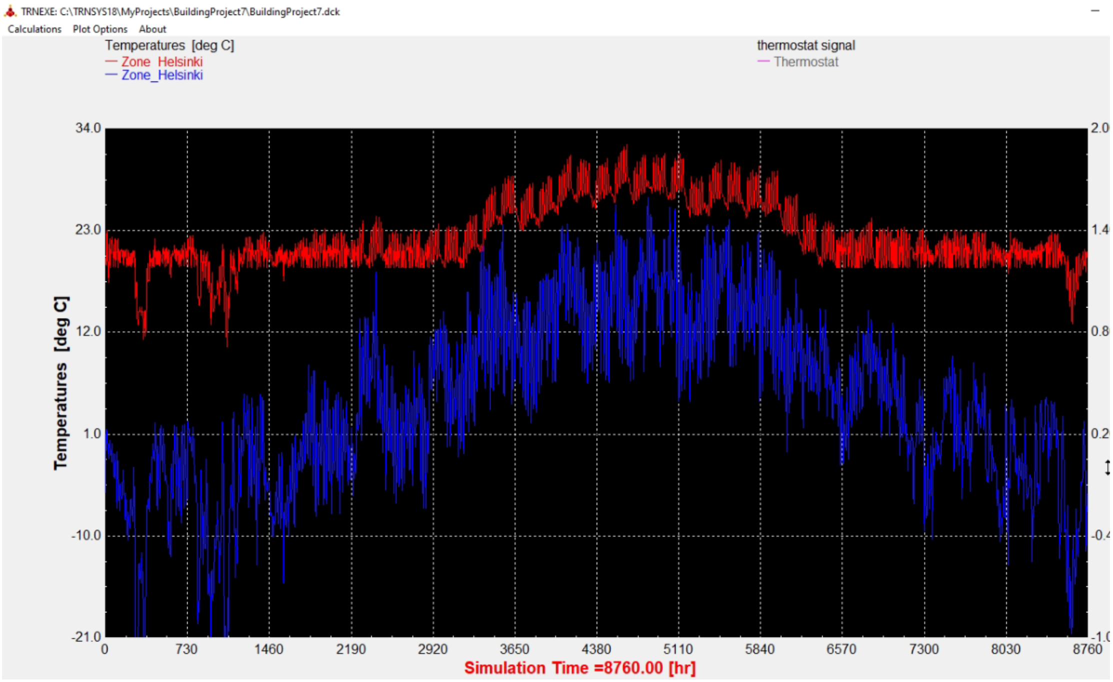


Figure 7.25: Contrast of inlet and outlet building's air temperature.

We see that our heating system performs positively on a very cold climate and it needs heating all the months of the year except summer.

<u>Use of a PV system for heating of the building</u>

It is important to note that in this case, when we have to provide electric power for heating systems in cities like Helsinki by using solar energy, it is very difficult to retrieve our energy from 100% renewable energy. So in this design, due to winter's enormous heating loads the solar panels assist the system. All the other months except winter we will try to have an important surplus of energy, in order to make our whole system more viable and economical.

The following table and diagram shows the electrical power that is produced from the photovoltaic system with different collector's area measurments.

Ac(m^2)	Qannual (kWh)
50	2716.6215
100	7933.243
150	15649.864
200	25866.5
250	32583.107
300	39489.729

Table 7.12: Electrical energy from photovoltaic system for various collector areas annually.

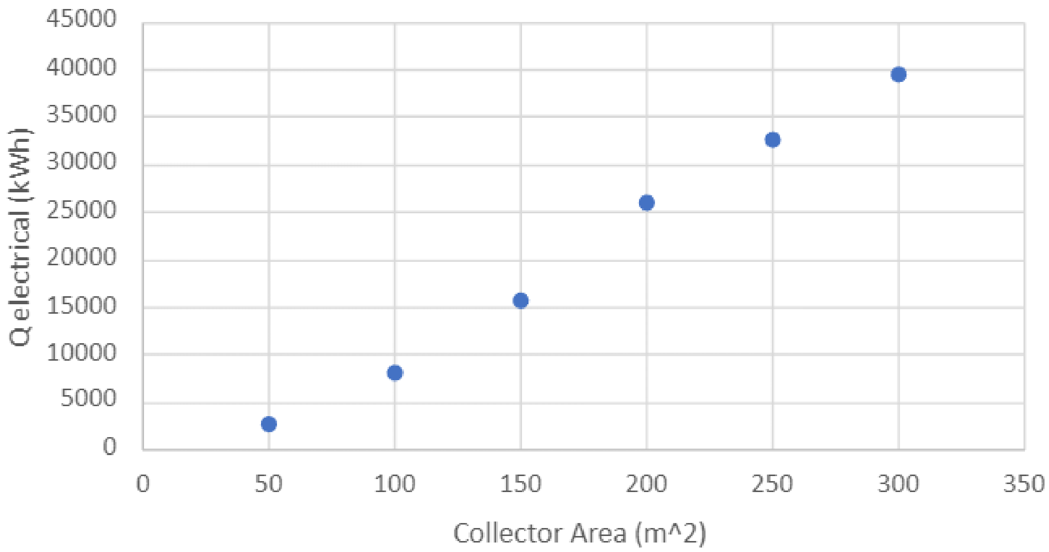


Figure 7.26: Electrical energy from photovoltaic system for various collector areas annually.

We observe that the more the collector's area is the more the electrical power becomes. As long as the heating system consumes 12966 kWh annually a choice of 150 m^2 could be a solution but this choice provides very low percentage of solar assistance to the system during the winter months. So we select 200 m^2 collector's area in order to have an important instant assistance of solar energy to the heating system. The bigger dimensioned photovoltaic systems could provide more energy power, but it could never provide the maximum instant heating load that our pump will need. So, as long as our building is 200m^2 we chose the equal area for the collectors in order to be a reasonable, realistic and economical solution.

We use the same type of p/v panels as in the previews case but now we use 15 series and 15 parallel formation of panels. So, we have 200.25m^2 collector area. Each panel is 0.89m^2. A battery of 8*8 cells of 150Ah is used and the slope of the surface of P/V panels is 60.1 degrees.

Now the next table and diagram will show the annually power that our system will retrieve from the grid.

Ac(m^2)	Qgrid (kWh)
0	12966
50	10249.379
100	5032.757
150	0
200	0
250	0
300	0

Table7.13: Electrical energy from the grid for various collector surface areas annually.

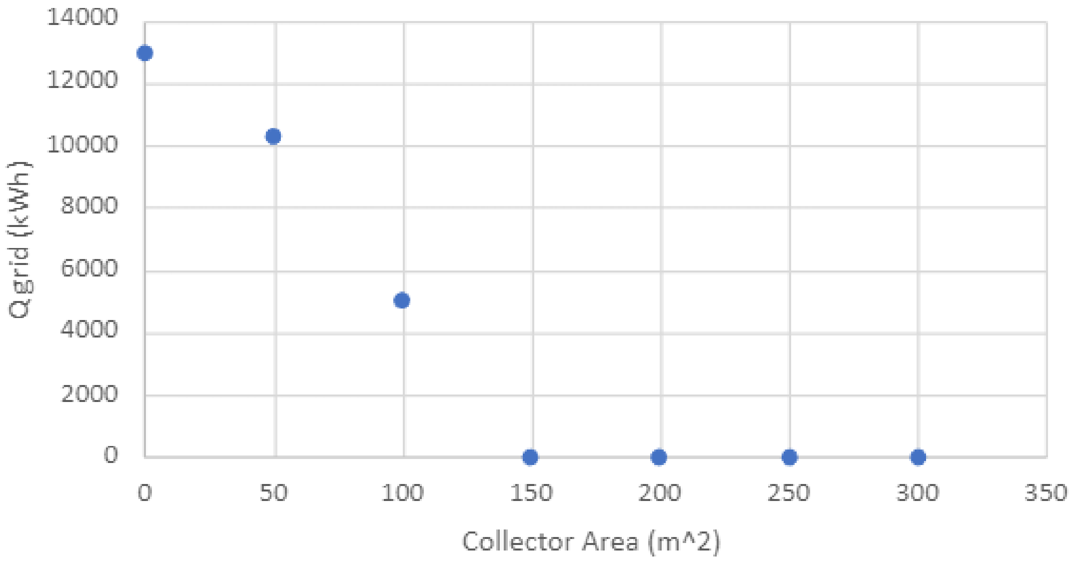


Figure 7.27: Electrical energy from the grid for various collector surface areas annually.

The next parameter that will concern us is the coverage ratio of the installation's needs from the photovoltaic system, represented by "f".

Ac (m^2)	f (%)
0	0
50	20.9
100	61.2
150	100
200	100
250	100
300	100

Table 7.14: Energy Coverage from PV as a function of Collecting Area .

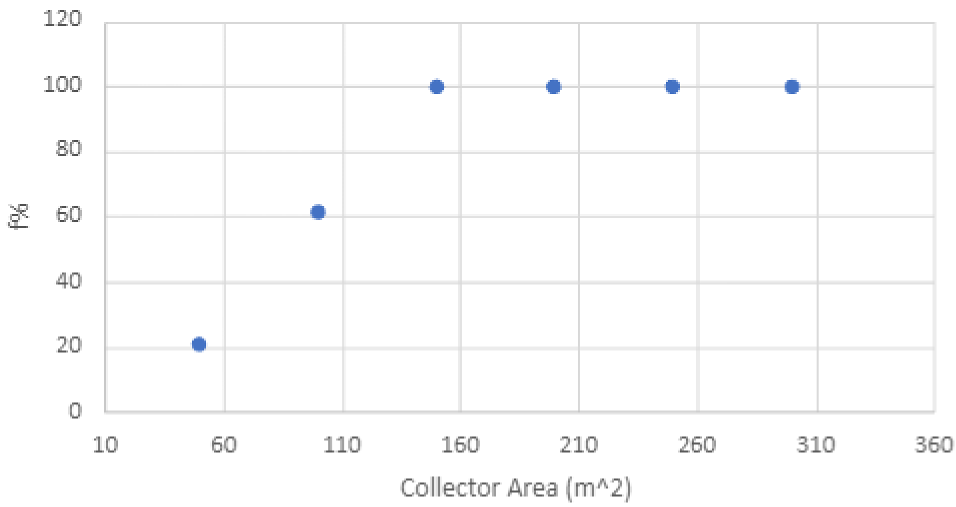


Figure 7.28: Percentage of Energy Coverage from PV as a function of Collecting Area.

The following table shows the monthly power production from the p/v system.

Month	Q (kWh)
January	490
February	1371
March	2498
April	3042
May	3763
June	3811
July	3509
August	3097
September	2139
October	1282
November	506
December	358

Table 7.15: Monthly electrical power produced from photovoltaic system.

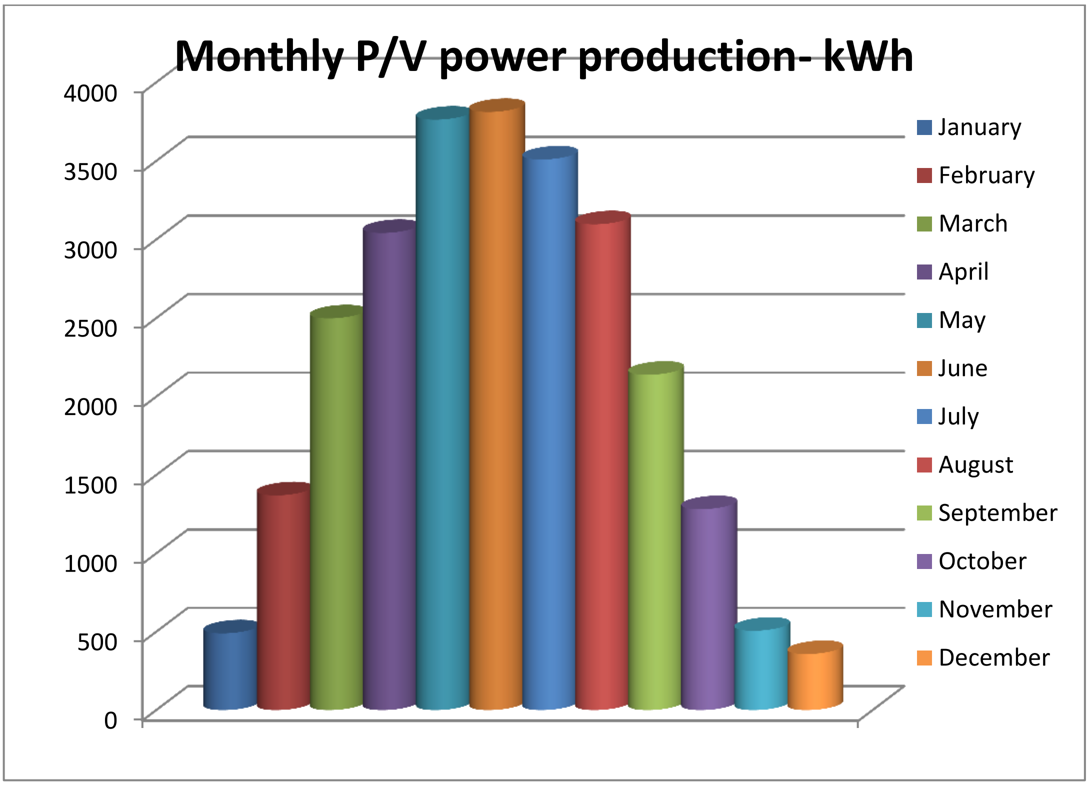


Figure 7.29: Monthly electrical power produced from photovoltaic system

As we expected, we have higher production of the system in summer and the lowest in winter. We observe a seasonal variation in PV power production which is physical as we have bigger solar irradiance and angle incidence during summer months. Moreover, we have higher temperatures and bigger day length, so our diagram's results are valid.

The following diagram shows the annually power that the system produces.

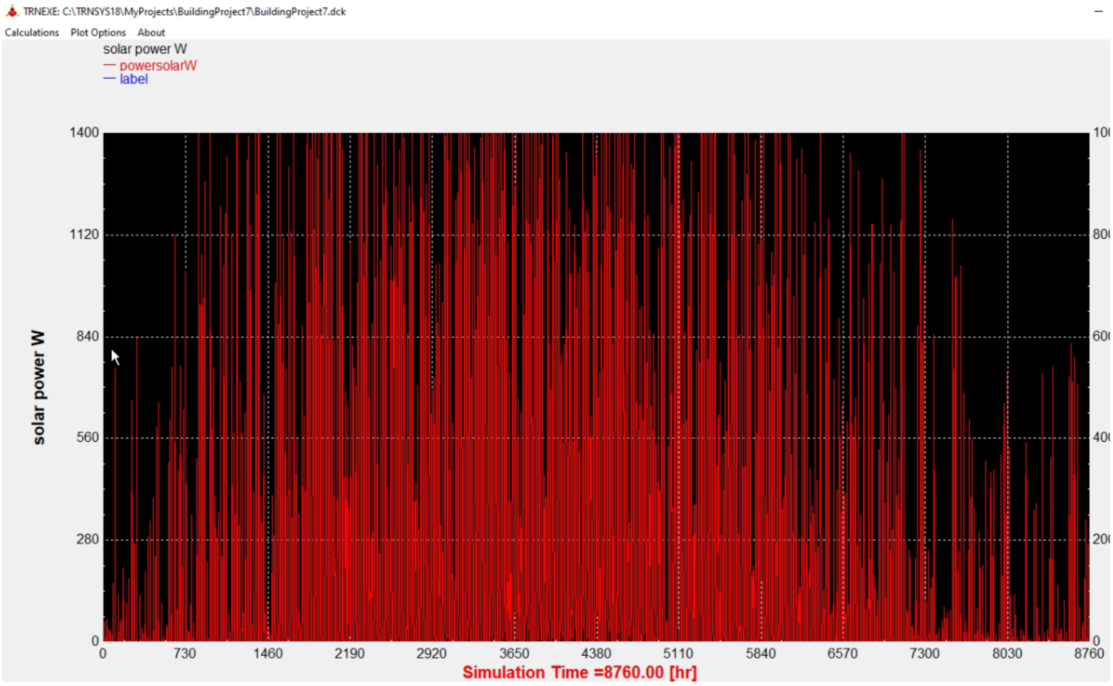


Figure 7.30: Annually power production of photovoltaic panel system.

An interesting aspect of our system is the monthly energy coverage of the solar assistance to the heating pump.

Month	f (%)
January	17.4
February	45.24
March	100
April	100
May	100
June	100
July	100
August	100
September	100
October	100
November	36.92
December	13.06

Table 7.16: Monthly energy coverage of the heating system from the photovoltaic system.

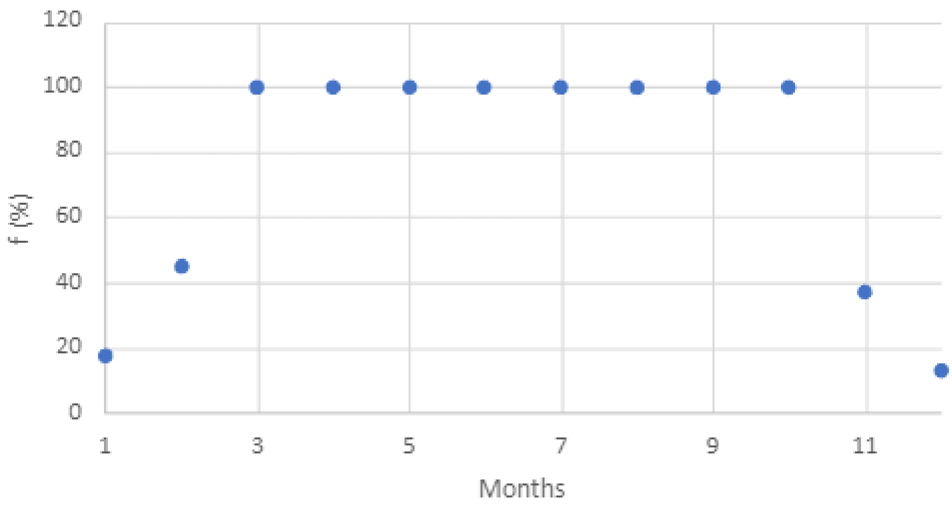


Figure 7.31: Monthly energy coverage of the heating system from the photovoltaic system.

By observing this diagram it is interesting to pinpoint the fact that even with 200 m^2 collector's area we can't provide a big coverage over 50% from the solar panels. From March to October our system is 100% powered by renewable energy sources. Finally, this installation provides a surplus of 12900.82 kWh which will be taken into account for the economic analysis.

7.6 Economic study of the installation

For the economic study of the installation we need the following metrics:

LCC: Life Cycle Cost

Co: Total investment cost of the installation

CF: Annual cash flow

R: Discount rate or interest rate

SPP: Simple Payback Period

The relationship between the variables can be expressed as follows:

$$LCC = Co + CF * R \tag{7.4}$$

$$Co = Collector\ Cost + Heat\ pump\ Cost + Inverter\ Cost + Battery\ Cost + Installation\ Cost + Fan\ Coil\ Unit\ Cost + Pump\ Cost + Cost\ of\ Ground\ Heat\ Exchanger + Cost\ of\ Single\ Speed\ Pumps \tag{7.5}$$

The table below presents indicative values for the aforementioned costs

Component	Cost (euro)
Collector P/V Cost/m^2	150
Cost of Heat Pump	4000-6000
Cost of Battery and Inverter	3000
Cost of Fan Coil Unit	3000
Cost of Single Speed Pumps	1000
Installation cost	9000
Cost of Ground Heat Exchanger	5000

Table 7.17: Installation Costs

Many of the installation costs were taken on average price, as every reliable company doesn't provide specific numbers for many of the upper component parameters. For the cost of the heat pump we take 4000€ for Athens and 6000€ for Helsinki.

So in the following table and diagram we compare the total cost of the installation for both cities.

City of the building	Cost of the installation
Athens	29806
Helsinki	57037.5

Table 7.18: Cost of the installation for the two cities

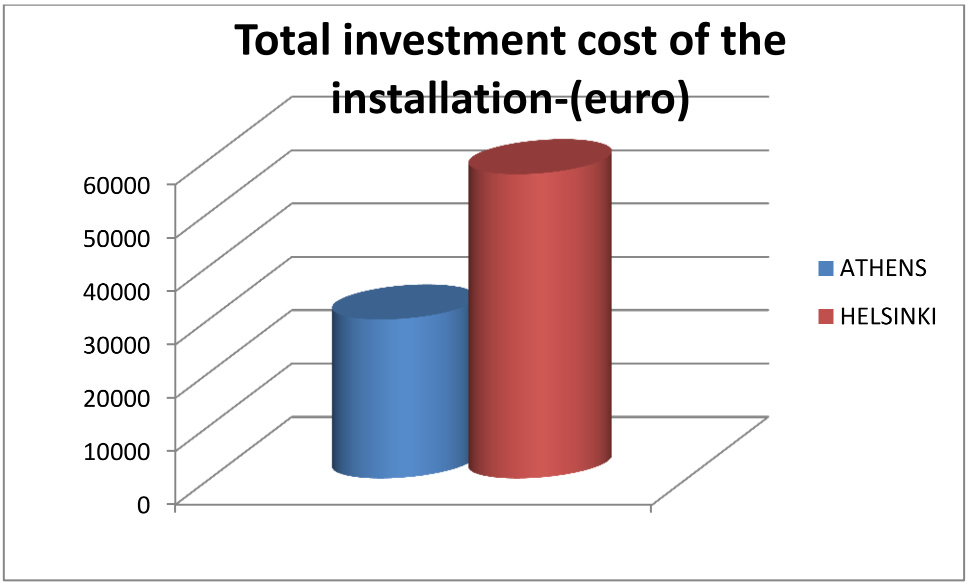


Figure 7.32: Cost of the installation for the two cities

From economical view, it is clear that the system of Helsinki requires more money cost than the system of Athens.

We have calculated the heating needs of each building and we will calculate the SPP by contrasting the cost of every case if there was no P/V system.

$$CF = Egrid * Kel + Kmaintenance \quad (7.6)$$

Where: Egrid: Kilowatt-hours needed from the Public Power Corporation per year (kWh)

Kel: Cost per kilowatt-hour (€/kWh), in this specific economic study, we assumed it to be €0.2/kWh

Kmaintenance: For this particular study, we considered it to be 100€ per year for Greece and 300€ for Finland.

$$R = \frac{(r+1)^N - 1}{r*(r+1)\hat{}N} = 14.9 \quad (7.7)$$

Where:

r: Cost of capital, assumed to be 3%.

N: Years, defined as 20 years.

$$SPP = \frac{Co(pv) - Co(non\ pv)}{CF(non\ pv) - CF(pv)} \quad (7.8)$$

Where:

Co (photovoltaic): Total cost of the installation.

Co (non-photovoltaic): Essentially, only the cost of the heating system.

CF (non-photovoltaic): The annual electrical energy required by the heating system.

CF (photovoltaic): Given by the upper equation.

City of the building	SPP (years)
Athens	28.02
Helsinki	13.2

Table 7.19: SPP for the two building cities.

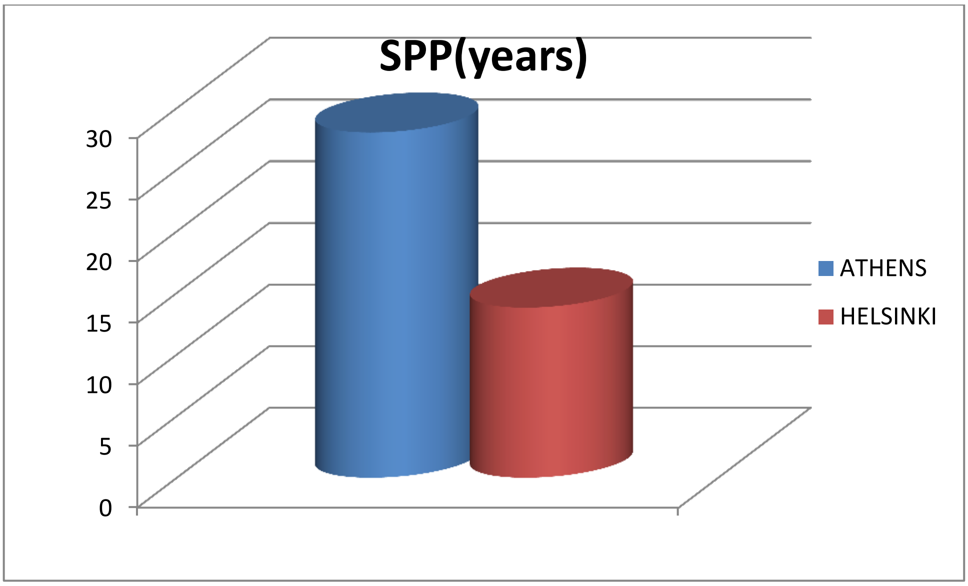


Figure 7.33: SPP for the two building cities.

Even though the cost of installation is bigger for Helsinki, the payback period is smaller because of the big heating needs that it has.

Now, we will see the life cycle cost of the two heating systems on the following table and diagram.

City of the building	LCC (euro)
Athens	31296
Helsinki	60017.5

Table7.20: Life cycle cost for the two cities of the building

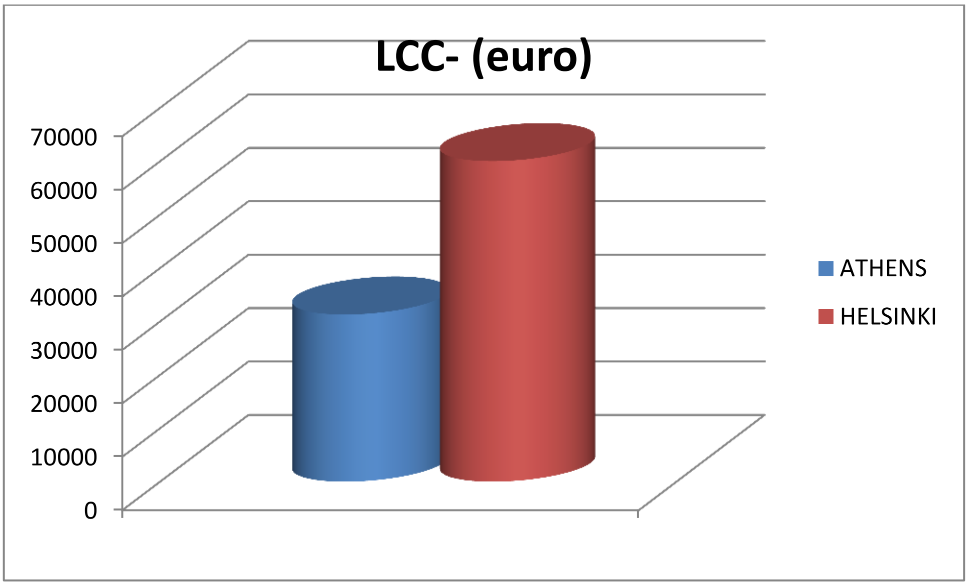


Figure 7.34: Life cycle cost for the two cities of the building

As expected, due to the big installation cost of the heating system in Helsinki the LCC is also bigger.

Now we will see the amount of power that we have as surplus in both cases which should be taken into account when thinking the economic view of the system. In our system in Athens we have 4744.8 kwh and in Helsinki

By utilizing surplus energy through net metering, we can significantly reduce our energy bills. The accumulated credits from feeding excess energy into the grid offset the costs of drawing energy during low generation periods. This cost-saving approach optimizes the use of renewable energy and maximizes the economic benefits of your PV system.

For this measurements we will set the cost per kilowatt-hour (€/kWh) at €0.15/kWh because the net metering keeps a percentage of your surplus power value given to the grid close to 25% because of some monthly fixed electricity charges.

City of the building	Annually economic value of the surplus power(euro)
Athens	711.72
Helsinki	1935.12

Table 7.21: Annually economic value of the surplus power for the two cities of the building.

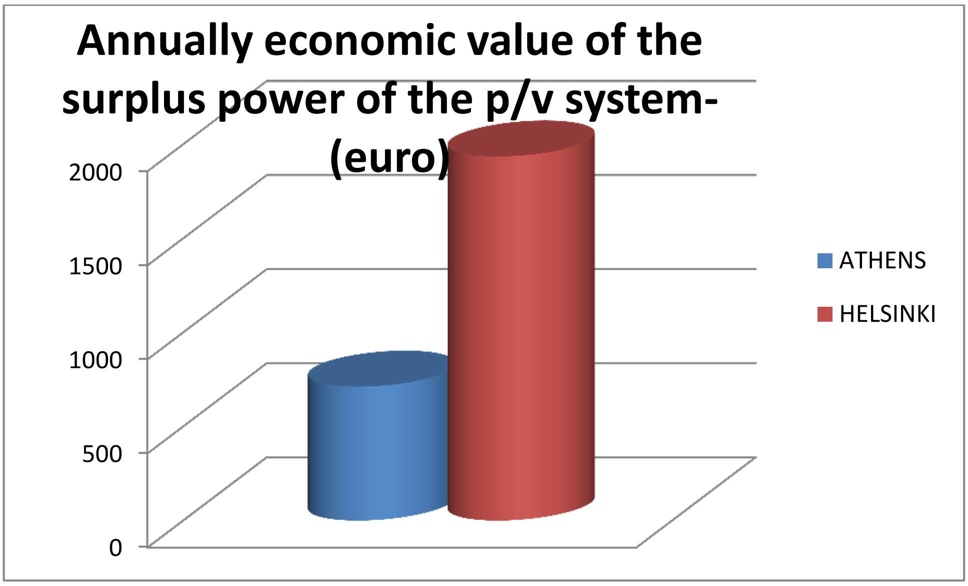


Figure 7.35: Annually economic value of the surplus power for the two cities of the building.

Although our system in Athens has more vivid sunlight and uses power from the p/v system for heating only 4 months, we observe that our system in Helsinki has much more valuable excess power from the p/v system. That is reasonable because of the 200 m^2 of collector's area in contrast with 32m^2 of Athens system. In the following 20 years and if the price of electricity stays stable, our installation could save up to 14234€ in Athens and 38702€ in Helsinki.

We thought that providing this economical point was important due to the big cost of our installation which could prevent someone from taking this heating system of a SAGSHPS as an innovative, efficient and economical way of heating.

8. Conclusions of the thesis

8.1 For the heating system

-The results of the study demonstrate that the solar-assisted ground source heat pump system exhibits efficient heating performance in both cities, Athens and Helsinki, despite the significant temperature difference observed in Helsinki. This efficiency can be attributed to the stable ground temperature, which enables the system to maintain a consistent coefficient of performance (COP) throughout the year.

-In the case of Helsinki, a higher-rated heating capacity water-to-water heat pump of 28 kW was utilized, whereas in Athens, a heat pump with a capacity of 14.2 kW was employed. This variation in the sizing of the heat pumps reflects the differing heating demands and climatic conditions between the two cities.

-A notable contrast was observed between Athens and Helsinki in terms of the electrical energy consumption required by the ground source heat pump systems for heating purposes. Specifically, in Athens, the heat pump consumed 1106 kWh, while the overall system consumed 1393.8 kWh. In contrast, the heat pump in Helsinki necessitated 11359 kWh of electrical power, with the entire system consuming 12966 kWh.

-The results indicate that both the Athens and Helsinki solar-assisted ground source heat pump systems exhibited a consistent coefficient of performance (COP) throughout the study period. The COP values remained stable, with an average value of 4 observed in both cases. This signifies the systems' ability to provide efficient heating while maintaining a favorable energy conversion ratio.

-The single speed pumps and fan coil unit consumed more energy in Helsinki. Specifically, the annual energy consumption for these components was 1607 kWh in Helsinki, whereas in Athens, it amounted to 286.4 kWh. This disparity highlights the greater energy requirements for heating purposes in the colder climate of Helsinki compared to the relatively milder climate of Athens.

-The heating system in Athens was observed to operate during the period from December to March, providing a total heating load of 4480 kWh. In contrast, the heating system in Helsinki had a longer operating period, spanning from September to May, and supplied a significantly higher heating load of 45100 kWh during these months.

-Among the months analyzed, February emerged as the month with the highest heating load requirement in Helsinki, totaling 10469.8 kWh. Conversely, in Athens, January exhibited the highest heating load demand, amounting to 1938 kWh. These results indicate the respective peak periods of heating demand in each city.

-The inlet fluid temperature of the water-to-water heat pump, sourced from the ground heat exchanger, exhibited distinct variations between Athens and Helsinki. In Athens, the inlet fluid temperature averaged at 17 degrees Celsius, while in Helsinki, it averaged at a lower temperature of 4.7 degrees Celsius. These discrepancies reflect the contrasting thermal characteristics of the ground as a heat source in the respective climates.

-The ground heat exchanger in Athens was designed with a storage volume of 2000 m^3 and a borehole depth of 50 meters. In comparison, the ground heat exchanger in Helsinki had a larger storage volume of 4000 m^3 and a deeper borehole depth of 80 meters. These specifications indicate the capacity and dimensions of the underground thermal energy storage systems implemented in each location, tailored to the specific heating demands and geological conditions of the respective areas.

8.2 For the photovoltaic system

-Following extensive evaluation and analysis, the optimal collector's area for the solar-assisted ground source heat pump system was determined to be 32 m^2 for Athens and 200 m^2 for Helsinki. This selection took into consideration the higher heating power requirements in Helsinki as well as the lower solar irradiance levels experienced in the city compared to Athens. By adjusting the collector's area accordingly, the system's performance and efficiency were optimized to meet the specific climatic conditions and heating demands of each location and provide 100% of annual energy coverage of annual’s electrical power consumption of heating system.

-The solar-assisted ground source heat pump system is designed to be connected to the grid, taking advantage of the surplus energy generated by the photovoltaic (P/V) system. This integration allows for efficient utilization of excess electricity produced by the P/V system, offsetting the energy consumption drawn from the grid when the instant load of the heat pump can’t be retrieved from the p/v system. In Athens, the annual electrical power generated by the system amounts to 5878.8 kWh, while in Helsinki, the annual production reaches 25866.5 kWh.

-During the months when the heating mode of the ground source heat pump system operates, the highest electrical production from the photovoltaic (P/V) system is observed. In Helsinki, the month of May stands out with a significant production of 3763 kWh, while in Athens, the peak month is March with an electrical production of 458.6 kWh.

-The solar assisted ground source heat pump system in both Athens and Helsinki demonstrates a surplus of electrical power production. In Athens, the system generates an annual surplus of 4744.8 kWh, while in Helsinki, the surplus amounts to 12900.82 kWh.

-In Helsinki, the month of December poses challenges for the solar assisted ground source heat pump system due to high heating load needs and limited sunlight. As a result, the system exhibits the lowest energy coverage rate of 13.06% during this month. This means that only a small fraction of the total energy required for heating is provided by the system's photovoltaic panels. So, in climates like Helsinki we can’t provide all the electrical power, that the worst cases of heating need, from the photovoltaic system.

- The combination of a solar-assisted ground source heat pump system and photovoltaic panels offers a sustainable and environmentally friendly solution for space heating and cooling in both climates. The renewable energy integration reduces greenhouse gas emissions and dependence on fossil fuel-based heating systems, promoting a greener and more sustainable approach to building energy management.

8.3 Economical view of the installation

-The initial cost of installation in Athens is €29806, while in Helsinki it amounts to €57037.5. The major contributors to these costs include the installation of the ground heat exchanger, the price of the heat pump, and the PV panels.

- In Athens, the Simple Payback Period (SPP) for the solar-assisted ground source heat pump system was determined to be approximately 28.02 years. This means it would take around 28.02 years to recover the initial investment through energy savings and cost reductions. On the other hand, for Helsinki, the SPP was calculated to be approximately 13.2 years, indicating a shorter payback period compared to Athens. Therefore, from an economic perspective, the system may be more financially viable in Helsinki due to its shorter payback period. So, the hot climates aren't favorable for ground source heat pumps because of the big installation costs that they need and small heating demands that they require. The SAGSHPS are favorable and efficient for cold climates for heating as the SPP for Helsinki shows. With better insulation on the building's cell the SPP could also drop significantly.

-The Life Cycle Cost (LCC) for the solar-assisted ground source heat pump system over a 20-year period is 60,017.5 euros in Helsinki and 31,296 euros in Athens. The higher LCC in Helsinki suggests that the overall cost of the system, including installation, operation, and maintenance expenses, is greater compared to Athens.

-The surplus energy economic value in the following 20 years is €14,234 for Athens and €38,702 for Helsinki. This factor should be taken into consideration when deciding to install the solar-assisted ground source heat pump system due to the high installation costs involved. The ability to offset grid energy consumption and potentially receive financial compensation or savings from the surplus energy can positively impact the economic feasibility of the system in both locations.

8.4 Proposals for future research

- Use larger building areas and mostly in cold climates where the heating needs are big in order to provide significantly smaller SPP values.

- Conduct a comparative study on the environmental impacts of solar-assisted ground source heat pump systems and conventional heating systems to quantify their carbon footprint and evaluate their contribution to sustainability.

- Explore advanced photovoltaic technologies and their integration with heat pump systems to enhance energy generation and optimize system performance.

- Assess the potential of incorporating energy storage systems, such as batteries, in solar-assisted ground source heat pump installations to optimize energy utilization and provide grid independence.

-Conduct a comprehensive economic analysis considering various financing models, incentives, and policy frameworks to evaluate the financial viability and cost-effectiveness of solar-assisted ground source heat pump systems

- Conduct field studies and performance monitoring of existing solar-assisted ground source heat pump installations to validate simulation models, analyze real-world performance, and gather data for further system optimization.