FACULTY OF INFORMATION TECHNOLOGY CTU IN PRAGUE

Assignment of bachelor's thesis

Title:	Economic and technical analysis of heat pump data
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Study program:	Informatics
Branch / specialization:	Information Systems and Management
Department:	Department of Software Engineering
Validity:	until the end of summer semester 2023/2024

Instructions

Heat pumps are one of the most widely used heat sources in today's energy crisis. The aim of the bachelor thesis is to perform an economic and technical analysis of the heat pump data from a household with respect to the cost of heat pump technology acquisition and information on the electricity consumption for heating the household with an electric boiler and a heat pump. Follow the below steps:

- Describe possibilities of heating households with a heat pump, explain principles of their operation, including a description of the heat pump's integration with the heating system and hot water heating.
- Describe datasets you will use for the analysis, acquisition costs, energy consumption, etc.
- Describe methods and metrics you will use to analyse the data.
- Analyse the operation of a heat pump using specific data, including the return on investment of the heat pump.
- Evaluate advantages and disadvantages of using a heat pump in a household.

Electronically approved by Ing. David Buchtela, Ph.D. on 17 January 2023 in Prague.

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Bachelor's thesis

Economic and technical analysis of heat pump data

Tereza Ehnová

Department of Software engineering
Supervisor: doc. Ing. Tomáš Vitvar, Ph.D.

May 11, 2023

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Doc. Ing. Tomáš Vitvar, Ph.D., for his invaluable guidance and responsible approach to this thesis. I would also like to thank my friends and family for their support throughout my studies. I would like to express my special thanks to my friend Barbora, who helped me overcome the challenges encountered throughout my academic journey.

Declaration

I hereby declare that the presented thesis is my own work and that I have cited all sources of information in accordance with the Guideline for adhering to ethical principles when elaborating an academic final thesis.

I acknowledge that my thesis is subject to the rights and obligations stipulated by the Act No. 121/2000 Coll., the Copyright Act, as amended, in particular that the Czech Technical University in Prague has the right to conclude a license agreement on the utilization of this thesis as a school work under the provisions of Article 60 (1) of the Act.

In Prague on May 11, 2023 . . . .

Citation of this thesis

Ehnová, Tereza. *Economic and technical analysis of heat pump data.* Bachelor's thesis. Czech Technical University in Prague, Faculty of Information Technology, 2023.

Abstrakt

Bakalárska práca sa zaoberá tepelným čerpadlom využívajúcim princíp vzduch-voda a asistovaným solárnym panelom. V práci sa vysvetľuje princíp fungovania konkrétneho systému a definujú sa metriky potrebné na opis jeho výkonnosti. V praktickej časti sú analyzované trendy v spotrebe a účinnosti a vysvetľuje sa, prečo účinnosť systému klesá počas letnej sezóny. Potom práca hodnotí vplyv rôznych faktorov na účinnosť a spotrebu elektrickej energie. Teplota má najväčší vplyv na účinnosť a rýchlosť kompresora má najvýznamnejší vplyv na spotrebu energie. Po analýze, boli najvplyvnejšie faktory použité na predikciu. Nakoniec finančná analýza ukázala, že investovanie do tepelného čerpadla je výhodné a v určitých prípadoch porovnatelne ziskové ako investovanie do akcií.

Klíčová slova tepelné čerpadlo, účinnosť, prehľad výkonnosti systému, technická analýza, predikcia účinnosti, predikcia spotreby energie, výnosnosť investície, porovnanie investičných možností

Abstract

This bachelor thesis analyzes an air-to-water heat pump system assisted by a solar panel, focusing on its operation, utilization, and necessary performance metrics. The thesis provides an overview of a specific system, analyzing trends in energy consumption and efficiency and identifying reasons for lower efficiency in the summer season. Additionally, the impact of various factors on the system's efficiency and electricity consumption is assessed, with temperature having the greatest influence on efficiency and compressor speed having the most significant impact on energy consumption. Afterwards, the most influential factors were used for predictions. The investment in a heat pump is advantageous compared to alternative investment options, particularly with the grant obtained, and can be comparable to investing in stocks in some cases.

Keywords air-to-water heat pump, efficiency, system performance overview, technical analysis, efficiency prediction, energy consumption prediction, investment efficiency, investment comparison

Contents

List of Figures

List of Tables

Introduction

As a society, we can see a population growth, advances in technology and a booming industry, all of which result in an increasing demand for global energy. However, the primary source of energy, fossil fuels, providing around 80 % of all energy [1], is finite and contributes to greenhouse gas emissions. In response, the EU has set a goal to reduce emissions by at least 50 % by 2030 and become climate-neutral by 2050 [2].

The Czech Republic has also taken action by implementing a National Action Plan for Renewable Energy, aiming to achieve 13 % renewable energy by 2020 and 20 % by 2030. This plan involves financial support, improved regulations and energy efficiency policies such as building retrofits and energy standards. [3]

Households can switch to renewable energy sources by installing heat pumps, which are increasingly popular. In 2021, a total of 30 165 heat pumps were installed in the Czech Republic, representing an increase of 6 000 installations compared to the previous year, and twice the number installed in 2016. [4]

Analyzing a heat pump's performance is crucial for optimizing its operation, identifying faults, and improving its efficiency and cost-effectiveness. In this analysis we determine the factors that impact the heat pump's COP (coefficient of performance) and energy consumption, which can help identify ideal deployment conditions and locations. Prediction models can be proposed after analyzing the heat pump's performance. Accurately predicting energy demands helps make decisions on energy generation and purchase, prevent overloading, and allow efficient energy storage. Predicting the COP helps determine the heat pump's performance and energy conversion effectiveness.

Numerous research papers have analyzed the relationship between different factors and the COP of heat pumps. However, many of these articles focus on only one parameter at a time and do not compare all the parameters together. Furthermore, they do not distinguish between summer and heating seasons. Additionally, there is a shortage of articles that evaluate the COP and energy consumption of a heat pump when coupled with a solar panel in the climate of the Czech Republic.

Besides performance analysis, it's essential to evaluate the profitability of investing in a heat pump. Most research in the Czech Republic calculates hypothetical profitability without considering an actual installation. While assessing the profitability of a potential investment is crucial, it's also vital to compare the performance of already installed systems and compare it to other investment opportunities.

Objectives and Goals

The aim of this thesis is to provide a thorough evaluation of the efficiency and cost-effectiveness of a heat pump system for space heating and DHW (domestic hot water) in a residential building. The thesis comprises a theoretical section, in which we explain the operating principles of heat pumps and provide information about heat pump systems focusing on the one used in our analysis. It is then divided into two main analytical parts, in which we focus on performance analysis and financial analysis, respectively.

We perform a performance analysis of the heat pump system to assess the building's energy consumption trends and the efficiency of the heat pump system during both the summer and heating season. We also identify independent variables with the strongest correlation with energy consumption and the COP, which includes the ambient conditions and technical parameters of the heat pump, to predict energy consumption and COP.

The financial analysis section of the thesis examines the profitability of investing in a heat pump system by using metrics such as ROI (return of investment), payback period, NPV (net present value), and IRR (internal return rate) to determine the economic feasibility of the system. We compare the different metrics to evaluate the investment's potential return and compare it to investment opportunities in bond and stocks.

We compare the heat pump system's performance and cost-effectiveness to an electric boiler, which was previously installed in the same building, in both analytical sections of the thesis. The purpose of this comparison is to evaluate the relative performance and cost-effectiveness of the heat pump system compared to the electric boiler.

Finally, we conclude the thesis by presenting the analysis's results and providing recommendations for optimizing the operation of heat pump systems. We also discuss the advantages and disadvantages of using heat pumps for space heating and DHW and implications for future research and practice in this field.

Thesis outline

The thesis comprises several chapters that cover various aspects of the analysis of a heat pump system. In Chapter 1, the introduction presents an overview of heat pumps, their principles, types, and potential for heating households. This chapter also summarizes and evaluates the current approaches to performance and financial analysis of a heat pump.

Chapter 2 describes the data sources and methodology used for data collection. It also includes a detailed description of the specific heat pump system that is analyzed.

Chapter 3 investigates the impact of different factors on the system's efficiency and energy consumption. The methodology used is described, and models are built to describe the relationship between these factors.

In Chapter 4, the profitability of the heat pump system is assessed by analyzing different financial metrics, such as ROI, NPV, IRR, and payback period. The analysis includes a description of the methodology used and factors that affect the system's profitability.

Chapter 5 summarizes the results of the analysis and discusses the advantages and disadvantages of installing a heat pump system.

Chapter **1**

Heat pumps

In this chapter, we explain the operation principle of heat pumps, discuss their history and present metrics that are used to assess heat pump performance. Additionally, we provide a brief overview of different types of heat pump systems along with their advantages and disadvantages.

1.1 Definition

A heat pump is an electrically driven device that moves heat from one place to another by using evaporative cooling. Several refrigerating systems (freezer, fridge, air-conditioner) are based on the same principle. Refrigerators cool down on the inside and get warm on the outside. For heat pumps, it's the opposite.

Heat pumps can be considered alternatives to furnaces, with an efficiency increase and operating cost reduction of approximately 50 % compared to electric resistance heating such as furnaces [5].

1.2 History of heat pumps

As early as 1852, British physicist Lord Kelvin realized that a „reverse heat engine“ could be used for cooling and heating. He pointed out that such a heating device would need less primary energy due to the extraction of heat from the environment. He described the working principle of "pumping" heat with a thermodynamic cycle to a higher temperature in his publication *On the economy of the heating and cooling of buildings using currents of air.* [6]

In 1856 and 1857, Peter Ritter von Rittinger built the first functioning "heat pump" with a capacity of 14 kW in Ebensee/Austria for the energy supply of salt production [7].

Some years later, Robert C. Webber is credited as having developed the first ground source heat pump during the late 1940s in America. He carried out numerous experiments with his deep freezer. Having burnt his hands touching the outlet pipes of the cooling system, he wondered whether he might be able to reverse the mechanics. Thereafter, he incorporated plastic pipe loops to circulate water in deep wells. [8]

Robert C. Webber's work inspired the development of a new generation of electrical technology that focused on air conditioning. As a result of this work, the first air conditioning systems were introduced in homes, and electrical and gas heat pumps were developed and put into use. Today, the same design is still used for heat pumps in most HVAC (Heating, Ventilation, and Air Conditioning) units. [9]

Improvements in heat pump technology over the past 20 years have focused on enhancing the COP by improving thermal exchange surfaces, compressors, and control and defrosting systems. Future equipment improvements aim to better utilize the properties of new refrigerants, as well as the pressure drop between the condenser and evaporator. [10]

1.3 Classification based on source

Three types of heat pumps are available for built environment, classified based on location of primary energy source: air, ground or water. Each has its benefits, depending on the application and specific design conditions. The advantages and disadvantages presented here are a summary from a website GreenMatch [11] and educational paper from Leonardo da Vinci programme [12]. More detailed information regarding a specific heat pump type can be found in either of these sources.

1.3.1 Air-to-water heat pump

Air to water heat pumps take heat from the outside air and transfer it to a water-based system.[13]
+ Air is the most accessible and ecological source
+ Easiest type to install
+ Cheaper than other heat pump systems
- Air is sensitive to temperature fluctuation
- At low temperatures, a supplementary source of heat might be required

1.3.2 Water-to-water heat pump

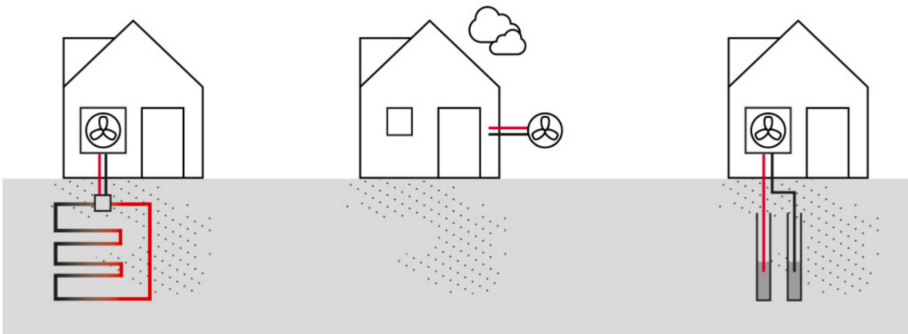
This heating system works by extracting heat from the groundwater beneath house and using it for heating.[13]
+ The temperature of this water is constant throughout the year and it is not affected by temperature of the atmosphere
+ Excellent levels of efficiency.
- Not every location has sufficient groundwater, therefore this type is not

suitable for every location
- Initial investment cost is higher than costs of other sources
- Lengthy and complicated planning and preparation phase

1.3.3 Ground source heat pump

Ground source heat pumps use a series of ground loops to absorb heat energy from the ground. [13]
+ Increases the value of property
+ Offer the best all-year-round efficiencies due to the potentially higher and consistent temperature of ground they draw energy from
- Can only be installed in a limited range of locations
- High installation cost

Figure 1.1: Different heat pump types



Source: [14]

Ground source heat pump on the left, Air-To-Water heat pump in the middle and Water-to-Water heat pump on the right.

1.4 Important components

In this section, we provide a brief overview of the essential components of a heat pump. It's worth noting that all types of heat pumps, such as air-source, ground-source or water-source, share the same fundamental components. To comprehend how heat pumps function, it is critical to understand these essential components. The description of these components was obtained from the website [15].

- *Refrigerant*: The refrigerant is a fluid responsible for absorbing, transporting, and releasing heat as it circulates through the heat pump. Depending on its location, it can exist in various states such as liquid, gaseous, or a mixture of both.

- *Reversing valve*: The reversing valve controls the refrigerant's flow direction in the heat pump and switches the heat pump between heating and cooling modes.
- *Coil*: A coil is a set of tubes used for heat transfer between the refrigerant and the source/sink. It can have fins that increase the surface area available for heat exchange.
- *Evaporator*: The evaporator coil absorbs heat from its surroundings, causing the refrigerant to boil and become a low-temperature vapor. If any excess liquid remains, the accumulator collects it as the refrigerant flows from the reversing valve to the compressor.
- *Compressor*: The compressor is responsible for squeezing the refrigerant gas molecules together, which increases its temperature and aids in the transfer of thermal energy between the source and sink.
- *Condenser*: The condenser coil releases heat to its surroundings, causing the refrigerant to become a liquid.
- *Expansion device*: The expansion device lowers the pressure produced by the compressor. This process causes the refrigerant's temperature to drop, turning it into a low-temperature vapor/liquid mixture.
- *Outdoor unit*: The outdoor unit of an air-source heat pump transfers heat to or from the outdoor air. It typically includes a heat exchanger coil, compressor, and expansion valve, and operates similarly to the outdoor part of an air conditioner.
- *Indoor coil*: The indoor coil of certain air-source heat pumps transfers heat to or from the indoor air. It generally contains a heat exchanger coil and a fan that circulates heated or cooled air to the occupied space.
- *Fan*: Draws air across the evaporator coil (for heat extraction) and moves air away from condenser coil (for heat distribution/removal).
- *Thermostat*: Thermostat controls and regulates the temperature in a building.

1.5 Operating principle

Heat pumps work through two primary cycles: refrigeration and defrost cycle. The refrigeration cycle is the main mechanism that heat pumps use to move heat from one place to another. However, as the number of defrost cycles a heat pump goes through can impact its overall performance, we also provide an explanation of this process.

1.5.1 Refrigeration cycle

The operating principle is described based on Figure 1.2, with a focus on the air-to-water heat pump, as this type of pump is used for most of the further analysis. However, all heat pump types follow the same principle. The description was derived from the information presented in [16].

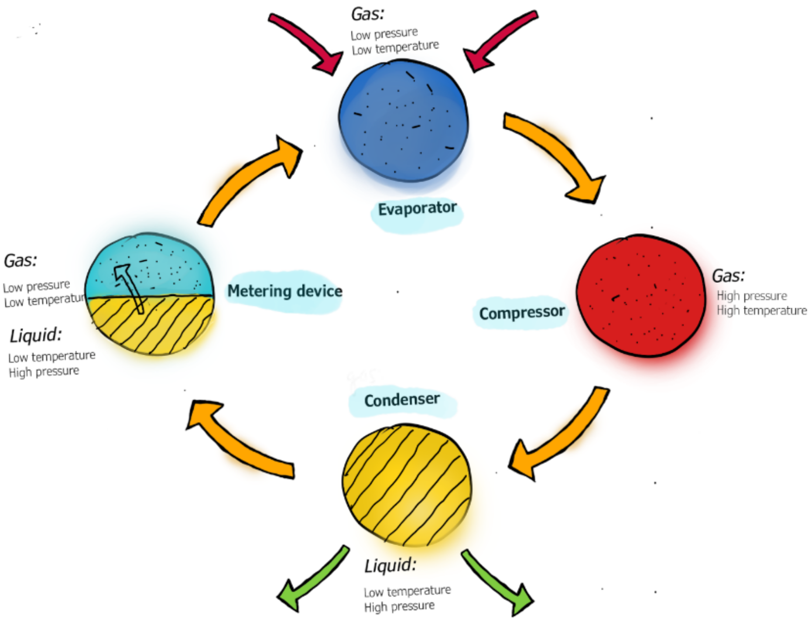


Figure 1.2 Schematic diagram of heat pump operation

- In the evaporator, low-pressure, low-temperature liquid refrigerant absorbs heat from its surroundings and evaporates, converting to a gas state and absorbing energy as it does so.
- It passes through a compressor where low temperature gas is reduced in volume, resulting in a rise in both temperature and pressure.
- As a heated and high-pressure gas, it passes through a condenser where gas condenses with a release of heat into the air surrounding the coil. A fan moves the warmed air away from coil to distribute it throughout indoor space.
- Still under pressure, the cooled refrigerant, now in liquid state, passes through a metering device, where rapid expansion results in a reduction in pressure
- In low-pressure, low-temperature state, the refrigerant flows back into the evaporator, and the cycle is repeated.

1.5.2 Defrost cycle

Defrosting typically commences when outdoor ambient temperatures drop significantly, causing the moisture in the air to freeze on the heat exchanger of the outdoor unit. An outdoor sensor detects the formation of ice on the heat exchanger and initiates a defrost cycle to prevent ice buildup. All the descriptions in this section are summarized from the source [17].

- Outdoor sensor detects ice forming on the heat exchanger.
- Reversing valve switches the refrigerant flow direction.
- Warm air from the indoor coil melts the ice on the outdoor coil.
- Water from the melting ice drains out of the outdoor unit.
- Heat pump resumes normal operation.

1.6 The coefficient of performance

The COP is an important parameter for efficiency and performance evaluation of a heat pump. A higher COP indicates that a heat pump is able to produce more heating, which results in a lower energy consumption and lower operating costs. The way the COP is calculated is outlined in the ČSN (Czech technical standard) and can be accessed through their website [18]. The norm *ČSN EN 14511* [19] provides specifics on how to calculate the COP and the norm *ČSN EN 14825* [20] sets minimum efficiency requirements for heat pumps based on the size and type of the unit.

1.6.1 Theoretical coefficient of performance

Under ideal conditions, a heat pump converts all absorbed energy (sum of the heat extracted from the source plus the energy required to drive the heat pump) into heat. The theoretical COP is the maximum possible COP that a heat pump can achieve under ideal conditions. It is calculated based on the Carnot cycle, which is a theoretical thermodynamic cycle that describes the maximum efficiency of a heat pump. The formula for the theoretical COP of a heat pump operating on a Carnot cycle is:

$$COP_{th} = \frac{T_h}{T_h - T_c} \tag{1.1}$$

where T_h is the desired hot temperature and T_c is temperature of the heat source. [21]

1.6.2 Real coefficient of performance

The real COP of a heat pump is typically lower than the theoretical COP, as the real COP is affected by various factors that impact the performance of the system. We explore and study these factors later in this thesis. The definition of the COP as a parameter of a heat pump efficiency is given in the standard *CSN EN 14511* [19]. The higher the *COP*, the greater the efficiency of a heating system. It is calculated by dividing heat output by electrical input [19].

$$COP = \frac{Q_b}{W} \tag{1.2}$$

where Q_b is the heat supplied and W is the work consumed by heat pump. Even though there are several metrics available to evaluate the efficiency of a heat pump, we focus only on COP. However, detailed description of other metrics, such as SCOP, Heating Season Performance Factor (HSPF), Energy Efficiency Ratio (EER), and Seasonal Energy Efficiency Ratio (SEER), can be found in the Czech technical norm [18].

1.7 Areas of application

Heat pumps have a variety of applications in both residential and commercial settings. Some areas of application include:

- *Space heating and cooling:* Heat pumps are commonly used for space heating and cooling in homes, offices and other buildings. It's important to note that while some heat pumps can provide both heating and cooling in a single unit, there are also heat pumps that only function in one mode. [22]
- *Domestic hot water heating:* Heat pumps can also be used to heat domestic water for showers, dishwashing and laundry. There are combination systems that heat both the area and the water. [22]
- *Swimming pool heating:* Heat pumps are an efficient way to heat swimming pools, making it possible to prolong the swimming season and reduce operating costs. [23]
- *Industrial process heating and cooling:* Heat pumps are versatile systems that can be utilized in various industrial applications to provide both heating and cooling for equipment and processes. Examples of industries that can benefit from the use of heat pumps include Pharmaceuticals, Food Processing, and Cement and Concrete. [24]
- *District heating and cooling:* Heat pumps can be used in district heating and cooling systems to provide energy to multiple buildings or areas from a central location. [22]

1.8 Description of the installed system

We start this section by explaining how a solar combined heat pump system operates and highlighting its benefits over standard heat pump systems. Then, we describe a specific heating system and the building in which it is installed, while also presenting important features of the system.

1.8.1 Solar assisted heat pump

A solar assisted heat pump is a system that combines a heat pump with a solar collector, which is a set of panels that convert sunlight into heat. This system is designed to extract heat from a specific source and transfer it to a desired location to provide space heating, water heating, or both.

The difference between a solar assisted heat pump and a regular heat pump is that the solar panels can extract heat directly from sunlight and use it to generate electricity. This system can be used to meet the heating needs of an entire building or to produce hot water. By using this combined system, energy bills can be reduced and the house can become more eco-friendly. In the analysis, the heating pump is supplemented with a solar panel that heats up the water during the summer season. [25]

1.8.2 Building Characteristic

The residential building under consideration is a single-family house situated in the northern region of the Czech Republic. It is a recently constructed building, covering an area of $648.58\,\mathrm{m}^2$, with an energy-related reference area of $242.9\,\mathrm{m}^2$ and thermal loss of 147.5 Kw. Electricity is the primary and sole source of energy for the building, which is obtained from the grid and renewable sources. The total energy consumed is distributed between grid energy and renewable energy, with renewable energy accounting for 38.6 % of the total energy used.

1.8.3 Heating system

Solar-assisted air-to-water heat pump system powered by electricity is installed in the building to provide both the domestic hot water needs and cover space heating demands. Other energy demands are covered by the electricity from the grid.

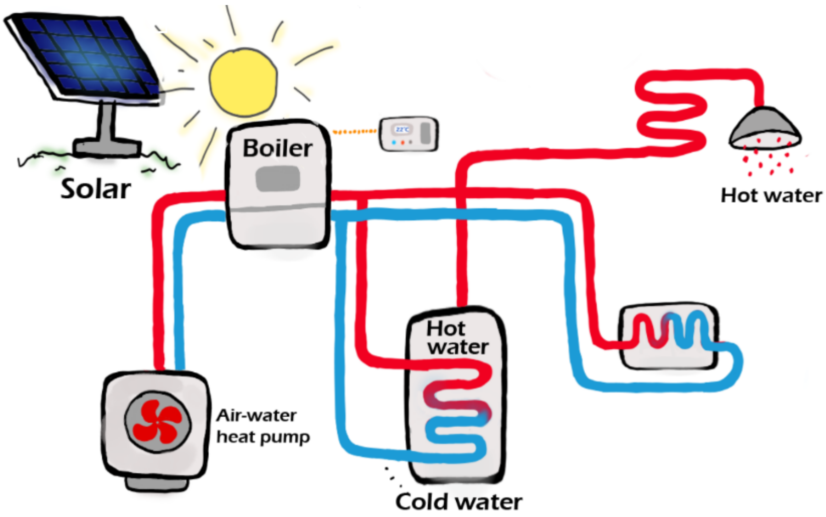


Figure 1.3 Installed heat pump system

The heat pump operates throughout the entire year, with highest demand occurring in the winter period (November – March) - the so called heating season. During the summer season (May-September) energy demands drops significantly, as the heat pump is only used to heat water. On sunny days, a solar panel partially covers domestic hot water demands. A schematic diagram of the heat pump system is shown in Figure 1.3.
It can be seen that there is a Heat pump (outdoor unit), which extracts energy from the air and moves it through the pipes to the indoor unit located the building. Inside is the hot water tank (boiler), connected to a bunch of pipes and other equipment's that allows heat pump to provide both heating and hot water for the building. There are also solar panels linked directly to the heat pump, sharing the same refrigeration circuit.

An electric boiler was installed in the building prior to the heat pump system for space heating and DHW purposes. The electric boiler has an efficiency of only 90 %, whereas the heat pump has an average efficiency of 250 % (See Data analysis chapter). However, this thesis does not require a detailed description of the electric boiler. Additional information on the electric boiler may be found in other sources, such as [26].

1.9 Literature review

Heat pumps have been analyzed since their invention, but in recent years, there has been a surge in research and development of heat pump technology. This is due to a combination of factors such as environmental concerns, technological advancements, regulatory incentives and economic benefits.

Research studies on heat pumps focus on a wide range of topics, including performance optimization, environmental impact, economic viability, system integration and user behavior. One common area of focus for researchers is performance optimization. Many papers investigate ways to improve the efficiency, reliability and overall performance of heat pump systems. This can involve developing new designs or materials, optimizing system controls or improving the integration of heat pumps with other energy systems. Such research often requires an understanding of the principles of thermodynamics, as well as knowledge of the mechanical construction of heat pumps, including heat exchanger design and refrigerant selection. However, for this particular thesis, which focuses on heat pump data analysis, we do not need to review the literature on the detailed mechanical construction of heat pump systems. Our aim is not to develop new designs or materials, but rather to analyze existing data to identify patterns and insights.

Another crucial area of research that affects the performance of heat pumps is the analysis of ambient conditions, including temperature and humidity, as these factors can significantly impact the COP of the system. A study [27] investigated the impact of temperature and solar irradiance on the COP and discovered that higher ambient temperature and more solar radiation can increase the COP. However, it is worth noting that this study was conducted in a lab setting in China, which may have faced limitations such as a smaller sample size, limited representation of real-world conditions and an artificial environment. Additionally, the study worked with the climate of China, which is vastly different from that of Czech republic. This claim, was confirmed by another study [28], which also examined effects of relative air humidity. The mathematical model developed in the study showed that fully humid air at 18°C increases performance, raising the COP, but below 6°C increased relative humidity causes performance loss. However, this model also only used experimental data.

Other studies have examined the impact of compressor speed on the COP, including differences between fixed and variable speed compressors. A study conducted in Poland [29] found that variable speed compressors provide greater heating capacity with increased compressor frequency, but result in the decreased COP at higher condensing temperatures.

The temperature difference between the evaporator and condenser is an important technical parameter that affects the COP of heat pumps. According to a study on cascade heat pumps [30], COPs decrease linearly as the temperature difference increases. The study also found that a smaller temperature difference can shorten the payback period.

Researchers use machine learning techniques to predict a building's energy consumption and evaluate heat pump performance. In one study [31], short-term dynamic monitoring combined with regression analysis and extrapolation is used to predict an Air-to-Water Heat Pump's (AWHP) heating Seasonal Coefficient of Performance (SCOP). The study recommends using linear fitting with ambient temperature as the independent variable and the typical-meteorological-day method for predicting AWHP. This method involves selecting a few days that represent typical meteorological conditions during the heating season to predict the system's SCOP. The model find, that temperature is a great factor to asses the efficiency. However, the model's limitation is that it only used 75 days of data, which could be a disadvantage.

A strategy for forecasting energy consumption in smart buildings was proposed in a paper [32]. This strategy predicts day-ahead hourly energy consumption using a dataset that includes historical, meteorological, calendar, and past series data. Various machine learning and deep learning models were tested, and the best models were combined to create an assembled model that yielded better results than individual models. The study was conducted on an office and a school campus, so the results may not be generalizable to residential buildings due to differences in heating demand.

Another group of scientists [33] tested several machine-learning methods (artificial neural network, support vector machine, random forest, and K-nearest neighbor), to discover which one gives the best result. The best model was found to be the Random Forest Regressor.

Because heat pump, are not only more ecological, but also decrease the monthly electricity cost, a lot of papers are accessing their profitability. For example analysis [34] compares the investment in a hybrid photovoltaic solution with a heat pump to long-term government bonds. It shows that the hybrid system provides a return on investment within just 5 years, making it a more attractive option compared to investing in government bonds. Furthermore, there are limited research papers that analyze investment profitability in great detail, especially in Czech republic. While some research, such as the following thesis [35], exists, it does not utilize real installations.

Chapter **2**

Dataset

In this chapter, we describe the datasets used in analysis, which include data from the heat pump system introduced in the previous chapter, data from an electric boiler and weather data. We provide a detailed description of each dataset, including its source, the time range it covers and its format. The data was primarily obtained by monitoring the heat pump and electric boiler. However, we also used an API to obtain additional data on air humidity and solar radiation to provide a more comprehensive overview for further analysis. The description of data related to acquisition cost is provided in Chapter 4.

2.1 Data sources

2.1.1 InfluxDB

Most of the data are stored in InfluDB. The database contains various types of data related to the building's energy consumption. This includes information from both the electric boiler and heat pump, as well as technical parameters of the heat pump, such as compressor speed, inlet/outlet water temperature, temperature of water in the boiler, and amount of heat generated. Additionally, it stores data related to ambient factors such as the number of solar hours,ambient temperature and solar panels temperature. We used two Python libraries, namely *DataFrameClient* and *InfluxDBClient* from the influxdb package [36], to access the data stored in InfluxDB.

2.1.2 Weather.com API

Since the database only provided information on ambient temperature and number of solar hours, additional data on air humidity and solar radiation was obtained to gain a more comprehensive understanding of the factors impact. The data were obtained using the https://api.weather.com API [37], which provides current and historical weather data. To retrieve the necessary weather data, we employed the use of two Python libraries *requests* and *json*. The requests library facilitated the sending of requests to the API, while the json library was used to handle the JSON-formatted data returned by the API.

2.2 Final dataset

In order to meet specific analytical requirements and group entities that belong to the same category, the data were organized into separate data frames. This process resulted in the creation of three distinct data frames: one focused on building energy consumption, another detailing the technical parameters of a heat pump and the third representing the weather conditions being monitored. The dataframes were created using Pandas library [38].

2.2.1 Energy consumption and performance

The dataframe utilized to assess the building's energy consumption and the heat pump's performance consists of multiple columns, each containing distinct information. Each row in the dataframe is indexed by timestamp. The electric boiler data were gathered over a span of 892 days, from August 22nd, 2018 to January 30th, 2021. Additionally, the data pertaining to the heat pump covers a period of 423 days, from December 30th, 2021 to February 26th, 2023. The data are recorded on a daily basis.

Table 2.1: Dataframe representing data about Energy Consumption

Column name	**Data type**	**Description**
Power consumed [KwH]	Float	Energy used in total.
Power heating [KwH]	Float	Energy used for space heating.
Power DHW [KwH]	Float	Energy used for DHW purposes.
Power Rest [KwH]	Float	Energy used for operating purposes.
Power Generated [KwH]	Float	Amount of energy generated by heat pump.
COP	Float	COP of the heat pump. If the energy source is an electric boiler, the COP is a fixed value of 90 %. Otherwise, the COP is calculated using the formula described in section 1.6.2.
Source	Categorical	Specifies the source of energy, with two possible values - "HP" and "EB".

2.2.2 Heat pump's variables

The dataframes include records of the compressor speed in revolutions per second, the temperature of the evaporator in degrees Celsius and the temperature of the condenser in degrees Celsius. Each row is timestamped to identify the specific day and time that the data were recorded. Similarly the data were collected from December 30th, 2021 to February 26th, 2023. The data is recorded every 15 minutes.

Table 2.2: Dataframe representing data about Technical parameters of the heat pump

Column name	Data type	Description
Evaporator temperature [°C]	Float	This is the inlet temperature.
Condenser temperature [°C]	Float	This is the outlet temperature.
Temperature difference [°C]	Float	Inlet - Outlet temperature
Compressor speed [rps]	Float	-
Water temperature [°C]	Float	Water in a tank used for showering.
Collector temperature [°C]	Float	Temperature of the solar panels.
Defrost cycle	Int	Specifies how many times per day heat pump underwent a defrost cycle.

2.2.3 Ambient Conditions

The data we collected includes information on both ambient temperature and the number of solar hours. As mentioned in the previous section, we obtained temperature and solar hour data from a database, while air humidity and solar radiation data were obtained from an API [37]. Solar radiation and air humidity data were collected from December 30th, 2021 to February 26th, 2023, but the temperature data were collected from August 22nd, 2018 to February 26th, 2023.

Table 2.3: Dataframe representing data about Ambient Conditions

Column name	Data type	Description
Ambient temperature [°C]	Float	-
Relative air humidity [°C]	Float	Obtained from API [37].
Water temperature [°C]	Float	Water in a tank used for showering.
Solar hours	Int	How many hours was sun shining in particular day.
Solar radiation [W/m^2]	Float	Obtained from API [37].

Chapter 3

Data analysis

In this chapter, we focus on energy consumption analysis of a building and the energy efficiency of a heat pump. We consider various factors and their relationship to energy efficiency and consumption to determine which variables contribute the most to both. To prepare for the analysis, we preprocess and transform the data as necessary. We also describe the methodology used for the analysis in this chapter.We used libraries including sklearn [39], scipy [40], plotly [41], and statsmodels [42] for various tasks such as machine learning modeling, statistical analysis, and data visualization.

3.1 Data manipulation

3.1.1 Preprocessing

The dataset was initially examined to detect any instances of nulls, duplicates, outliers and missing values. The majority of data was complete, but some air humidity and solar hours data were missing. As the missing data were required for assessing correlations with other variables, it was filled using the Simple Arithmetic Mean Method. This method replaces missing values with the average of the values before and after the missing data point, and in this case, the average of the values for the week was used.

After handling missing values, the next step in the data preprocessing pipeline involved performing outlier detection. For this purpose, we employed the Grubb's test, which is a statistical method designed for detecting outliers in normally distributed data. The test involves calculating a Z-score for each data point in the dataset, and then comparing it against a critical value (known as the threshold) to determine if the data point is an outlier. [43]

$$z = \frac{(x - \mu)}{\sigma} \tag{3.1}$$

where x is the value that will be standardized, μ - is the mean of the distribution and σ is the standard deviation of the distribution.

Any outliers that were detected using this method were then removed from the dataset. However, before analyzing the correlation and building Machine learning (ML) models, outliers were not removed as they could potentially indicate issues with the heating system that required further assessment. Once ML models were used, outliers were removed.

3.1.2 Normalization

The variables used in the analysis were normalized using the min-max method. This technique rescales the data to a range between 0 and 1, allowing for easier comparison between variables. The equation used for normalization is as follows:

$$X_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{3.2}$$

Here, X_{min} represents the smallest value in the dataset, while X_{max} represents the largest value in the dataset. The min-max method was chosen because the range of values in the dataset was not very large.

3.1.3 Train-test split

For building regression models, we first split the data into training and testing sets using an 80 %-20 % split. We opted for this split method over the train-validation-test method due to the relatively small size of our dataset, which allowed for more accurate results.

3.2 Methods and measures

3.2.1 Clustering

Applying a clustering algorithm helps to organize seemingly scattered data points into clusters, allowing for the identification of natural groupings and outliers for anomaly detection.[44] In this thesis, we utilized the K-means clustering algorithm, which partitions objects into k clusters (the number of clusters specified) based on feature similarity. We used elbow method to define the right number of clusters [45].

Initially, our plan was to analyze the heating and summer seasons separately. In general, splitting the data into these two seasons was sufficient, and creating additional clusters did not significantly improve the models. However, there were some instances where creating more groups led to better results.

3.2.2 Correlation

Correlation is a statistical measure that is used to indicate the strength and direction of the relationship between two variables [46]. There are many types of correlation coefficients, but for the purpose of this thesis the Pearson correlation coefficient is used. Pearson correlation is appropriate when both variables are continuous and have a linear relationship. It is also useful when the distribution of the data is normal or approximately normal. For two variables, x and y, the Pearson correlation is defined as follows [47]:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{3.3}$$

The strength of a correlation is a measure that ranges between 0 and 1 and is used to quantify the relationship between two variables. A perfect relationship between two variables is indicated by a correlation of 1, which means that the variables are perfectly aligned with each other. If the correlation is 0, it means that there is no relationship between the variables.

The relationship between variables can be positive, meaning that both variables move in the same direction, or it can be inverse, meaning that the variables move in opposite directions.

When calculating a correlation, a p-value is also generated, which indicates the statistical significance of the correlation. The p-value represents the probability of obtaining the observed correlation by chance alone, assuming that there is actually no correlation between the two variables. [46]

3.2.3 Linear regression

Linear regression is a statistical technique used to model the relationship between a dependent variable and one or more independent variables [44]. We can use this method for both predictive and descriptive purposes by examining the relationship between one dependent variable and one independent variable, such as how ambient temperature affects COP. In this case, the dependent variable (COP) is affected by the independent variable (ambient temperature). To establish this relationship, we used the train-test split method outlined in 3.1.3, and we can describe the relationship between variables using an equation, such as:

$$Yi = \beta_0 + \beta_1 \cdot X_1 \tag{3.4}$$

where: β_0 is the y-intercept (representing the value of y when x is 0) and β_1 is the slope and describes the relationship between the independent variable and the dependent variable.

3.2.4 Model evaluation strategies

Various statistical techniques can be used to evaluate model performance, including assessing fit to data, testing for statistical significance, and evaluating variable importance.

We use the *R-squared measure* (RMSE) to evaluate the goodness of fit of our regression model and determine how well it fit the data. A higher value of RMSE indicates that the regression model fits the data better. RMSE is defines as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\Sigma_{i=1}^{n}\left(Y_i - \check{Y}_i\right)^2} \tag{3.5}$$

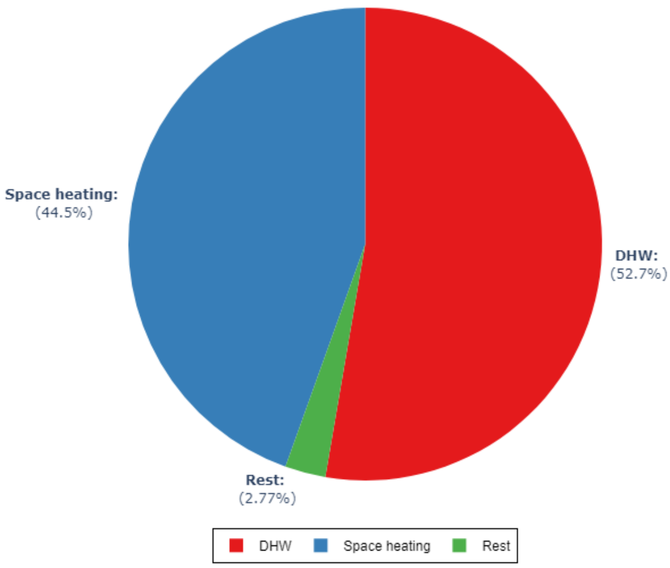
where Y_i is the actual value, $\check{Y}_i$ is the predicted value, and n is the number of samples. [44]

3.3 Energy consumption of the building

First, we identified patterns and trends in energy use. Only the heat pump's energy usage was considered for this analysis, and it was not necessary to consider the energy usage of other household activities.

The figure 3.1 illustrates how the annual energy consumption of the heat pump, which was 4 030 KwH, was allocated between DHW and space heating demands. Additionally, the graph displays the percentage of energy lost in transmission and technical needs of heat pump, such as restart or defrosting.

Figure 3.1 Energy consumption per end uses (2022)

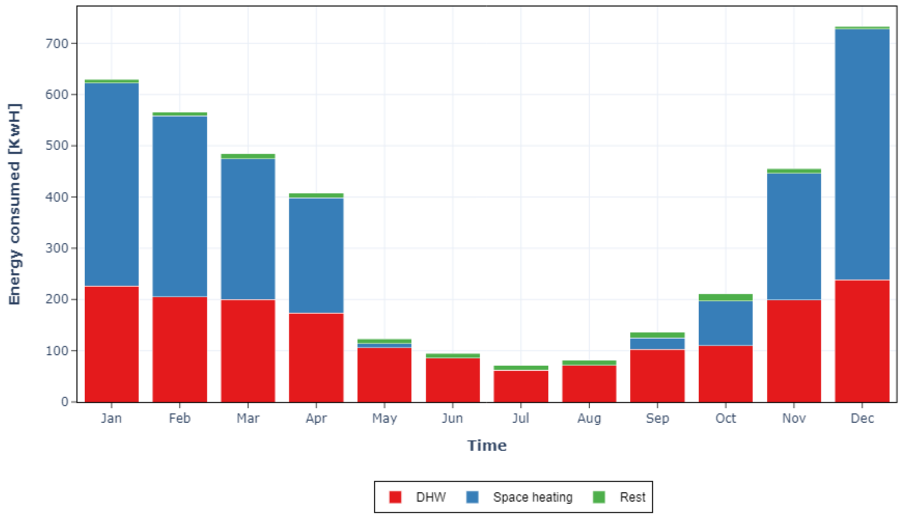


It is evident that the energy consumption for DHW was almost equivalent to the energy required for space heating. Nevertheless, only a small proportion of the energy was utilized for meeting the remaining energy demands.

3.3.1 Monthly energy consumption

Figure 3.2 illustrates that energy consumption is higher during the heating season and lower during the summer months. This is because, during the winter, the heat pump is used for both space heating and DHW, while during the summer, it is solely used for DHW.

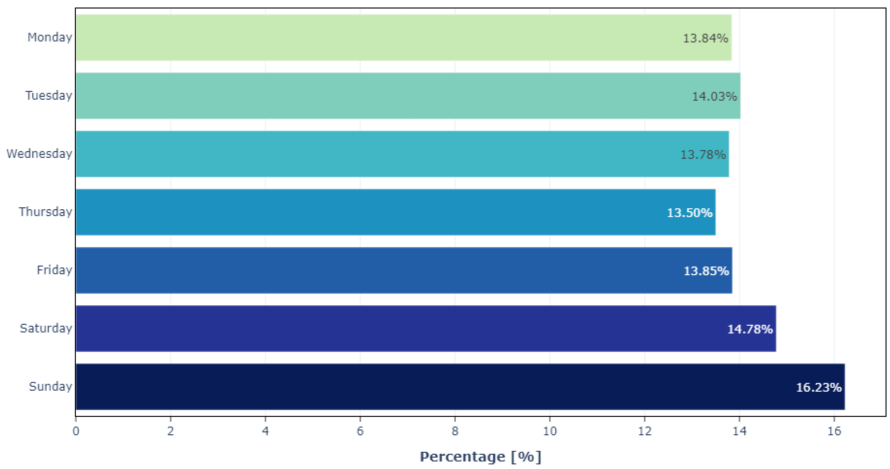
Figure 3.2 Monthly energy consumption per end uses (2022)



3.3.2 Consumption by weekday

Figure 3.3 shows the total energy consumption for each day of the week over a year.

Figure 3.3 Consumption by weekday (2022)

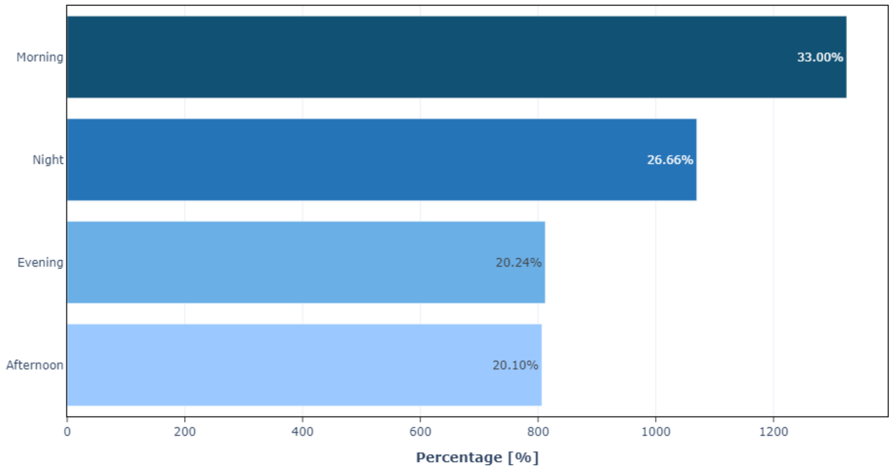


The bars indicate that energy usage is higher on weekends due to people spending more time at home, while energy usage is lower on weekdays when people were typically away.

3.3.3 Consumption by time of the day

Figure 3.4 displays energy consumption over a 24-hour period, showing a gradual increase in the morning as people start using appliances like showers. Energy consumption remains relatively low in the afternoon when many people are away from home.

Figure 3.4 Consumption by time of the day (2022)

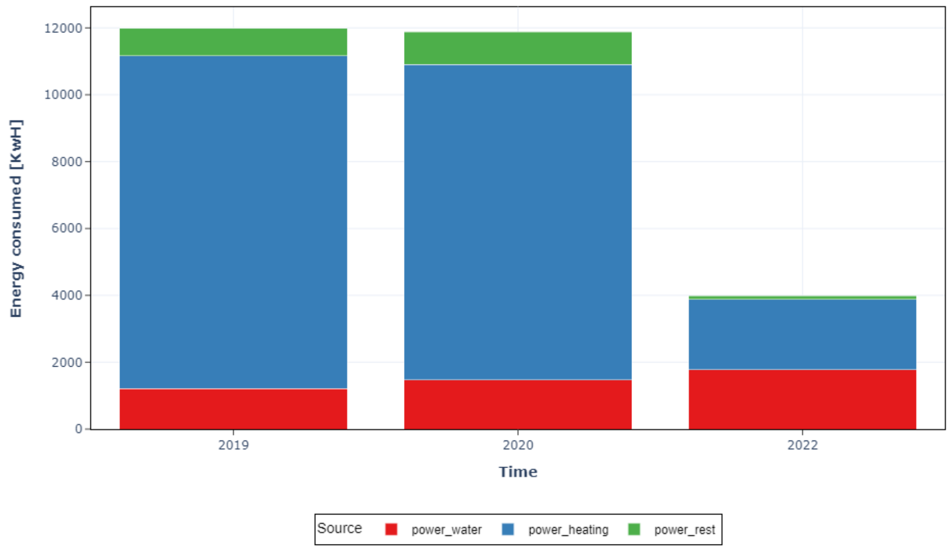


3.3.4 Electric boiler comparison

Figure 3.5 presents a comparison of energy consumption between an electric boiler and a heat pump. The comparison is based on data from 2019 and 2020, when the electric boiler was in use, and from 2022 when it was replaced by the heat pump. Data from 2021 is not included due to incomplete records.

The results show that the installation of a heat pump has significantly reduced energy consumption, with a noticeable decrease during the heating season. In fact, energy consumption during this period was three times lower than before the replacement. However, the amount of energy for DHW was around the same. Further analysis would be needed to determine the reasons for this, but this thesis will not conduct that analysis.

Figure 3.5 Energy consumption comparison (2019-2022)

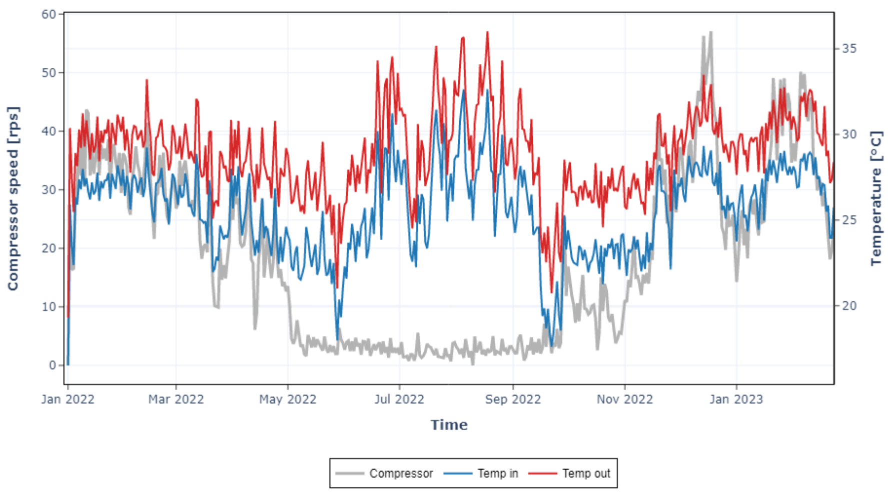


3.4 Performance of the heat pump

3.4.1 Heat pump's variables

The compressor is a crucial part of a heat pump and its performance has a significant impact on other variables. In Figure 3.6, the performance of the compressor is illustrated along with the refrigerator temperatures at the inlet and outlet.

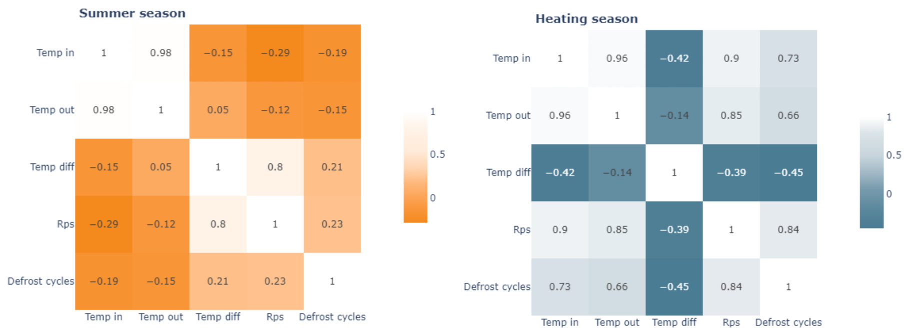
Figure 3.6 Heat pump inlet/outlet temperature and compressor speed, daily data (2022)



During the summer season, compressor speeds tended to be lower, whereas inlet and outlet temperatures were much higher. On the other hand, there was a bigger difference between these temperatures in colder months. Towards the end of the year, mild fluctuations were observed in all of these factors. The reason for the variation in heating demands was that they varied during the heating season, whereas they remained around the same during the summer.

Refer to Figure 3.7 to observe the correlation coefficient of individual parameters during both the heating and summer seasons. Since these seasons are analyzed separately for most of the subsequent analysis, it is important to examine the correlations for each season individually.

Figure 3.7 Correlation matrix of technical parameters

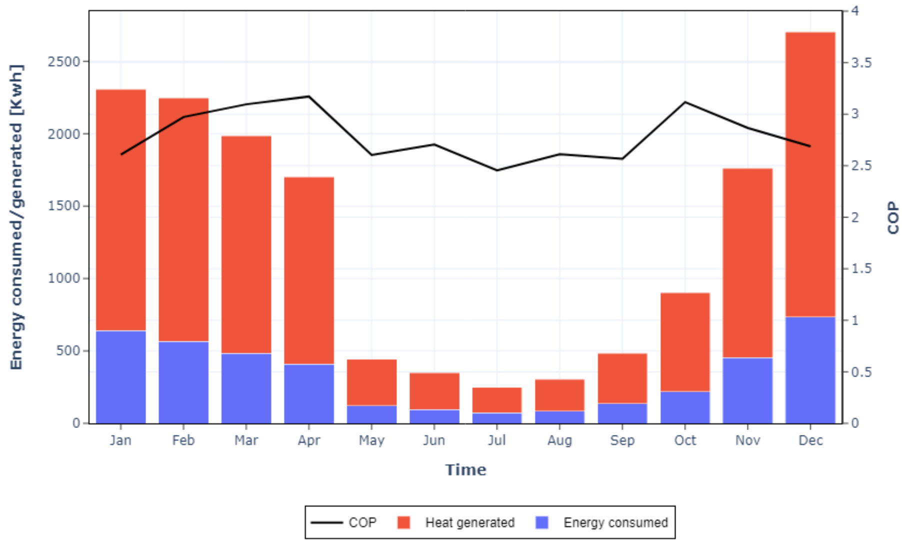


Upon examination, it becomes evident that most of the individual parameters are inversely correlated in both seasons. This is true for all parameters except for the inlet and outlet temperature, which exhibit a positive correlation in both seasons.

3.4.2 Heat pump's efficiency

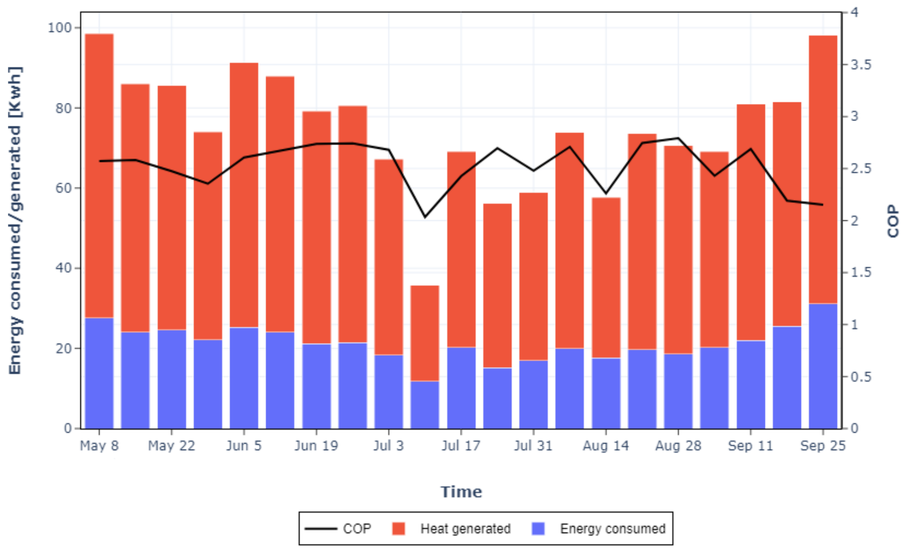
A Figure 3.8 illustrating the monthly COP of a heat pump system shows data from the full year, taking aggregated data for each month. There are also two additional figures, one displaying the COP during the heating season (Figure 3.11), and the COP in summer months (Figure 3.9). The yearly COP graph provides an overall view of the system's efficiency throughout the year, whilst the seasonal graphs provide a more thorough insight into the heat pump's performance over distinct temperature ranges.

Figure 3.8 Monthly COP (2022)



The average COP for the entire year was 2.83. During the heating season, the average COP was 3, while during the summer season, it was 2.5.

Figure 3.9 Summer season, weekly COP (2022)



A heat pump's COP is often anticipated to be higher in the summer. Yet, this is untrue. In summer, energy is used solely to heat water in the tank since there is no need for space heating. This results in a larger temperature difference between the outdoor and indoor units, as the water is heated to 55°C. In winter, most of the energy is used for space heating, resulting in a smaller temperature difference (refer to equation 1.6.1), which can lead to a seemingly higher COP compared to summer. The heat pump may also consume energy when switched on but not in use, maintaining standby mode, restarting, or running the fan.

The Figure 3.10 displays the status of the heat pump during both the summer and heating seasons. The chart illustrates that during the summer season, the heat pump is primarily in standby mode. In contrast, during the winter season, most of the energy is used for heating. The remaining portion of the chart includes other activities such as defrosting, flow control, and malfunctions.

Figure 3.10 Heat pumps status (2022)

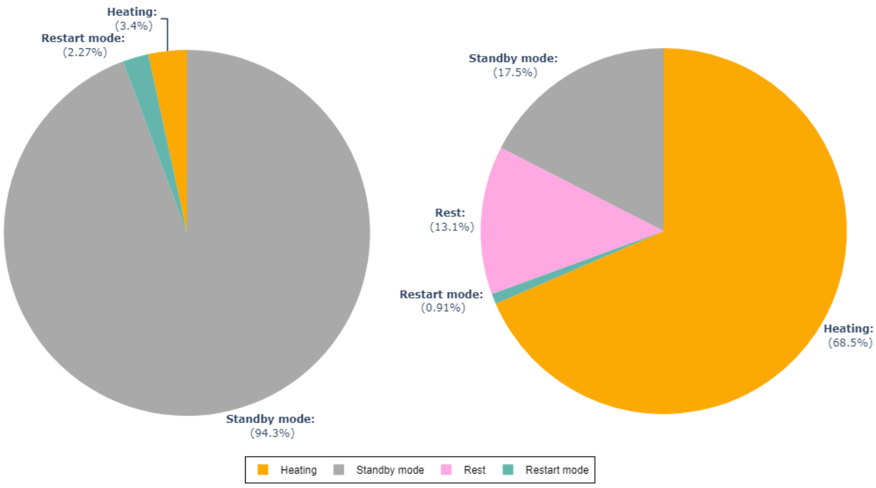
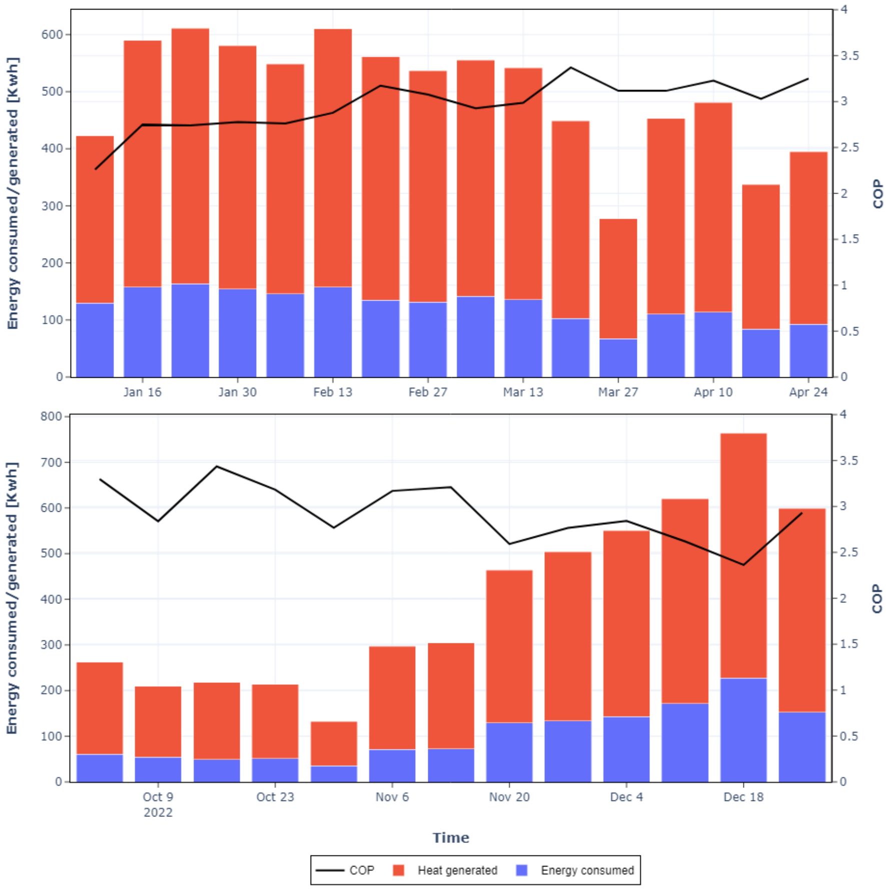


Figure 3.11 Heating season, weekly COP (2022)



It is evident that there are more fluctuations in COP during the late heating season. This can be attributed to the increased temperature variability, which is further analyzed in subsequent sections.

3.5 Ambient conditions

In the location of the building in the Czech Republic, the ambient temperature experiences low fluctuations, as illustrated in Figure 3.12, with hot summers and cold winters following a consistent pattern. Solar radiation also follows a typical pattern in both seasons, and the data shows a normal distribution throughout the year. However, the humidity data does not seem to follow a pattern for either season.

Figure 3.12 Ambient conditions (2022)

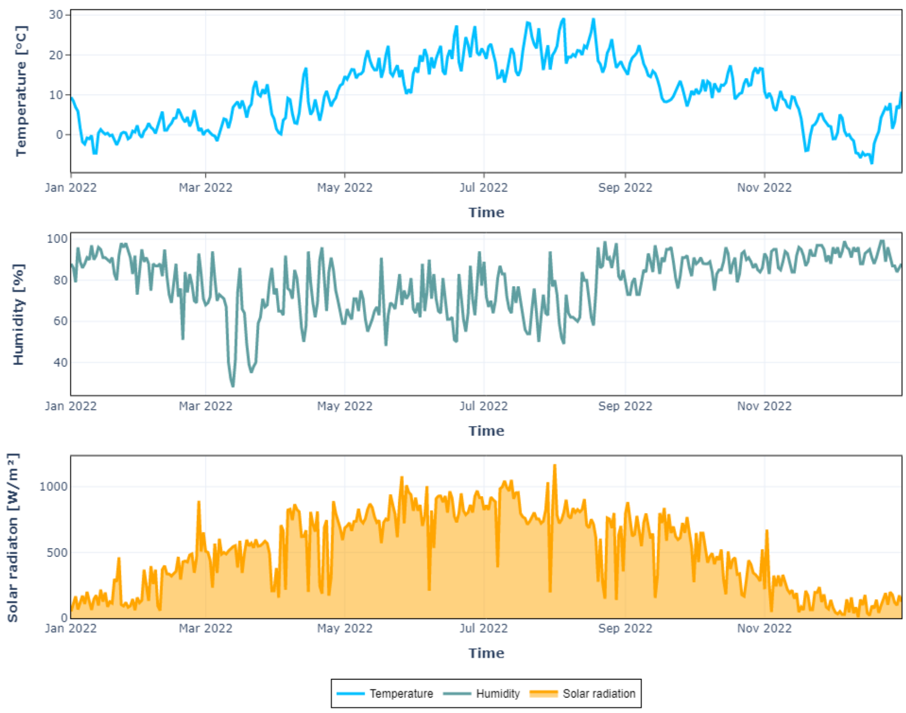
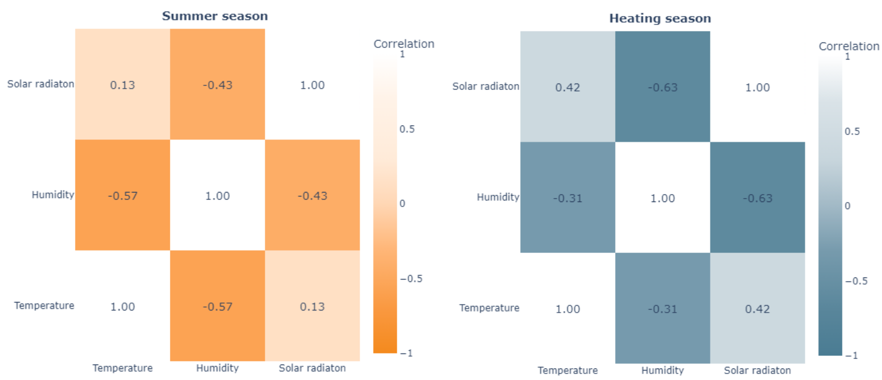


Figure 3.13 shows the correlation between ambient factors. It reveals that the air humidity and ambient temperature have a negative correlation, which indicates that the colder the weather, the more humid the conditions become. The correlation between the amount of solar radiation and other variables is stronger in the heating season, while in summer, it appears to be less significant.

Figure 3.13 Correlation matrix of ambient conditions



3.6 Relationship between energy consumption and variables

3.6.1 Ambient conditions

We analyzed the impact of weather conditions on a heat pump system and found that energy consumption is strongly correlated with ambient temperature. When considering both seasons together, the correlation coefficient is -0.91. When assessing the seasons separately, we found a correlation coefficient of -0.93 for the heating season, indicating an even stronger relationship. For the summer season, the correlation coefficient is -0.41, which suggests that temperature alone does not explain all the variance in data during this season. However, the p-value is 0.0 for both season, indicating that there is strong evidence that the ambient temperature has a significant effect on energy consumption.

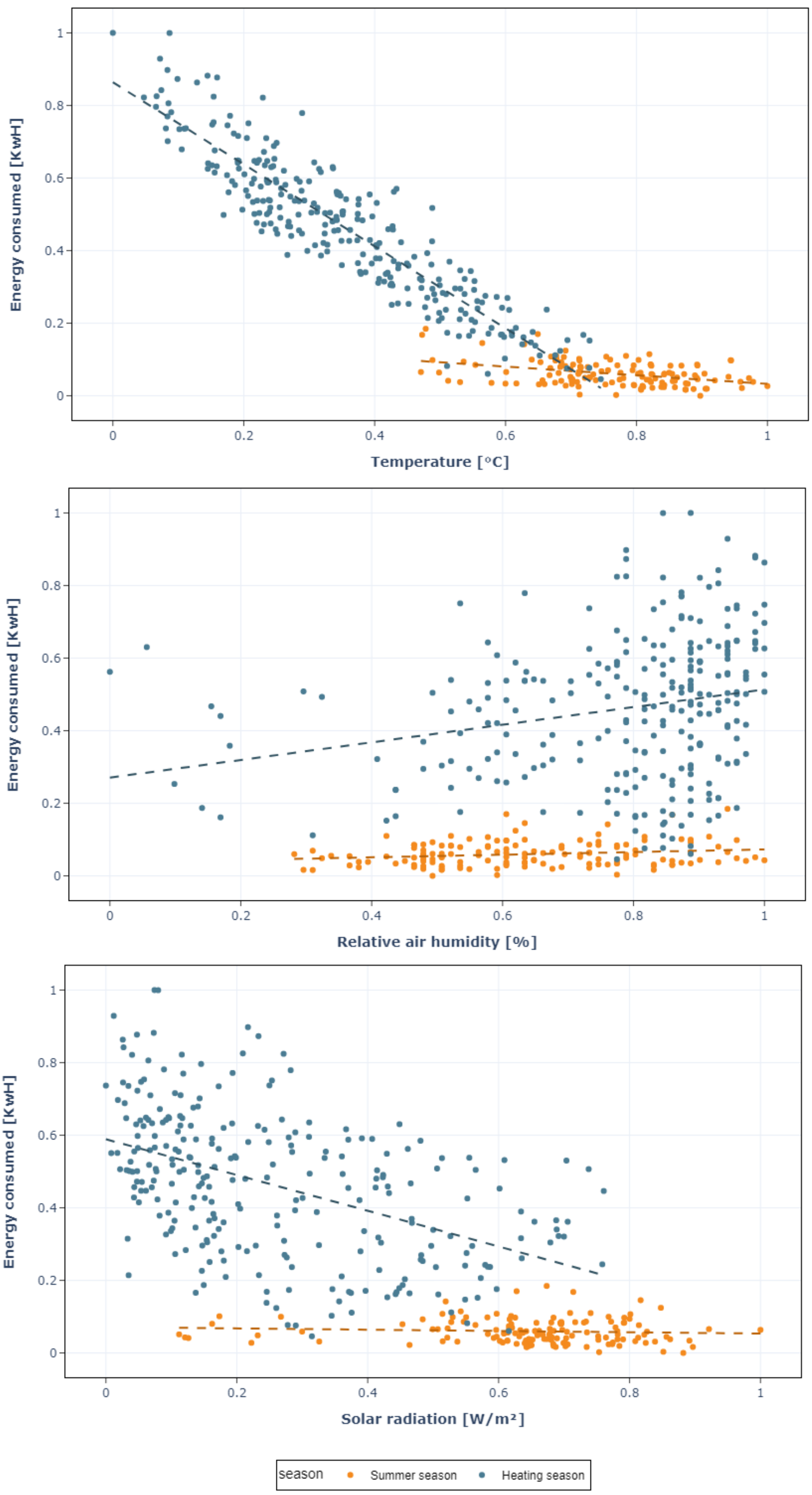
Overall, data from both heating and summer seasons show similar trends and can be analyzed together without forming detached clusters. However, the heating season separately shows a stronger relationship, and the summer data separately doesn't explain enough variance.

The impact of humidity on energy consumption is not as strong as the impact of temperature. However, there is some effect and the patterns vary between the two seasons. In the heating season, there is a moderate positive correlation of 0.21 between energy consumption and humidity.

In the summer season, where the average temperature is 16°C and the average sun hours are 9, there is a negative correlation of -0.302 between energy consumption and humidity. This relationship suggests that a small increase in humidity might lead to a decrease in energy consumption. For rest of the time, the correlation is rather positive.

The data shows that there is a negative correlation between the amount of solar radiation and energy consumption. This means that as solar radiation increases, energy consumption decreases. However, this relationship is particularly evident during the heating season, as indicated by the correlation coefficient of -0.44. In contrast, during the summer season, there appears to be almost no relationship between the variables. This is supported by the p-values of 0 for the heating season and 0.354 for the summer season.

Figure 3.14 Correlation of energy consumption and ambient conditions



Since temperature has a major effect on the energy consumption, it is a great variable that can be used for predictions. Also, because the data not necessarily form clusters, the data were accessed both together and separately. While the overall linear regression analysis of energy consumption and temperature produced some significant results, the analysis of the heating season data yielded more accurate results. The overall analysis had RMSE of 0.870. However, the heating season separately had a higher RMSE of 0.874, making it a better fit.

In addition to predicting values for the heating season, we also applied the model to the summer season data. RMSE of 0.21 suggest that temperature explains only a small amount of the variability in energy consumption during the summer season.

Figure 3.15 Linear regression model of energy consumption and ambient temperature in the heating season

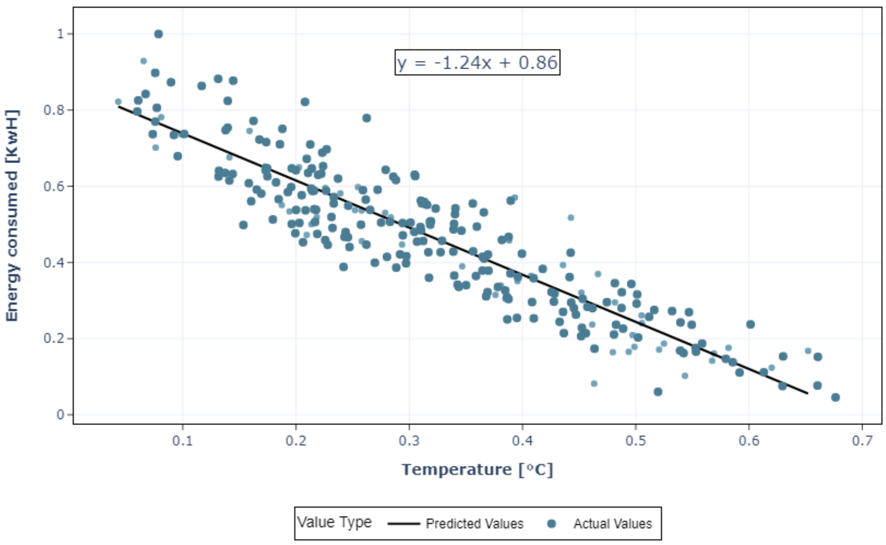
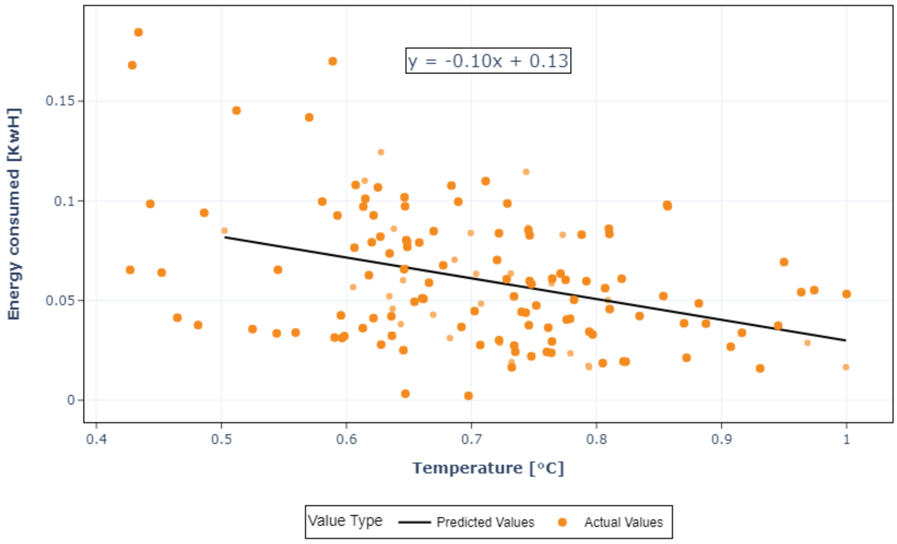


Figure 3.16 Linear regression model of energy consumption and ambient temperature in the summer season



3.6.2 Heat pump's variables

The Figure 3.17 suggests that there is a strong positive correlation between compressor speed and energy consumption. This relationship is supported by a correlation coefficient of approximately 0.996.

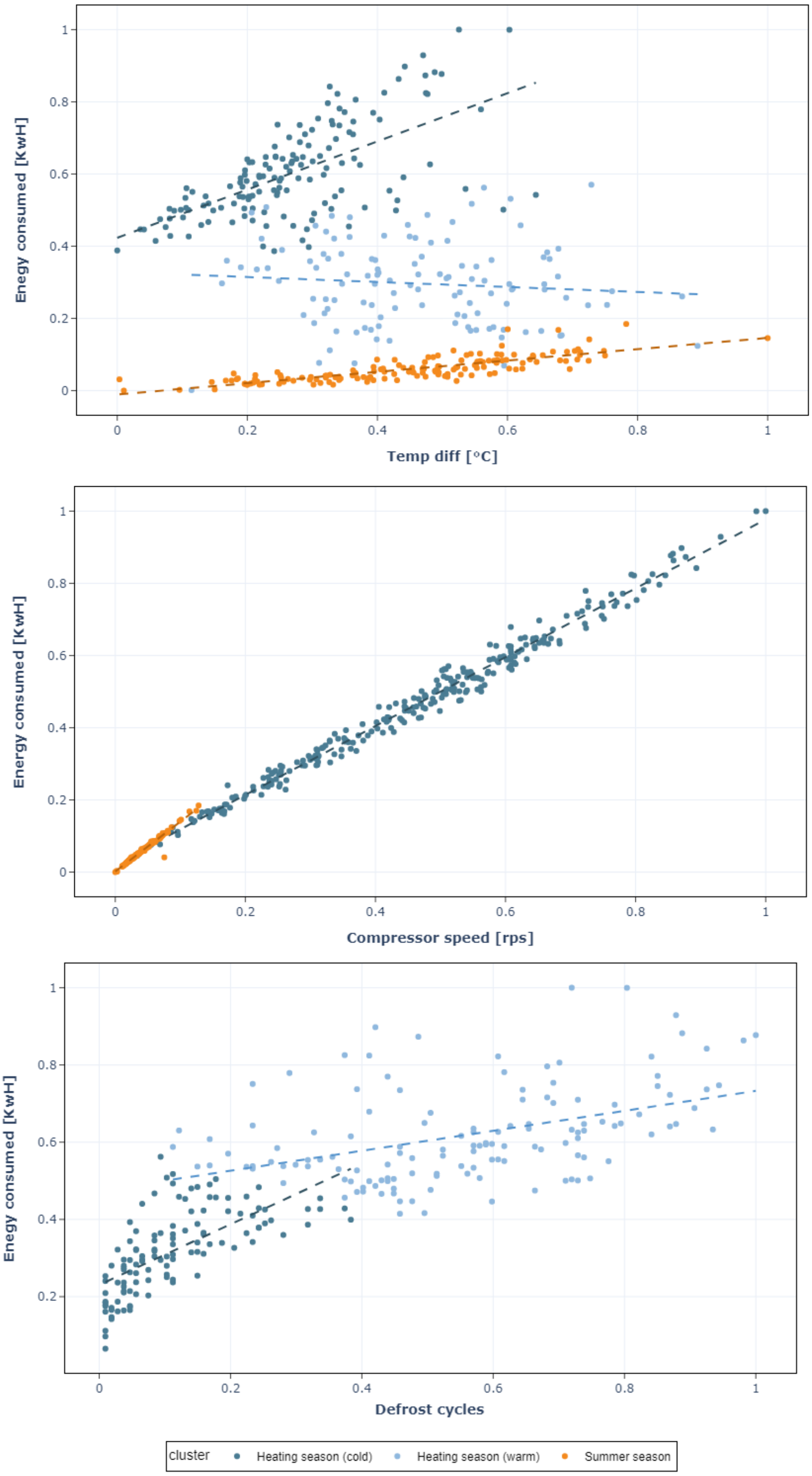
When looking at the heating season separately, there is still a strong positive correlation between compressor speed and energy consumption, with a correlation coefficient of around 0.993. In the summer season, the relationship is even more precise, with a correlation coefficient of 0.999. The p-values are 0 for all cases.

There is relationship between energy consumption and temperature difference. However, the former separation to heating season and summer season, is not sufficient to capture the full extent of the relationship, since there seem to be three clusters. To confirm, prior to running K-mean clustering, the correct number of clusters was predicted, and confirmed to be three using the elbow method.

The data can be divided into three groups based on factors such as energy consumption, ambient temperature, and temperature difference. Cluster ”Heating season (cold)” and ”Heating season (warm)” contain data from the heating season but have different energy loads due to variations in ambient temperature. First cluster has a mean temperature of 0.58 °C, ranging from 5 to -7 °C, while second cluster has a mean temperature of 9.54 °C, ranging from 4 to 22. Both cold heating and summer season show strong correlation.

Similarly, the number of defrost cycles has positive effect and is more significant in colder heating season.

Figure 3.17 Correlation of COP and energy consumption of a heat pump



Fully positive correlation with compressor speed, can be used greatly to predict energy consumption of heat pump using the data of how the compressor behaved.

The first linear regression model, which did not separate data according to season, showed high RMSE of 0.996. This suggests that the model is a good fit for the data and explains a high percentage of the variance in energy consumption based on the compressors behavior.

After dividing the data according to season, we found that the model for the summer season showed an even better fit, with an extremely high RMSE of 0.999. The model for the heating season performed also well with an RMSE of 0.983.

Figure 3.18 Linear regression model of energy consumption and compressor speed in the heating season

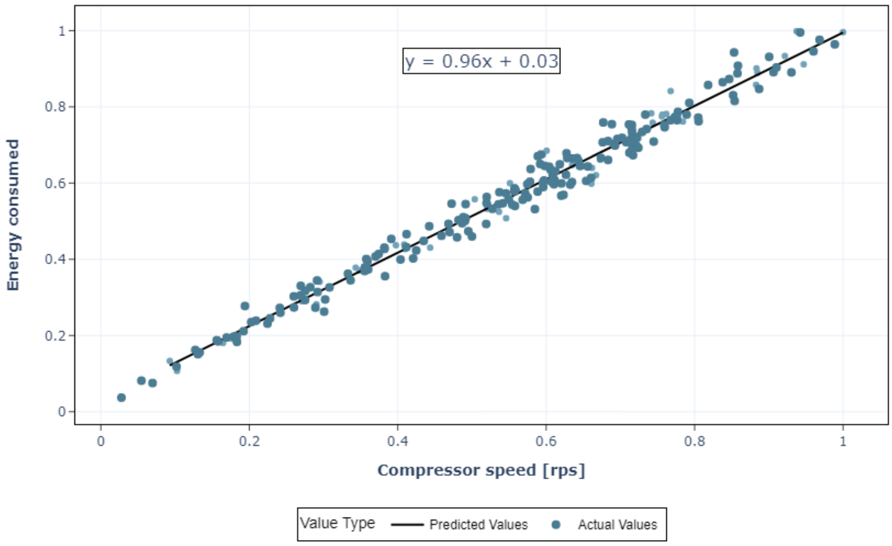
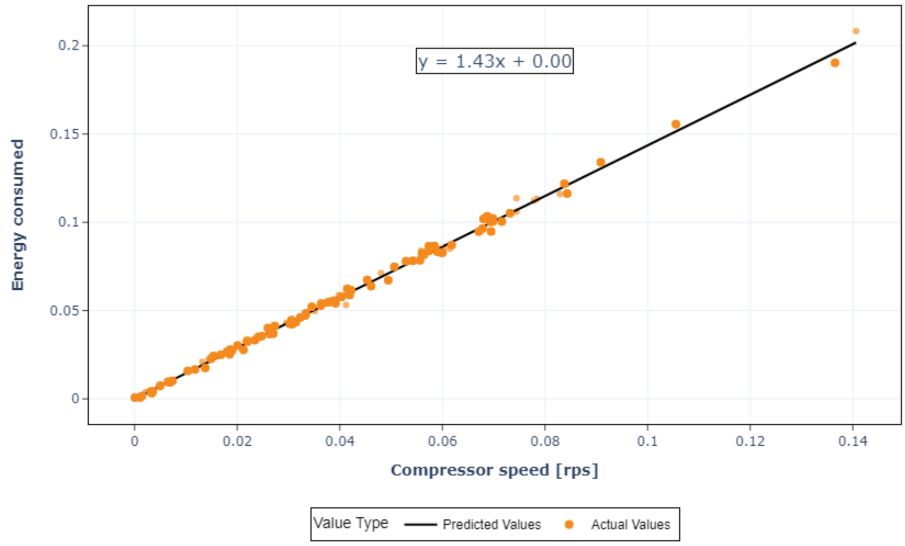


Figure 3.19 Linear regression model of energy consumption and compressor speed in the summer season



The findings suggest that analyzing the compressor behavior can lead to accurate predictions of heat pump energy consumption. However, when data was separated according to season, the model performed even better.

3.7 Relationship between COP and variables

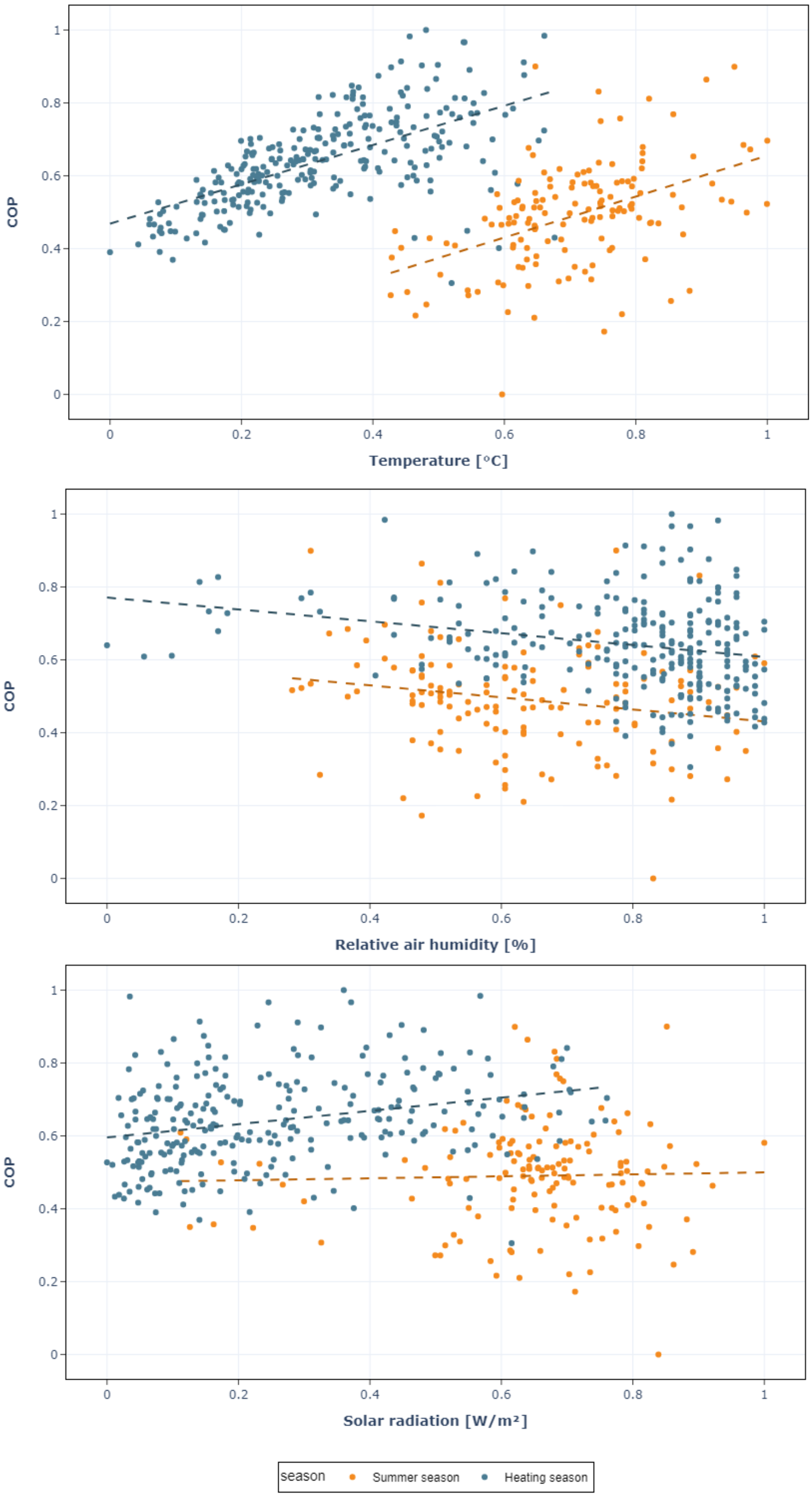
3.7.1 Ambient conditions

Figure 3.20 displays the correlation between various ambient factors and COP. The analysis shows that the COP has the strongest correlation with ambient temperature. Furthermore, we discovered that the relationship between temperature and COP is linear for each season and that they form distinct clusters. Specifically, during the heating season, the coefficient is 0.66, and during the summer season, it is 0.46.

On the other hand, humidity has a weak negative correlation with COP compared to ambient temperature.

The analysis shows that there is no significant correlation between the efficiency of a heat pump and the amount of solar radiation. However, in winter, there is a small positive correlation with a coefficient of only 0.27, indicating that radiation can increase the COP to some extent. On the other hand, in summer, there is a no correlation. Although, we observed a slight negative correlation when the solar panels were heated to over 30°C. This can be attributed to the reduced usage of the heat pump as DHW is being supplied by the solar panels.

Figure 3.20 Correlation of COP and ambient conditions



Since, COP is strongly influenced by the surrounding temperature. By monitoring the ambient temperature, we can estimate the efficiency of the heat pump in the future.

We employed linear regression to predict COP, defining temperature as the feature variable and COP as the target variable, for both seasons separately.

The regression model for heating season can be seen on Figure 3.21. The results show that the linear regression model was able to predict the COP values reasonably well, with RMSE of 0.54. The RMSE 0.54 indicates that the model explains 54 % of the variability in the COP values, which is considered a moderate fit. Therefore, based on these metrics, the linear regression model can be considered reasonably good at predicting COP values based on temperature.

In the summer, the model's RMSE was 0.223. RMSE suggest that the model has limited predictive power and may not be the best fit for the data.

Figure 3.21 Linear regression model of COP and ambient temperature in the heating season

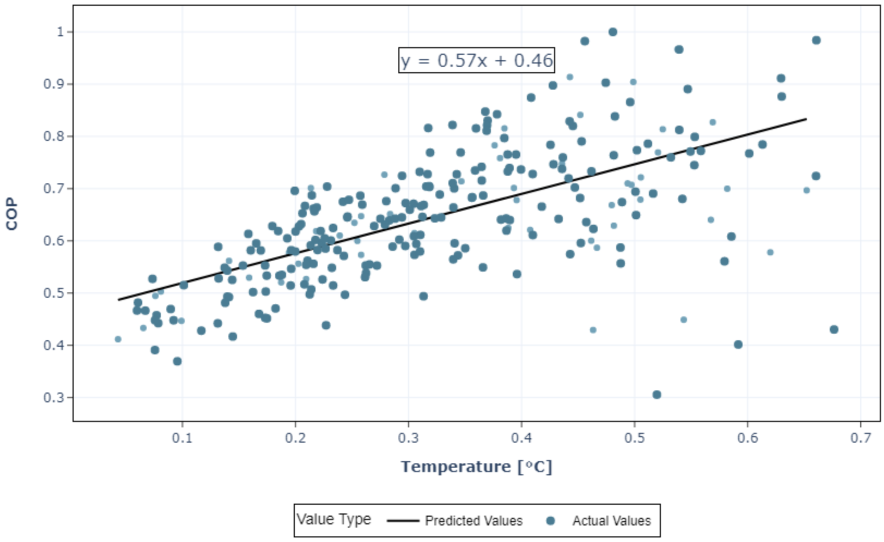
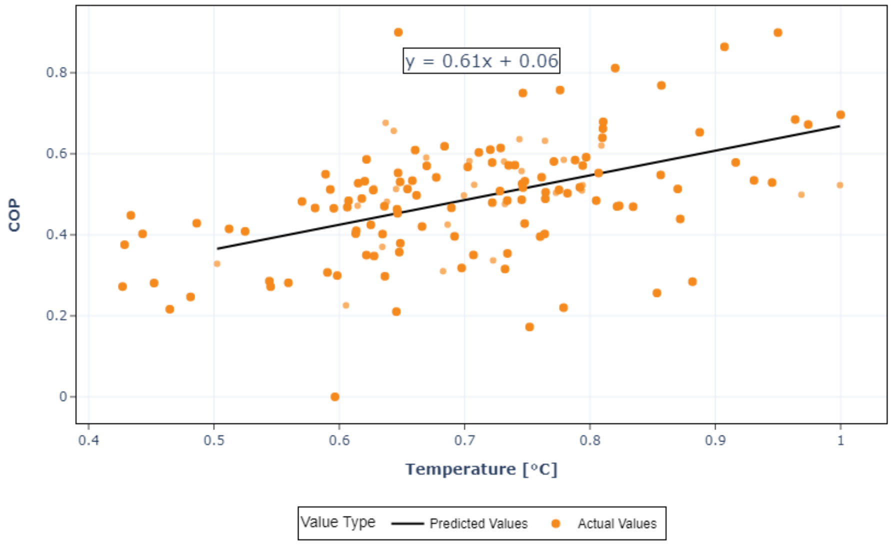


Figure 3.22 Linear regression model of COP and ambient temperature in the summer season



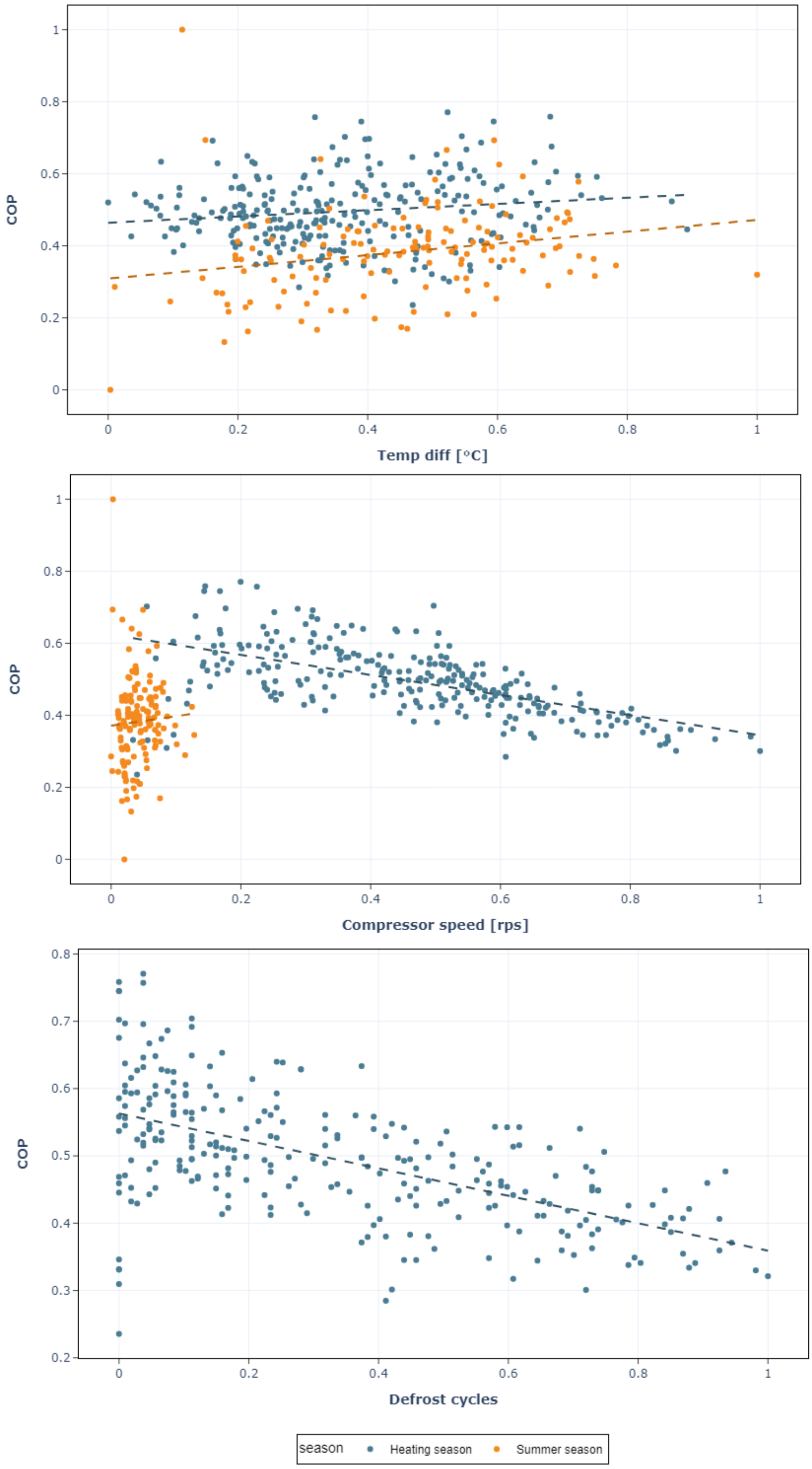
3.7.2 Heat pump's variables

Upon examining Figure 3.23, it is clear that the compressor speed has a minimal impact on COP during the summer season. However, during the heating season, there is a stronger effect on the COP, as shown by the correlation coefficient of -0.59. The lack of effect during the summer season may be due to other factors that have a more substantial influence, such as temperature. In addition, the compressor speed appears to remain relatively stable during the summer season, as depicted in the Figure. Moreover, the correlation between compressor speed and COP becomes stronger as the temperature decreases, indicating a greater impact of speed on COP at lower temperatures.

Regardless of the season, it appears that the temperature difference between the inlet and outlet temperatures has no discernible effect.

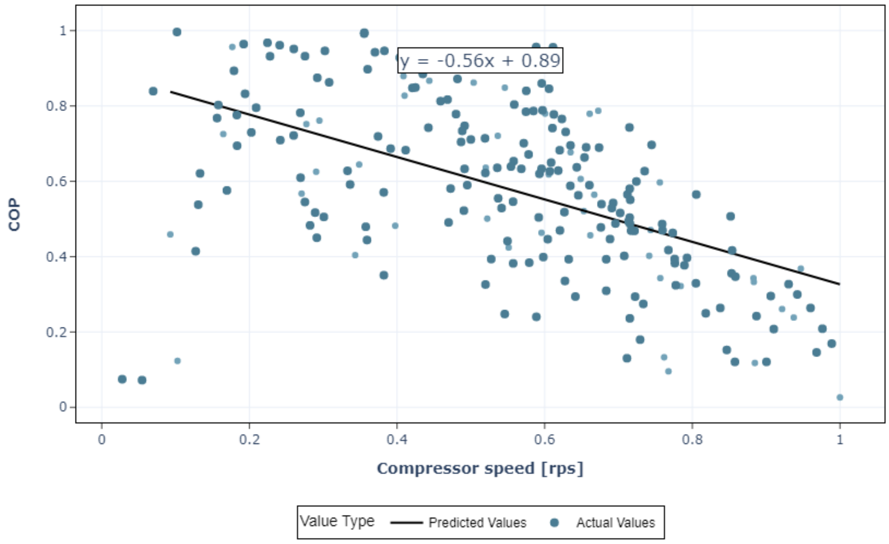
The number of defrost cycles is negatively correlated with COP, as shown in the graph. The correlation coefficient is -0.58, and the data is only displayed for the heating season, as defrost cycles do not occur in the summer.

Figure 3.23 Correlation of COP and technical parameters of a heat pump



To take advantage of the strong correlation between COP and compressor, we created a predictive model using this data. However, the model's predictions had an RMSE of 0.23, indicating moderate performance rather than great performance.

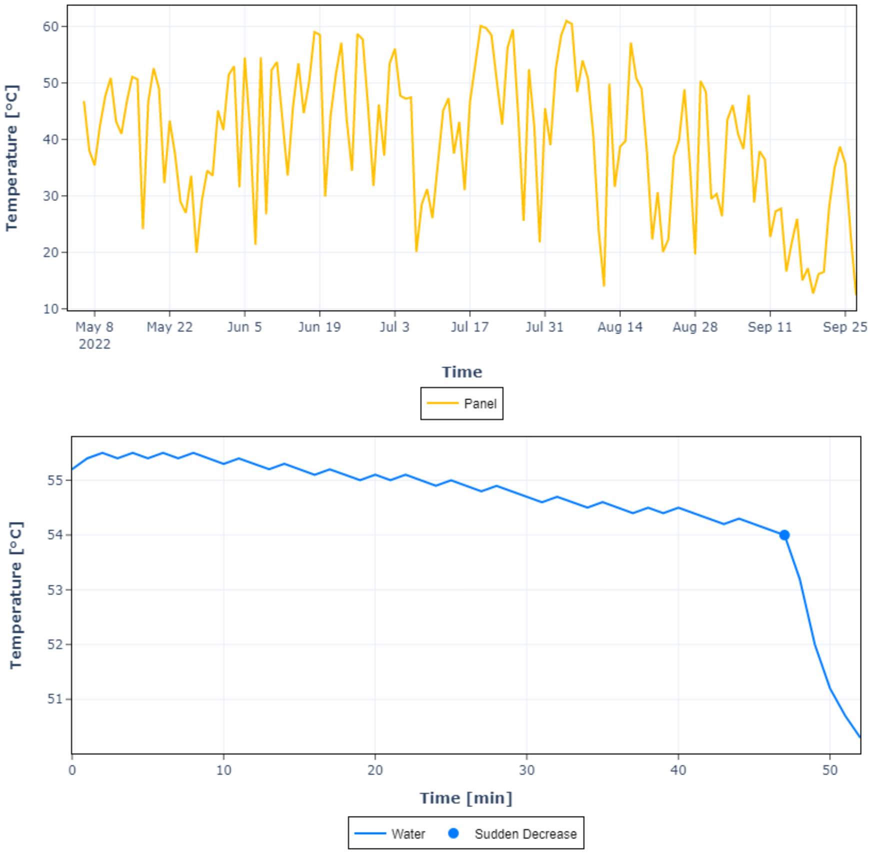
Figure 3.24 Linear regression model of COP and compressor speed in the heating season



3.8 Solar panel efficiency

To evaluate the solar panel's efficiency, we studied the rate of water cooling during the summer season. When the water temperature falls below 50°C, the heat pump heats it until it reaches 55°C. We collected data on the wash water temperature in segments and calculated the curve's gradient. However, the water was being used for showers throughout the day, leading to scattered data and sudden decreases. To avoid bias in our analysis, we excluded these sudden decreases from the data. Figure 4.26 illustrates a gradual increase in water temperature, but there is a marked point indicating a sudden decrease. We excluded the data from this point from our analysis.

Figure 3.25 Solar panel and washwater temperature



After removing the chunks from the data and eliminating outliers and data from periods when there was no sunlight, we examined the relationship between the temperature of the solar panels and the average gradient. The analysis revealed that the hotter the panels were, the smaller the gradient, indicating that it took longer for the water to cool down.

The statistical analysis of the data showed that both coefficients were significant, with p-values less than 0.05.

Figure 3.26 Solar panel and gradient of cooling curve

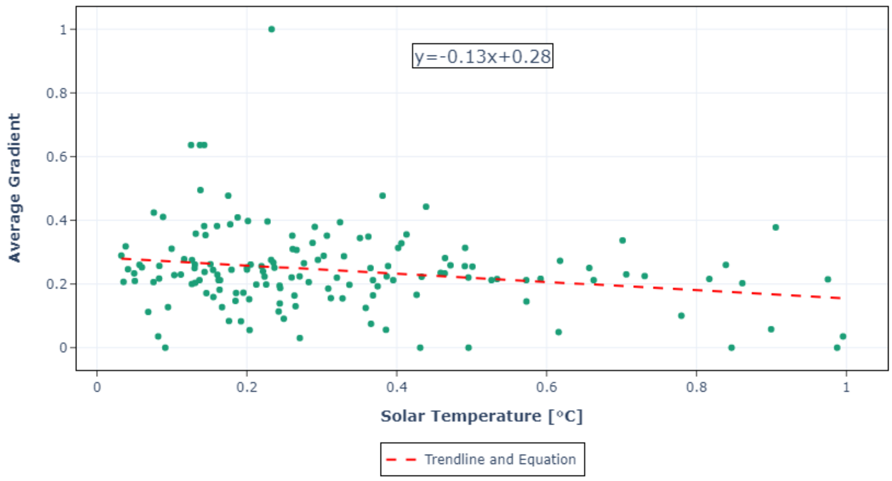
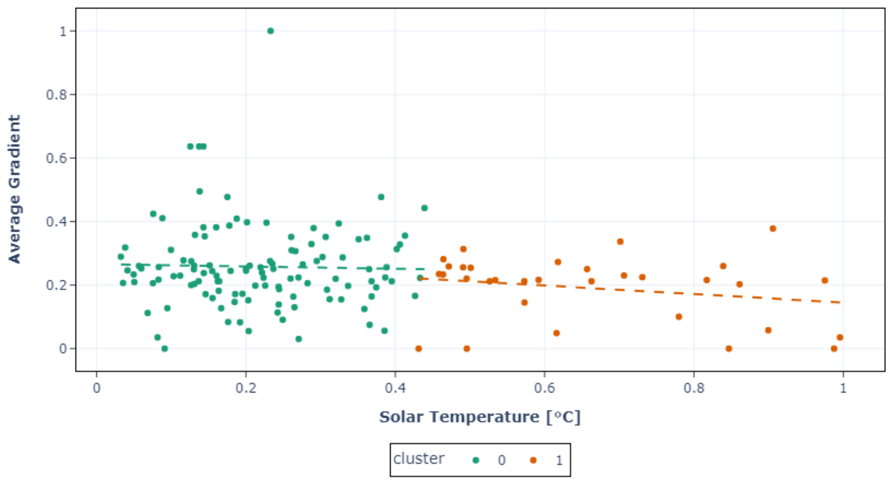


Figure 3.27 Solar panel and washwater temperature



The data was analyzed using cluster analysis and divided into two clusters based on features like solar radiation, ambient temperature, and number of solar hours. Cluster 1 had a higher average solar radiation of 510.7 W/m^2 than cluster 0, which had a mean of 415.8 W/m^2.

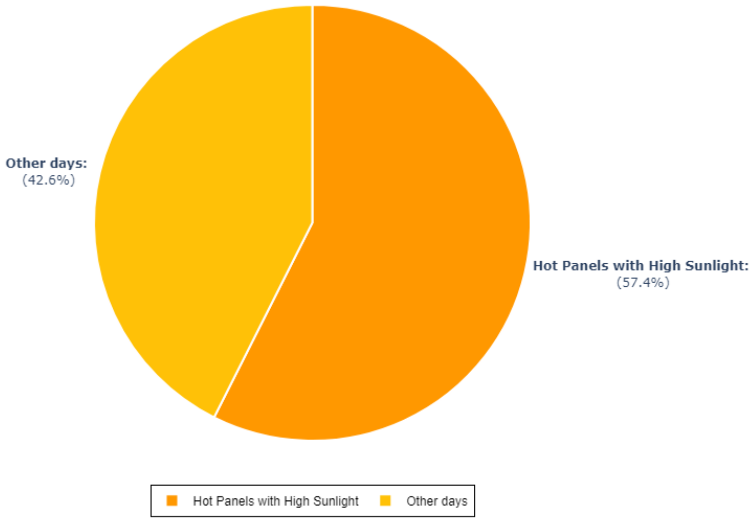
Cluster 1 had an R-squared value of 0.11 and a p-value of 0.064, indicating a moderate level of statistical significance. This suggests that there may be a relationship between the independent and dependent variables, but it is not strong enough to be considered conclusive at a 5 % significance level.

In Cluster 1, the average temperature of solar panels was 54.0°C, whereas in Cluster 2, it was 20°C. This indicates that once the solar panel temperature reaches a certain threshold, it starts to be affected. However, further data is needed to confirm this claim and determine the exact temperature that triggers this effect.

If there were more than 9 sun hours per day, the rate of cooling of water during evening hours (17:00 - 21:00) is slower. However, it's important to note that solar panels are unable to heat water after this time.

Upon further analysis, it was found that the solar panel temperature needs to be above 30°C and there must be at least 9 hours of sunlight for optimal performance. To determine how many summer days satisfy these conditions, we performed calculations and the results are presented in Figure 3.28.

Figure 3.28: Division between days when solar panel is efficient and when not



3.8.1 Result and discussion

Based on the analysis of the conducted research, the following conclusions can be drawn:

1. The installation of a heat pump has resulted in a significant decrease in the energy consumption of a building. Prior to the installation, the average annual consumption using an electric boiler was recorded as 11,993 KwH. However, after the heat pump was installed, the annual consumption decreased to 4,030 KwH.
   Furthermore, an analysis of the energy demand patterns revealed that the highest energy demand occurs on weekends and during the morning and night. The portion in which energy consumption is divided per uses is evenly distributed between DHW and space heating.

2. Throughout the year, the COP of a heat pump was continuously monitored and recorded, with an average value of 2.83. The average COP during the heating season was almost 3, while during the summer season, it was 2.5. This was mainly due to the heat pump operating in a maintenance mode, where it was not producing any heat, but was still running constantly. Despite this, there were no significant fluctuations in COP.

3. An investigation was conducted to determine the factors that affect the COP of a heat pump. The results indicated a strong positive correlation between ambient temperature and COP, particularly during the heating season. However, humidity was found to have a weak and negative correlation with COP, suggesting it may not be a reliable factor for assessing COP. The relationship between solar radiation and COP was found to be significant during winter, with more sunlight resulting in improved COP, but was negative during the summer season, particularly on days with more solar hours. With regards to technical parameters, there was a weak correlation between the temperature difference between inlet and outlet temperature and COP, while compressor speed had no correlation during the summer season but a stronger correlation during the heating season.

4. To predict the COP values of a heat pump based on ambient temperature, separate linear regression models were developed for each season due to the strong correlation between them. The model for the heating season performed moderately well, with an RMSE value of 0.54. However, the model for the summer season had limited predictive power, with RMSE of 0.223. Additionally, a model was created for compressor speed during the heating season, which had a moderate fit with RMSE of 0.43.

5. To investigate the relationship between energy consumption and the same factors, a similar approach was followed. Temperature had the strongest correlation with energy consumption among the ambient conditions, whereas humidity had a weak correlation, with no correlation found in the summer season. Although there was a slight correlation between the number of solar hours and energy consumption in winter, no significant correlation was found during the summer season. On the other hand, compressor speed had a strong positive correlation with energy consumption. In the case of the temperature difference, the data was divided into three clusters and analyzed separately to provide a better understanding of the correlation.

6. We used temperature and compressor speed to predict energy consumption. For temperature, the linear regression analysis indicated more

accurate results during the heating season with higher RMSE of 0.874. The overall data analysis had lower RMSE value of 0.870. During the summer season, the analysis showed relatively low error, but only a small amount of energy consumption variability was explained by temperature, as indicated by the low RMSE value of 0.21. For compressor speed, the first linear regression model had a high RMSE value of 0.996. After separating the data by season, the summer season model had an even better fit. The study suggests that analyzing compressor behavior and separating data by season can lead to more accurate predictions of heat pump energy consumption in the winter season, but not as much in the summer season.

7. Our research indicates that the use of solar panels can have a positive impact on energy consumption. We found that as solar radiation increases, the temperature of the solar collectors also increases, which reduces the cooling of water in the tank. Based on our analysis, we have determined that solar panels are most effective when their temperature is above 30°C and there are more than 9 hours of sunlight per day. We have also discovered that over half of the summer days meet these requirements. However, it's worth noting that the significance level of our findings is low with a p-value of 0.06. This may be due to the limited amount of data, and further investigation is necessary to validate these claims in the future.

Chapter **4**

Economic profitability

This chapter focuses on investigating the investment efficiency of heat pumps through the use of different financial tools. We consider the heat pump installation mentioned in Section 1.8 and the technical analysis results. We also examine the economic inputs, including installation costs, energy prices, and government incentives, and evaluate their impact on the investment efficiency of heat pumps.

In addition to evaluating the investment efficiency of the heat pump, we compare it with other investment opportunities to provide a comprehensive assessment. We consider scenarios for different lifetimes of a heat pump (15, 20, and 25 years).

4.1 Economic inputs

In this section, we analyze some of the crucial economic factors that need to be considered when assessing the profitability of an investment in a heat pump.

4.1.1 Investment cost

The expense of setting up a heat pump in the Czech Republic is not fixed and can differ based on various factors. These factors may include the kind of heat pump, its size, the complexity of the setup process, and the location of the property. Based on some estimates, a basic AWHP installation in the Czech Republic can cost anywhere from around 220,000 Czk to 350,000 Czk. If additional solar panels are installed, the cost will likely increase. Despite the high initial investment, the expected lifespan of the heat pump climb up to 20-25 years.

The Czech Republic offers two grants to promote the use of sustainable energy sources, including heat pumps and solar systems. Although the initial costs may seem high, these grants can help cover the expenses of installation. To be eligible for the grants, the systems must meet specific requirements, which can be found on the State Environmental Fund of the Czech Republic's website [48]. The two available grants for heat pumps are the Kotlíkova dotace (KD) program and the Nová Zelená úsporám (NZU) program.

- *KD* - The state refunds up to 95 % of eligible costs for low-income households. But maximum of 130,000 Czk is granted. This program has been running for longer time than NZU. [48]
- *NZU* - The NZU program, starting in fall 2021, offers funding of up to 80 000 Czk for a heat pump without heating domestic hot water and up to 100 000 Czk with heating domestic hot water. [48]

In this analysis, we utilized the prices listed in Table 4.1 to calculate profitability. These are the official prices for the installation cost of the heat pump. We also take into account the reduced prices, even though we did not obtain a grant for this particular heat pump purchase, to demonstrate the impact of subsidies. The reduction in prices due to grants can also be observed in the aforementioned table.

Table 4.1: Cost and grants for teat Pump installation

	Initial Price [Czk]	**Lifespan [year]**	**With Grants [Czk]**
Heat pump	391 960	15-25	
			Grant KD: 261 960
			Grant NZU: 291 960

4.1.2 Electricity prices

The annual heat demand and energy consumption of the heat pump were already calculated in the previous section. It was discovered that the annual cost of electric boiler was 11 9923 KwH, while the annual energy consumption is 4 030 KwH for the heat pumo.

The annual electricity bill is a crucial factor to consider when calculating profitability because it typically makes up the largest portion of the bill. However, recent events, such as the war in Ukraine, have caused a sharp increase in energy prices and significant volatility in energy markets. After Russia's invasion of Ukraine, oil prices went up by around 40 %, coal prices by 130 %, and gas prices by 180 % in the first two weeks [49].

As electricity prices are tied to the price of gas, they have also increased. owever, the increase has been most significant in the Czech Republic. To compare the Czech Republic to some of its V4 neighbors, the cost of electricity in the country is more than 60 percent higher than Poland (around 0.83 Czk per kilowatt-hour), over double that of Slovakia (around 0.61 Czk), and more than triple prices in Hungary (around 0.43 Czk).

In 2023, the government approved a cap on energy prices, which means that everyone pays the same price for electricity and gas. The price for electricity delivery is fixed at 6.05 Czk/KwH including VAT [50]. It is currently unknown whether the law will continue to be enforced after 2023. However, electricity prices are expected to remain high even in the upcoming year, and it is not until 2024 that they are predicted to return to the level at which traders had bought electricity in advance for the current year.

It's important to note that installation of a heat pump makes a household eligible for the D57 tariff, which allows for a lower tariff for 20 hours per day, with a higher tariff being paid for the remaining hours. However, due to the lack of available data on hourly consumption, we will estimate the profitability using the average of these tariffs. Since the difference between these tariffs is small, there will be no significant discrepancies created. As a point of reference, we begin our analysis with the year 2022, which marks the start of the heat pump's usage.

Table 4.2: Annual energy costs comparison: electric Boiler vs. heat Pump

Heat pump				
Source	Medium	Price [Czk/KwH]	Energy consumption [KwH]	Expenses [Czk]
Space heating	Electricity	4.50	2 105	9 473
DWH	Electricity	4.50	1 779	8 006
Rest	Electricity	4.50	111	500
Total				17 979
Electric boiler				
Source	Medium	Price [Czk/KwH]	Energy consumption [KwH]	Expenses [Czk]
Space heating	Electricity	4.50	9 949	44 771
DWH	Electricity	4.50	1 214	5 463
Rest	Electricity	4.50	830	3 735
Total				53 969

The table 4.2 compares the annual energy costs of electric boiler and heat pump. To estimate the potential profitability of using a heat pump, it will be assumed that the heat demand remains the same for future and that weather patterns stay consistent.

4.1.3 Service and maintenance

To ensure efficient and safe operation of the heat pump, it is important to have it professionally maintained by an authorized service technician once a year. The company that provided the analyzed heating system offers maintenance services at the prices presented in table 4.3. To provide a comparison, an annual service price for an electric boiler is also included.

Table 4.3: Services prices for heat pump and electric boiler

	Price [Czk]
Heat pump	3 000
Electric boiler	1 500

We must also consider the possibility of decreased system efficiency. For systems similar to this one, the decrease can be as much as 15 % [51]. For the purposes of our analysis, we assume an annual decrease of 8 %.

4.1.4 Inflation rate

Inflation refers to the increase in the overall pricing of goods and services over time, and it can significantly affect the long-term cost of running and maintaining a heat pump system. As noted earlier, electricity prices are subject to change due to various factors over time. To determine the rates for our analysis, we examined how inflation rates and electricity prices have changed over the last 10 years, as shown in Figure 4.1. The final rates are presented in Table 4.4.

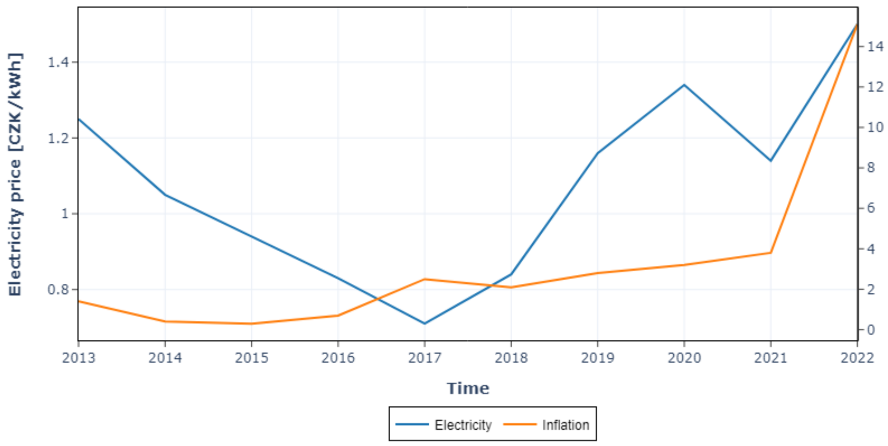


Figure 4.1 Average annual inflation in years 2013 - 2022

The rates were calculated, using historical data depicted on the previous Figure. Data are from [52] and [53].

Table 4.4: Inflation rates for electricity and service prices

	Inflation rate [%]
Electricity prices	2.3
Service prices	3.7

4.2 Measures of investment efficiency

There are several measures of investment efficiency that can be used to evaluate the profitability of an investment.

Each of these measures provides a different perspective on the efficiency and profitability of an investment. In order to gain a comprehensive understanding of an investment, multiple metric should be considered.

4.2.1 Return of investment

ROI is a financial metric that measures the profit or loss generated by an investment relative to its cost. It is calculated as the ratio of the investment's net profit to its initial cost, expressed as a percentage. A higher ROI indicates a more profitable investment, while a negative ROI indicates a loss.

While ROI is a useful metric for assessing investment profitability, it doesn't factor in the time value of money, potential risks, or non-financial impacts.

$$ROI = \frac{Profit}{Investment} \tag{4.1}$$

In this context, the term $Profit$ refers to the Average annual profit obtained from the savings generated by the heat pump each year, minus the initial investment cost. The $Investment$ mentioned here is the cost of the heat pump itself. [54]

4.2.2 Payback period

The payback period is a financial tool that investors use to figure out how long it will take for an investment to generate enough cash flow to pay for itself. The payback period is calculated by dividing the initial cost of the investment by the expected annual cash inflows. This will tell you how many years it will take for the investment to break even. It's worth noting that like ROI, the payback period doesn't take into account the time value of money.

$$Payback\,period = \frac{Investment}{C_{avg}} \tag{4.2}$$

where $Investment$ is Initial investment C_{avg} Average annual cash flow. Again the Initial investment is the cost of the heat pump, and average annual cash flows are the annual savings. [55]

4.2.3 Net present value

NPV is a financial tool that calculates the present value of all expected cash inflows and outflows associated with an investment, adjusted for the time value of money. It is a useful method for evaluating the profitability of an investment, with a positive NPV indicating a profitable investment and a negative NPV indicating a net loss.

Unfortunately, NPV has limitations, as it relies on assumptions about future cash flows and interest rates that may not be accurate. [56]

$$NPV = \sum_{0}^{n} \frac{R_t}{(1+d)^t} \tag{4.3}$$

where R_t represents the net cash flow for a particular time period, d is the discount rate, and t is the number of time periods.

Discount rate

The discount rate should reflect the expected risk of the investment, the expected return, and the impact of inflation.

To determine the best discount rate, there are several approaches, but a common method is to consider the opportunity cost of capital. This approach is typically used by individual investors.

For corporate investments, the Weighted Average Cost of Capital (WACC) is commonly used to select the discount rate for financial decisions.

For this analysis, we consider two investment opportunities: a government bond and shares of the company Honeywell. We consider the coupon rate as the discount rate for the bond, which is 1.95%, and the specific bond labeled CZ0001006316 [57], with a maturity date of 30.07.2037, giving it a lifespan of 16 years - similar to the expected lifetime of the heat pump. For the Honeywell shares, we use a discount rate of 6.14 % selected using WACC [58], since it is a corporate investment.

4.2.4 Internal rate of return

IRR is the rate at which the investment is expected to generate a return equal to the initial investment cost. The higher the IRR, the more profitable the investment.

However, IRR has limitations, such as the possibility of producing multiple rates of return and difficulties in evaluating projects with non-conventional cash flows. IRR calculations rely on the same formula as NPV does. It is calculated in a following way:

$$NPV = \sum_{0}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{4.4}$$

where C_t - Net cash inflow during the period t, C_0 is Total initial investment, IRR is the internal rate of return and t - number of time periods. Meaning of the individual variables, has already been described in previous sections. [59]

4.3 Calculations

In this section, we calculate the profitability of investments using all the methods and taking into account all the economic inputs mentioned in the previous section.

4.3.1 Annual cash flow

Assumed annual cash flows for the selected life expectancy are presented in Table 4.5, taking into account rising electricity prices, inflation, and possible decrease in heat pump efficiency.

Table 4.5: Summary and analysis of cash flows for heating with a heat pump replacing electric boiler

Year	Efficiency	Energy Consumption	Electricity Prices	Operating Costs	Cash Flows
	[%]	[KwH/Year]	[Czk/KwH]	[Czk]	[Czk]
0					-391 960
1	100 %	4 030	4.50	3,500	34,650.46
2	99.20 %	4 095.53	4.60	3 629.50	31 285.63
3	98.40 %	4 129.10	4.70	3 763.80	31 790.78
4	97.60 %	4 163.22	4.82	3 903.05	32 299.14
5	96.80 %	4 197.91	4.93	4 047.46	32 810.44
6	96.00 %	4 233.20	5.04	4 197.22	33 324.37
7	95.20 %	4 269.07	5.16	4 352.52	33 840.61
8	94.40 %	4 305.56	5.28	4 513.56	34 358.79
9	93.60 %	4 342.67	5.40	4 680.56	34 878.56
10	92.80 %	4 380.43	5.52	4 853.74	35 399.50
11	92.00 %	4 418.85	5.65	5 033.33	35 921.16
12	91.20 %	4 457.96	5.78	5 219.69	36 443.10
13	90.40 %	4 497.76	5.92	5 412.69	36 964.79
14	89.60 %	4 579.55	6.05	5 612.96	37 486.87
15	88.80 %	4 621.55	6.19	5 820.64	38 009.32
...	...	...	...	...	...
25	80.80 %	4 987.62	7.76	8 370.63	42 503.14

Figure 5.6 shows the cumulative cash flows of the heat pump installation over time, without taking into account any discounting. The type of grant received affects the profitability of the installation. The years in which the cash flows turn positive are indicated for all scenarios.

If no grant is obtained, the heat pump becomes profitable in the 12th year. However, if the KD grant is used, the time to profitability is reduced to 8 years. Similarly, if the NZU grant is used instead, the time to profitability is also shortened to 9 years.

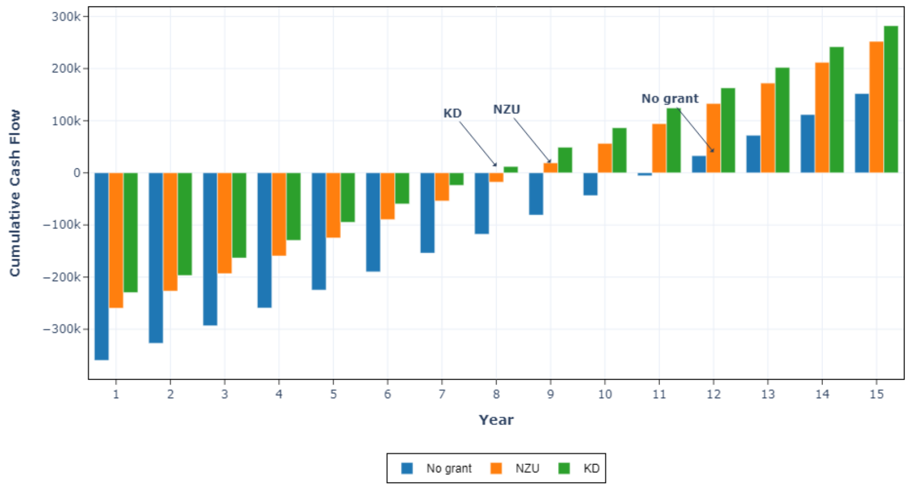


Figure 4.2 Cumulative cash flow comparison of heat pump options with and without grants

4.3.2 Profitability analysis using ROI and Payback period

To calculate the ROI, we followed the formula explained in section 4.2.1. We used the annual cash flows, which were computed from the values in table 4.5. Different life expectancy's for the investment were taken into account by incorporating these values into the formula. The resulting ROI values for a heat pump investment with and without grants over different periods are presented in Table 4.6.

Table 4.6: ROI for different grant scenarios

	15 years	**20 years**	**25 years**
No grant	38 %	92 %	150 %
KD	107 %	187 %	273 %
NZU	8 6%	158 %	235 %

The results indicate that the investment in the heat pump with the KD grant is the most profitable, providing an ROI of 107 %, 187 %, and 273 % for 15, 20, and 25 years, respectively. The ROI for the NZU grant is also promising, ranging from 86 % to 235 %, while the ROI for the investment without any grant is significantly lower, ranging from 38 % to 150 %. These findings suggest that applying for and receiving a grant can significantly enhance the profitability of the heat pump investment.

To calculate the payback period, we utilized the formula 4.2 by inputting the corresponding values for grants and without grants. The computed payback periods are presented in Table 4.7 for ease of understanding.

Table 4.7: Payback period for different grant scenarios

	15 years	**20 years**	**25 years**
No grant	11.75	11.15	10.75
KD	7.8	7.45	7.19
NZU	8.75	8.30	8

With no grant, the payback period is 11.75 years, while with the KD grant, it decreases to 7.8 years. The NZÚ grant has a payback period of 8.75 years. As the time horizon increases, the payback period decreases slightly for all grant scenarios, indicating a more favorable return on investment over a longer time period.

4.3.3 Profitability analysis using NPV and IRR

The table 4.8 shows the IRR for different grant scenarios over different time horizons (15, 20, and 25 years). The table indicates that the IRR increases with the length of the investment horizon. Additionally, it shows that the grant scenarios have a significant impact on the IRR, with the highest IRR being achieved with the NZU grant scenario, followed by the KD grant scenario and then the No grant scenario.

Table 4.8: IRR for different grant scenarios

	15 years	**20 years**	**25 years**
No grant	3.29 %	6.00 %	7.32 %
KD	9.27 %	11.25 %	12.13
NZU	7.54 %	9.72 %	10.72 %

The table 4.9 shows the NPV values for different grant scenarios at interest rate of 1.95 %. The results show that the NPV values are higher for the scenarios with grants, and the longer the project duration, the higher the NPV values.

Table 4.9: NPV for different grant scenarios 1.95 %

	15 years	**20 years**	**25 years**
No grant	42 332.81	180 177.32	313 371.63
KD	172 332.81	310 177.32	443 371.63
NZU	142 332.81	280 177.32	413 371.63

Table 4.40 presents the NPV calculations for the different grant scenarios using a discount rate of 6.14 %, which is the WACC of the opportunity cost

for the company. All scenarios resulted in a positive NPV, except for the investment without a grant and an expected life expectancy of 15 years.

Table 4.10: NPV for different grant scenarios 6.14 %

	15 years	**20 years**	**25 years**
No grant	-48 905.72	23 161.17	80 316.77
KD	81 094.27	153 161.17	210 316.77
NZU	51 094.27	123 161.17	180 316.77

4.3.4 Comparison of investment opportunities

In order to compare investment opportunities, we consider investing in a heat pump, as well as government bonds and company stocks that pay dividends. The initial investment in the heat pump is used as the benchmark for purchasing a specific number of bonds and stocks at the same price, considering whether a grant was obtained.

Since the maturity time of the government bond mentioned in section 4.2.3 is 16 years, we evaluate the earnings of all investment opportunities over the same period.

Honeywell is a company that pays dividends quarterly at the current price of 20.82 Czk per share. We assume a constant annual growth rate of 6.96 % for dividends based on historical data [60]. We also consider an annual growth rate of 9.9 % per share [61], although it's challenging to predict stock prices in the long term. At the time of calculation, one share was priced at 4 184 Czk. To account for the time value of money, we will discount the earnings using the discount rate calculated from the WACC of the company mentioned earlier.

Investing in a heat pump without obtaining a grant would yield 39 government bonds at the initial investment price. With a coupon payment of 195 Czk per bond per month, the total monthly earning from the bonds would amount to 7 605 Czk. It should be noted that investing in government bonds becomes profitable only in the year of their maturity, when the nominal price is paid. The resulting return from investing in a heat pump is calculated to be 191 972 Czk, whereas investing in bonds would yield 114 075 Czk.
Instead of investing in a heat pump without a grant, we could purchase 93 stocks at the current price of 4 184 Czk per share. If we assume that the stocks can be sold at an expected price of 679 160.42 Czk in the observed period, the potential return would be significantly higher.

Figure 4.3 displays the cumulative cash flows for all options without the grant.

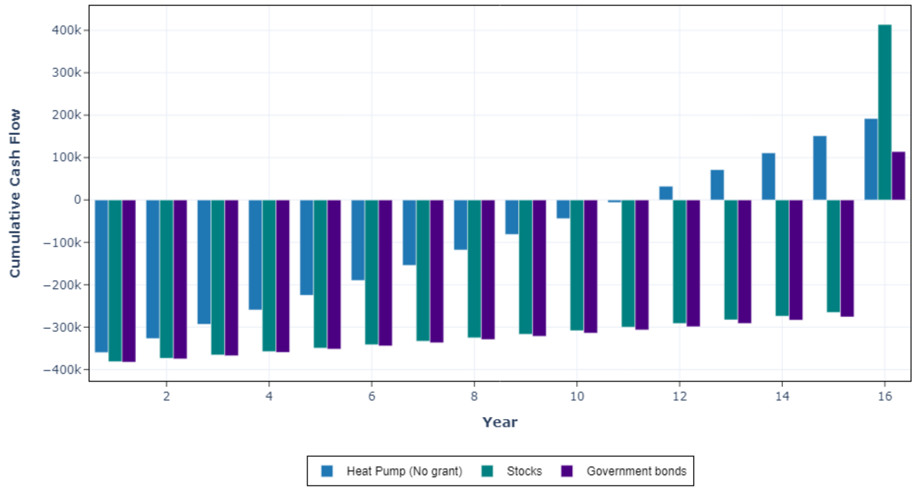


Figure 4.3 Comparison of annual cash flows for heat pump without grant

If the NZU grant is obtained, investing in the heat pump becomes a more profitable option even when compared to investing in stocks. The potential earnings from stocks would be 338 816 Czk, which is comparable to the earnings from the heat pump, amounting to 291 977 Czk. However, in this scenario, investing in government bonds would be even less profitable.

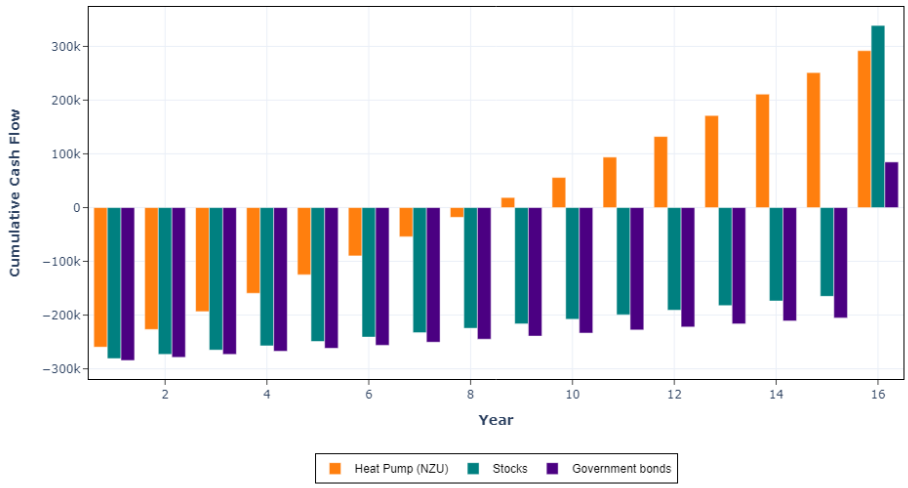


Figure 4.4 Comparison of annual cash flows for heat pump with NZU grant

The last option considered is obtaining the heat pump with a KD grant, which would make it the most affordable. With the same initial investment as the heat pump, we could buy 62 shares in a company. Thus, investing in a heat pump would be almost as profitable as investing in company shares, with only a difference of 25 010 Czk in earnings.

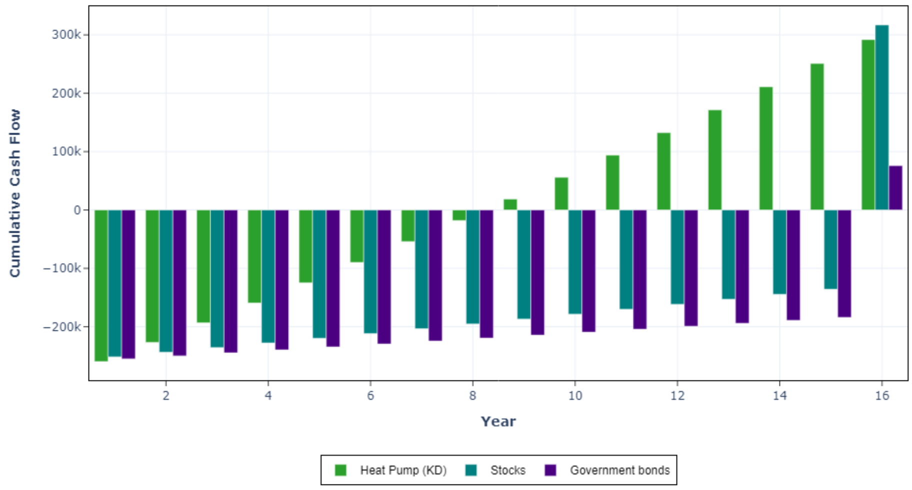


Figure 4.5 Comparison of annual cash flows for heat pump with KD grant

4.4 Results and discussion

Based on our financial analysis, which included scenarios with and without grants, different life expectancies, and a comparison with investment alternatives, we identified several key findings:

1. Different metrics were used to assess the profitability of the investment, and all calculations indicated that the investment is likely to be profitable except for one scenario where no grant was obtained. In this specific scenario, the NPV method with an assumed discount rate of 6.14 % resulted in a negative final cash flow. It's worth noting that this scenario assumed a lifespan of only 15 years, while the heat pump is expected to be functional for a much longer period.

2. The analysis showed that obtaining a grant significantly improves the profitability of the investment and lowers the point at which the investment starts generating profits. Without a grant, the investment breakpoint is nearly 12 years. However, with the NZU grant, the breakpoint is slightly over 8 years, and with the KD grant, it is only 7 years.

3. Despite a gradual decline in the installation's efficiency over time, the investments became increasingly profitable each year. However, the decline in efficiency was outweighed by the expected rise in electricity prices due to inflation.

4. When comparing the investment in a heat pump to government investments in various scenarios, the results varied. However, the heat pump investment was consistently found to be more profitable. While the

difference in profitability was not significant without a grant, the investment in a heat pump became substantially more profitable after obtaining a grant, even surpassing the profitability of government bond investments.

5. In all the scenarios we considered, investing in medium-risk stocks proved to be more profitable. However, the difference in returns was not significant when taking into account the grants. It's important to note that although investing in stocks can be risky, investing in a heat pump is a relatively low-risk option.

Chapter 5

Advantages and disadvantages summary

In this chapter, we provide an overview of the benefits and drawbacks of installing a heat pump system. This summary is based on the results of previously conducted financial and technical analysis, as well as a broader evaluation of the potential benefits and drawbacks of the solution.

5.1 Advantages

1. The installation of a heat pump can greatly improve energy efficiency, as demonstrated in the case study where annual energy consumption decreased from 11 993 KwH to 4 030 KwH. Additionally, heat pumps rely on renewable energy sources, which leads to lower carbon emissions and ensures a sustainable energy supply.

2. A heat pump can become increasingly profitable as energy prices rise, due to its high COP. This creates a greater price differential between heat pumps and other energy sources.

3. Another advantage of installing a heat pump system is that it is possible to obtain a grant or financial incentive from various sources, which can significantly reduce the initial investment cost.

4. Heat pumps are especially efficient during the heating season when the weather is milder, and they can attain an average COP of nearly 3.

5. Utilizing solar panels can have a beneficial effect on energy consumption. Further investment into more solar system should be considered.

5.2 Disadvantages

1. It should be noted that heat pumps may not be suitable for all climates. In areas with extremely low temperatures, the COP of heat pumps decreases, which can reduce their overall efficiency and effectiveness. Therefore, it is important to consider the specific climate of a region before deciding whether to install a heat pump system.

2. Heat pumps may not be suitable for areas with high humidity because they work by removing heat from the outside air and transferring it indoors. In humid conditions, the heat exchange process can be less efficient.

3. Another disadvantage of heat pump systems is the initial investment required. The cost of installation can be significantly higher than other heating and cooling systems, such as traditional gas or electric systems. This can be a major deterrent for some consumers, especially those who are not able to afford the upfront cost or those who do not plan to live in the building for an extended period.

4. Another disadvantage of heat pumps is that they can have higher service prices in comparison to electric boilers. This is due to the complexity of the system and the need for specialized technicians for installation and maintenance.

Conclusion

The aim of the thesis was to thoroughly evaluate the efficiency and cost-effectiveness of a heat pump system for space heating and DHW in a residential building. The thesis consisted of a theoretical section explaining the operating principles of heat pumps and the specifics of the system used in the analysis, followed by two main analytical parts focusing on performance and financial analysis.

The performance analysis identified independent variables strongly correlating with energy consumption and the COP separately for heating and summer seasons. However, clustering revealed the need for further separation into more groups to gain better insight. Temperature was found to have the strongest impact on the COP and compressor speed on energy consumption and prediction models were built and evaluated by using various metrics.

The financial analysis used metrics such as ROI, payback period, NPV and IRR to determine the economic feasibility of the heat pump system, and compared it with investment opportunities in bond yields and stocks. The system was found to be efficient in most cases, especially with grants, where profitability almost equaled that of investing in stocks.

Both analytical sections compared the heat pump system's performance and cost-effectiveness to that of an electric boiler previously installed in the same building.

Future research can focus on conducting a more in-depth evaluation of individual factors related to the heat pump system's efficiency and cost-effectiveness. Additional variables can also be included in the analysis to provide a more comprehensive understanding of the system's performance. Improvements to the prediction models can be explored, including the comparison of different machine learning algorithms.

As the current dataset covers only a little over a year, it is possible to conduct the same analysis again after collecting more data, particularly regarding solar efficiency, as there is only data from one summer season available.

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Appendix A

Acronyms

AWHP Air-Source Water Heat Pump

COP Coefficient of performance

SCOP Seosonal coefficient of performance

ČSN Czech technical standard

DHW Domestic hot water

IRR Internal rate of return

ML Machine learning

NPV Net present value

RMSE Root mean square error

ROI Return of investment

Appendix B

Contents of enclosed CD

```
jupyter_notebooks ............ the main directory of jupyter notebooks
 |__ 1.data_loading ................................... data loading
 |    |__ data_influxDB.ipynb ....................................
 |    |__ data_Weather.API.ipynb ..................................
 |__ 2.general_overview ......................... trends and patterns
 |    |__ general_groups.ipynb ...................................
 |    |__ general_efficiency.ipynb ...............................
 |    |__ general_consumption.ipynb ..............................
 |    |__ general_weather.ipynb ..................................
 |    |__ general_technical_parameters.ipynb .....................
 |__ 3.efficiency_relationship_analysis ........... efficiency analysis
 |    |__ efficiency_temperature.ipynb ...........................
 |    |__ efficiency_humidity.ipynb ..............................
 |    |__ efficiency_solar_radiaton.ipynb .........................
 |    |__ efficiency_compressor_speed.ipynb .......................
 |    |__ efficiency_temperature_diff.ipynb .......................
 |    |__ efficiency_defrost_cycles.ipynb .........................
 |__ 4.consumption_relationship_analysis.ipynb consumption analysis
 |    |__ consumption_temperature.ipynb ...........................
 |    |__ consumption_humidity.ipynb ..............................
 |    |__ consumption_solar_radiaton.ipynb ........................
 |    |__ consumption_compressor_speed.ipynb ......................
 |    |__ consumption_temperature_diff.ipynb ......................
 |    |__ consumption_defrost_cycles.ipynb ........................
 |__ 5.solar_efficiency_analysis ................ solar panel efficiency
 |    |__ solar_efficiency.ipynb ..................................
 |__ 6.financial_analysis.ipynb ................ investment efficiency
      |__ investment_efficiency.ipynb .............................
|__ text ..................................... the thesis text directory
 |__ thesis.pdf ......................... the thesis text in PDF format
 |__ thesis.zip ..................................... zip of TeX files
|__ readme.md ................ brief description of the content of the media
```