FACULTY OF SCIENCE AND TECHNOLOGY

BACHELOR'S THESIS

Study programme / specialisation:

Energi- og petroleumsteknologi

The spring semester, 2023

Open

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Thesis title: Investigation of the performance of a heat pump that uses CO_2 as working fluid.

Credits (ECTS): 20

Keywords: Heat pump, CO_2, COP

Pages: 32

+ appendix: 0

Stavanger, 15.05.23

Abstract

Climate change is one of the greatest challenges facing the world today, and reducing greenhouse gas emissions is a critical part of mitigating its impacts. Conventional residential heat pumps use Hydrofluorocarbons (HFCs) as the working fluid which are very potent green house gases. CO_2 has zero-ozone depletion potential, low Global Warming Potential (GWP), non-toxicity, non-flammability, and superior thermodynamic properties, showing good promise as a replacement candidate for the conventional working fluid. In this thesis the performance of a trans-critical CO_2 was investigated using modeling tool Dymola. The model was calibrated against a real-world protype heat pump to show its validity. The optimal parameters were found, and it shows that the system gives 39% performance over the baseline, showcasing just how important effective design is.

Acknowledgement

I would like to thank my supervisor Homam Nikpey Somehsaraei for his help and insight. A special thanks must also be given to Thor Alexis Salazar Sazon for all his help, especially with the modeling with Dymola.

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Nomenclature table

Symbol	**Meaning**
EU	European Union
DHW	Domestic Hot Water Heating
SH	Space heating
HFCs	Hydrofluorocarbons
Q_c	Heat extracted from cold side
Q_h	Heat given to hot side
W_{in}	Work input
hp	Heat pump
COP	Coefficient of performance
EER	Energy efficiency ratio
Tc	Temperature cold side
T_h	Temperature hot side
ODP	Ozone Depletion Potential
GWP	Global Warming Potential
CFCs	chlorofluorocarbons
HCFCs	hydrochlorofluorocarbons
VLE	Vapor-Liquid Equilibrium
AM	Annual maintenance cost
N	Number of years
i	Interest rate
Ac	Annuitized cost
Av	Annuitized value
EC	Yearly electricity cost
ES	Yearly electricity saved by the heat pump
LCOE	Levelized cost of energy
T_E	Temperature at evaporator inlet
P_{GC}	High side pressure
Q_{TOT}	Total thermal energy output
T_{SH}	Temperature over space heating par
Q_{SH}	Thermal output of space heating part
T_{DHW}	Temperature over domestic how water part
Q_{DHW-R}	Thermal output of domestic hot water
P_C	Power consumed by compressor
T_I	Temperature at heat pump inlet
M_I	Mass flow at heat pump inlet

1.0 Introduction

1.1 Motivation

Climate change is one of the greatest challenges facing the world today, and reducing greenhouse gas emissions is a critical part of mitigating its impacts. A technology that can offer significant potential for emissions reduction is the heat pumps. Heat pumps have already been identified by the European Union (EU) as a key technology for decarbonizing space heating, domestic hot water (DHW) production and cooling in both residential and industrial applications [1]. While heat pumps are already the biggest contributor to the increase in renewable heating and cooling in the EU [2], recent geopolitical events have disrupted and caused uncertainty over Europe's gas supply, signaling a stronger case for self-reliance and hence more demand for heat pumps [3],[4]. Most current heat pumps operate with a sub-critical vapor-compression cycle that uses Hydrofluorocarbons (HFCs) as the working fluid [5]. HFCs are however a very potent greenhouse gases. For instance, one of the most common working fluids, R134a, has a global warming potential that is more than 1300 times higher than that of CO_2 [6]. Recent initiatives such as the EU`s F-gases regulations and the Kigali amendment to the Montreal Protocol, points to and phase-down of HFCs [7],[8]. The combination of using sustainable energy technology with environmentally- safe working fluids is an important notion in the future of the heat pump industry. This has revived the interest in natural working fluids. Among them, CO_2 (R744), seems to be the most promising candidate, owing to its zero-ozone depletion potential, low GWP, non-toxicity, non-flammability, and superior thermodynamic properties [9-11]. Lorentzen first proposed the modern use of CO_2 in a trans-critical heat pump cycle [12]. The reliability of the CO_2 heat pump system still requires thorough study since it could exhibit large performance variations with changing operating conditions [13]. To push for larger technology uptake, the performance, and operating characteristics of the CO_2 heat pump according to various expected operating and design conditions should be carefully studied.

1.2 Objectives

This thesis aims to investigate the performance of an electrically driven CO_2 heat pump under different running conditions. This will be achieved by developing a model of a simple energy system that uses a CO_2 heat pump and to investigate its performance under various operating conditions. The model will be developed using Modelica [14], an equation-based object-oriented modeling language that implements dynamics simulation.

2.0 Literature review and technical background

2.1 A simple heat pump

A simple heat pump transfers heat with the use of a fluid as the primary medium. Normally the heat pump uses a compressor to circulate the working fluid through a closed loop. A simple loop is shown in Figure 1 underneath. In the outside evaporator heat is transferred to the working fluid from the cold outdoor air (Q_c). The working fluid turns into gas. The gas then follows the loop into a compressor that requires a work input to operate (W_{in}). The compressor raises the temperature and pressure of the gas and forces it into the condenser. Because the temperature of the gas is higher than the temperature inside, heat transfer to the inside happens (Q_h), which causes the gas to condense to liquid. The liquid then flows through the expansion valve, reducing pressure and being cooled through expansion. The working fluid is now back in the evaporator completing the loop.

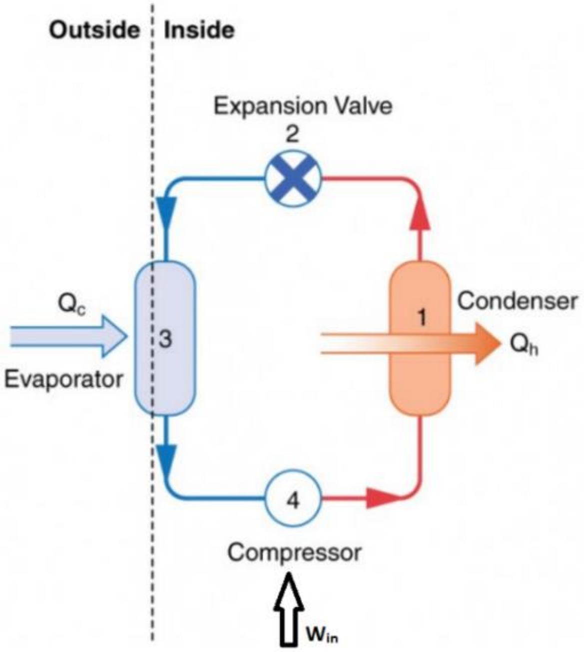

Figure 1. A simple heat pump. [15]

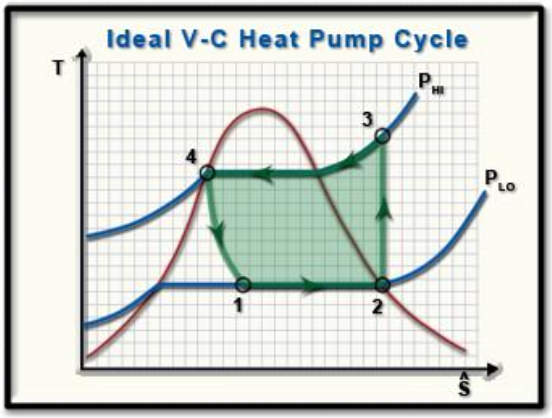

Figure 2. T-s diagram of a simple heat pump. [16]

The quality of a heat pump is determined by how much heat transfer happens to the inside (Q_h), compared to how much work was put in. This is defined as a heat pump coefficient of performance (COP_{hp}).

$$COP_{hp} = \frac{Q_h}{W} = \frac{1}{Efficiency}$$

Equation 1

Since some weather conditions will require cooling energy efficiency ratio (EER) is also useful. EER is the ratio of cooling output relative to the work put inn, determined as:

$$EER = \frac{Q_c}{W}$$

Equation 2

To highlight a key characteristic of heat pumps, we can look at the equation of a perfect heat pump, known as a Carnot engine.

$$Efficiency_{Carnot} = 1 - \frac{T_c}{T_h}$$

Equation 3

It shows that the smaller the temperature difference, the smaller the efficiency and therefore greater $COP_{hp.}$ In simpler terms heat pumps work better in moderate climates than in extreme colds [15].

2.2 Heat pump sources

2.2.1 Source comparison

Heat pumps can have three different types of sources, namely air, ground, and water. An air-source heat pump absorbs heat from the air outside and transfers it to the indoor part of the cycle. It is generally easier and quicker to install than ground or water-sourced heat pumps, as it does not require digging up land or access to water. However, the outdoor unit of an air-source heat pump has fans that generate noise while running, and it may not be suitable for all properties. Air-source heat pumps usually do not require planning permission and are a good option for retrofitting an existing house to reduce carbon emissions [17].

Ground-source and water-source heat pumps, on the other hand, offer a more stable source of heat. They require more initial capital and planning permission to install, but can be calibrated for a smaller operating range, leading to high efficiency and long-term energy and cost savings. Ground-source heat pumps use the stable temperature of the ground to extract heat, while water-source heat pumps use the stable temperature of water, such as a lake or river. These heat pumps may require access to a significant body of water and additional environmental considerations, but they can provide a reliable and renewable source of energy.

2.2.2 Typical performance

Table 1 shows the performance of a ground source CO_2 heat pump at different operating conditions that can be used later to compare with the simulation result documented in the results section, while the real-world heat pumps may differ in specifications, they can still provide a general indication of whether things are functioning correctly or not.

Table 1. Showing COPs at difference operating conditions [18]

High side pressure in bar	COP
82.6	3.36
91.4	3.36
100.6	3.14
112.6	2.86
100.0	3.04
90.2	3.34
98.9	3.06
108.4	3.02
85.4	3.47

2.3 Working fluids

As mentioned earlier most current heat pumps are based on using HFCs working fluids. However, as these are not the best for the environment having other options is needed. Natural fluids seem like a promising option. Out of the natural fluids CO_2 stands out and below is a reasoning for why. Table 2 presents a comparison of the fundamental properties between CO_2 and other prevalent natural fluids, namely ammonia and propane.

Table 2. Basic properties of ammonia (R-717), propane R-290 and CO_2 (R-744) [10][17].

Properties	R-717	R-290	R-744
Ozone Depletion Potential/Global Warming Potential	0/0	0/3	0/1
Flammability/Toxicity	Y/Y	Y/N	N/N
Molecular mass (kg/mol)	17.0	44.1	44.0
Critical pressure (MPa)	11.4	4.3	7.38
Critical temperature (°C)	132.4	96.7	31.1

2.3.1 Ozone Depletion Potential and Global Warming Potential

Two good metrics when assessing the environmental impact are to look at Ozone Depletion Potential referred to as ODP and Global Warming Potential referred to as GWP. The ozone layer serves a crucial purpose in protecting life on earth by shielding the earth from harmful ultraviolet radiation. It is therefore important that large-scale emissions are not harmful to the ozone layer.

ODP measures the amount of damage a substance can cause to the ozone layer. It is expressed as a numerical value that represents the relative amount of ozone depletion caused by a substance compared to the amount of ozone depletion caused by the same mass of chlorofluorocarbon-11, which has been given the value of 1.0 [19]. That means that the lower the value the less damage it causes to the ozone layer. A value of zero means it has no impact. The other metric is GWP, which is a measure of how much a particular gas contributes to global warming over a set period, compared to the same amount of CO_2. The time period used is usually a hundred years and since CO_2 is the reference gas it has a numerical value of 1. Greenhouse gases trap heat in the atmosphere and therefore contribute to global warming. The GWP of a greenhouse gas depends on its ability to trap heat, its atmospheric lifetime and the amount in the atmosphere. For instance, a gas with a high ability to absorb heat but a low atmospheric life would have a higher GWP if a shorter time period was used but the longer the period chosen the GWP would go down for this gas. It is therefore important to know that the listed GWP used the same time periods and relative amounts when comparing them [20].

2.3.2 HFCs

HFCs or hydrofluorocarbons are a class of greenhouse gases that are used as working fluids in heat pumps and air conditioning systems. HFCs are a type of fluorinated gas, known as F-gases that were introduced as a replacement for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which got phased out due to their very harmful effect on the ozone layer. While HFCs do not deplete the ozone layer, they do have a very high GWP with some having more than a thousand times CO_2 GWP making them some of the most potent greenhouse gases and therefore contributing heavily to climate change [21]. As cited in the motivation, global efforts such as the Kigali Amendment and the Montreal Protocol aim to reduce the production and consumption of HFCs, with the ultimate goal of having and using more climate-friendly alternatives.

2.3.3 Natural fluids

Firstly, we should identify what a natural fluid is and why it differs from a synthetic/artificial fluid, like for instance R-134a. A natural fluid is a substance that occurs naturally in a liquid or gas state at standard temperature and pressure conditions, without the need for artificial compression or cooling. A common example could be water. Natural fluids usually have similar advantages over synthetic fluids due to characteristics as being non-toxic, non-flammable and readily available.

Ammonia (R-717) has been used as a working fluid for over 140 years and is still widely used, but mostly limited to industrial applications. It does not have ozone depletion potential, nor does it have any global warming potential meaning it would be a very favorable candidate if we were only looking at it from that perspective. Also favorable with ammonia is its high latent heat and refrigeration capacity per unit mass, being the highest of all working fluids used in normal vapor compression systems. Also because of its low molecular mass it can have much higher particle velocity, meaning mass flow per area will be higher allowing for smaller piping. The downside of ammonia is that it is both flammable and toxic. Its threshold limit value is 50 ppm and poses an immediate danger to life at 300 ppm, coupled with its flammability means that measures must be taken to ensure safe operating conditions. It is necessary for an ammonia-based system to be confined in a separate room and for the personnel operating the system to be well-trained. It is therefore clear to see why these systems are limited to mostly industrial application and would not be well suited to be installed in a private residence where no trained personnel are present [22].

Propane (R-290) is another example of a natural working fluid with intriguing properties. It has no ozone depletion potential and a very high global warming potential. However, as it is a hydrocarbon chain, it is highly flammable. It, therefore, poses an extra local risk, if goes wrong. An option that did not have this downside would therefore take a clear lead.

Carbon dioxide (R-744) also has no ozone depletion and very low global warming potential. It is also not toxic nor is it flammable, meaning it is safe to work with. It is also abundant in nature and therefore comes at a low cost. The thermodynamic properties of CO_2 have unique characteristics. It has a high critical pressure point of around 7.38 MPa and a low critical temperature point of 31.1 Celsius. These characteristics give CO_2 many advantages when utilizing heat from low-grade heat sources. The high critical pressure makes the system more compact compared to other systems, meaning piping and component sizing can be reduced. The excellent heat transfer characteristics help reduce the impact of pressure drop on efficiency. The low critical temperature also means even a low-temperature heat source allows a trans-critical cycle, which ultimately gives higher efficiency than normal heat pump cycles [23].

2.3.4 CO_2 as a working fluid in a trans-critical cycle

The heat pump cycle described earlier has been a traditional cycle with sub-critical heat rejection, but because of CO_2 characteristics higher efficiency can be achieved using a different cycle. This id due the fact that in most applications the source temperature is lower than the critical temperature, while the rejection temperature is higher than the critical temperature. This implies that there is a period under which the fluid is sub-critical and a period when it is in the supercritical region. The evaporator performs as a two-phase vapor liquid device and the condenser is replaced with a supercritical heat-rejection unit called a gas cooler.

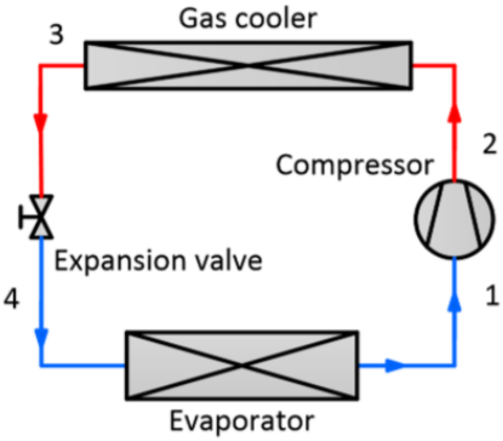

Figure 3. A simple trans-critical heat pump [23]

A trans-critical CO_2 heat pump will usually have a high side pressure from 8 MPa to 12 MPa, which is approximately 5 times higher than conventional heat pumps. This leads to higher manufacturing costs and increased challenges with the reliability and safety of the systems. CO_2's poor energy consumption under high ambient temperatures is also an know issue. When compared to R-134a, the COP of CO_2 was 21% lower at 32.2 °C ambient temperature and at 48.9 °C ambient temperature the COP was 34% lower. The challenges faced by the technology have prompted the development of various sub-technologies aimed at addressing these issues [24].

This thesis aims to evaluate a cycle using two of these technologies, internal heat exchanger and subcooling. The cycle works the following way. In the evaporator heat is transferred to the working medium. The fluid then travels to the internal heat exchanger (also be called the suction gas heat exchanger); the main purpose of this unit is to superheat the fluid going into the compressor. The compressor raises the pressure and temperature and forces the working medium into the gas cooler. In the gas cooler heat is rejected at a supercritical level. The fluid then passes through the subcooling system. The primary objective of the subcooler is to lower the CO_2 temperature before the expansion valve and to reduce the amount of flash gas at the evaporator inlet. After the subcooler it passes through into the expansion valve. In the expansion valve the fluid pressure is further reduced turning it into the liquid phase and the temperature also drops. The medium is now back in the evaporator and the cycle is thereby complete [25]. The cycle is represented in Figure 4 and Figure 5.

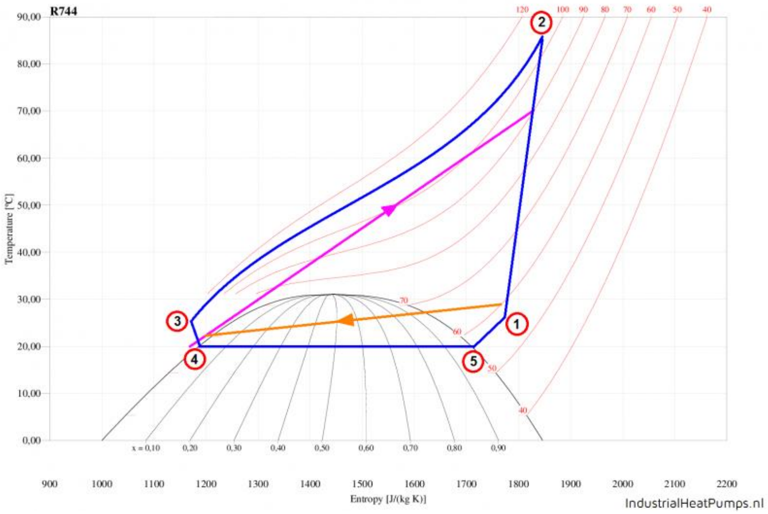

Figure 4. Showing T-s diagram a trans-critical CO_2 heat pump [26]

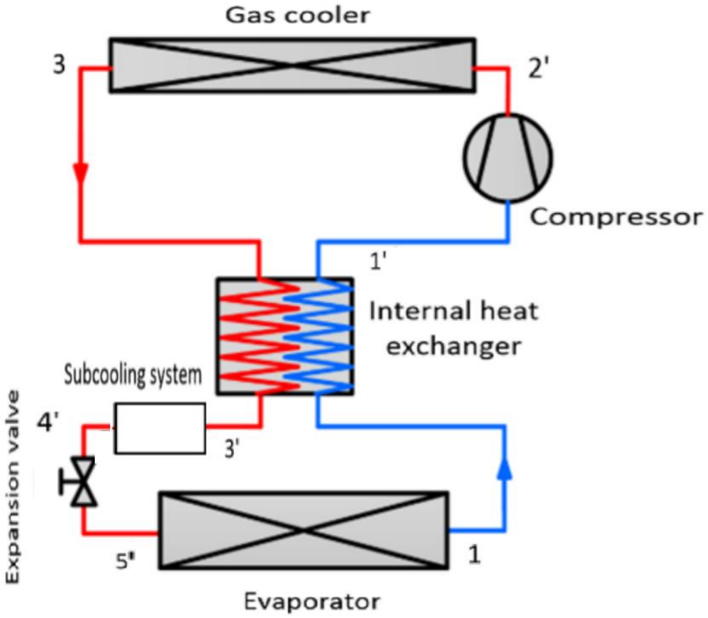

Figure 5. Showing a trans-critical heat pump [24]

More efficiency could be gained using different sub-technologies, for instance ejectors, vortex tubes, two-stage compression, or a mixture of CO_2 with some other working fluid. A combination of these or similar technologies would also be interesting but require more study and research before any proper real-world application, due to both cost and complexity restraints [25]. So, to sum up, CO_2 seems like an outstanding working fluid in many heat pump applications in the future due to its excellent properties, low environmental impact, non-toxicity, and non-flammability.

The main applications where trans-critical CO_2 system has been commercialized so far are heat pump water heaters, refrigeration systems for supermarkets and within small size commercial refrigeration [27]. As mentioned above there is a lot of study going into the field to expand the commercial applications of the systems. These include using/optimizing the technology for; cooling/heating in passenger cars and commercial vehicles, improving heat pump water heater/space heating efficiency, defrosting of the heat pump water heater, heat pump dryer, improving commercial freezing and refrigeration [28]. This thesis aims to address the research gap by investigating the impact of various operating conditions on performance. Through the examination of this aspect, it is expected that valuable insights can be obtained, resulting in improved efficiency during the design phase.

2.4 Applications

Heat pumps have many applications both in an industrial setting, but also in residential settings. For this paper we will only focus on residential applications. Heat pumps applications in residences are the following: space-heating water heating, cooling, and water cooling. Heat pumps are used to either heat or cool induvial rooms or entire homes/buildings. In heating mode as mentioned earlier heat is absorbed from the outside medium and transferred to the indoor air while if put in cooling mode the process is reversed. In cooling mode heat pumps can also be used to dehumidify indoor air, as they remove moisture from the air as part of the heat transfer mechanisms. Another use is the domestic hot water production. Heat pumps are used to warm up domestic water that is for instance used for showers, baths and washing dishes. This is usually achieved using a heat exchanger and a tank for the hot water. However not all heat pumps setups can deliver al the types of heating and cooling needs as mentioned above, they usually come in four main configurations. (1) heating-only heat pumps, are used for space heating and domestic hot water, (2) heat and cooling heat pumps for, both space heating and cooling, (3) integrated heat pump systems for, space heating, cooling, and domestic how water production, and (4) heat pump water heaters for, water heating only [29].

As cited earlier the EU has identified heat pump as a key technology for decarbonizing space heating and domestic hot water production. The UK has also stated that they aim for 600 000 heat pump installations per year by 2028 [30]. This is a big goal, and it is therefore important to remind homeowners who are taking the cost of installation, of the other benefits with heat pumps other than reducing emissions and thereby fighting man-made climate change. High energy efficiency is one of these benefits. Heat pumps use electricity, but unlike older heating technology like panel ovens where the electricity input is equal to the heating output heat pumps will have a coefficient of performance at around three and even higher. This means that you get three times the heating output with the same electricity input. This leads to cost savings for homeowners since less electricity is needed to fulfill the heating demands. This means that even with the higher upfront cost of a heat pump, they will usually pay for themselves by providing lower energy bills. Heat pumps also provide versatility for homeowners, as they can provide a variety of applications as mentioned earlier. They are also good for indoor comfort as they produce a consistent, even temperature throughout their heating space. Air quality can also be helped by a heat pump as unlike some traditional heating systems, heat pumps do not use combustion to produce heat. This means less dust and other particles are blown throughout the home nor are any harmful gases made such as carbon monoxide. Additionally, most heat pumps are equipped with air filters that can remove pollutants and allergens from the indoor air, this can be a major advantage for homeowners/residents that have respiratory issues or allergies. Another comfort increase with heat pumps is their quiet operations. This would be helpful for homeowners that are looking to reduce noise levels for a variety of reasons. A final benefit for homeowners mentioned here is that most newer heat pumps offer compatibility with smart home technology. That means that homeowners can control the temperature remotely using, for instance, a smartphone. This is of course convenient for numerous reasons including for instance pre-heating a cabin before you get there.

2.5 Modeling

In this work the modeling language Modelica will be used. More specifically Dymola, which is a commercial modeling and simulation environment that is based on the Modelica language. A key advantage of Dymola is multi-engineering. Dymola has unique multi-engineering capabilities, which means that models can consist of components from many engineering domains. In addition, the intuitive modeling using Dymola graphical editor makes modeling easier. Dymola is also open and flexible, which means users of Dymola can introduce components or libraries themselves [31]. This work has taken advantage of that and has used a commercially available library called the thermal system library made by TLK-Thermo GmbH, which will significantly help model a CO2 heat pump.

3.0 Methodology

3.1 System description and modelling approach

The system depicted as shown in Figure.6 consists of three primary components. Heat pump, thermal energy storage (TES), and thermal energy demand. The model is constructed using various components from the Modelica library, with the real expression block being one of the most employed ones. These blocks are either linked to a static number input or a string input that extracts values from various parts of the system. Due to this, the system is considered static, and once it has reached steady-state conditions from the initial state, it produces a constant output. To evaluate how the system functions under varying operating conditions, the input variables are adjusted and compared to the system's baseline performance. Assumptions made in the model are that steady-state operating conditions are achieved, heat or pressure losses within transfer between components are negligible, and target temperature can be achieved.

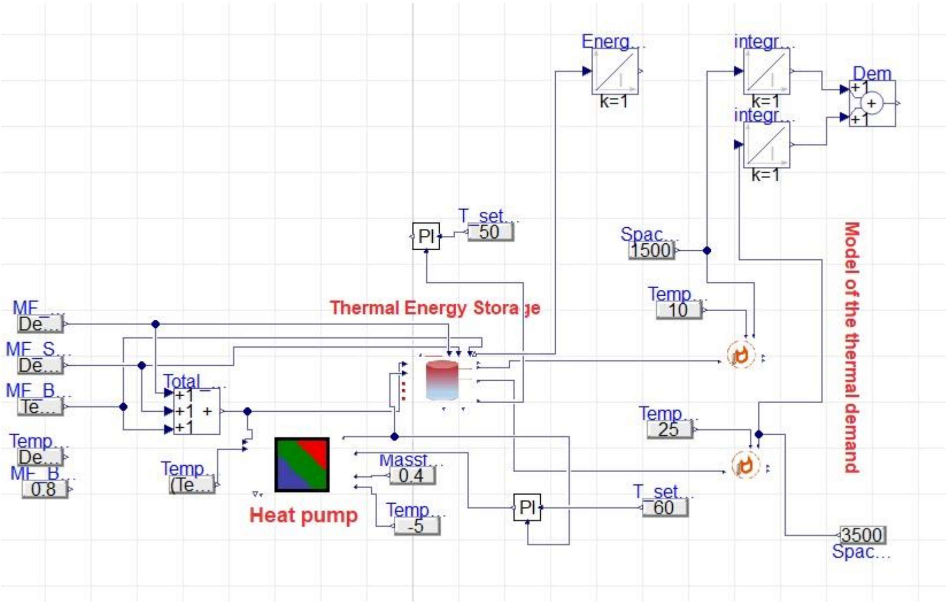

Figure 6. Shows the energy system modeled.

Figure.7 shows a heat pump cycle created in Dymola, which consists of the same major components as the heat pump in figure 5. The heat pump is the central component of the system modeled, developed using some Modelica library components, while the majority of its components came from the thermal system library. This includes all heat exchangers and the compressor. The heat exchangers are parallel flow units, with most being VLE fluid to liquid heat exchangers, while the suction gas heater is VLE fluid to VLE fluid. The insulation thickness in the heat exchangers was between 10-25 mm while the conductivity was 0.032 W/m-K. No pressure loss was assumed in the heat exchangers. The weight of the heat exchangers ranged from 2.5 kg to 18 kg. The compressor displacement was maintained at a constant value of 3.33e-6 m^3, with a maximum operating speed of 120 Hz. To control the compressor and the heat pump, a desired temperature was set at the upper part of the thermal energy storage (TES), and a PI controller was employed to attain and maintain this temperature.

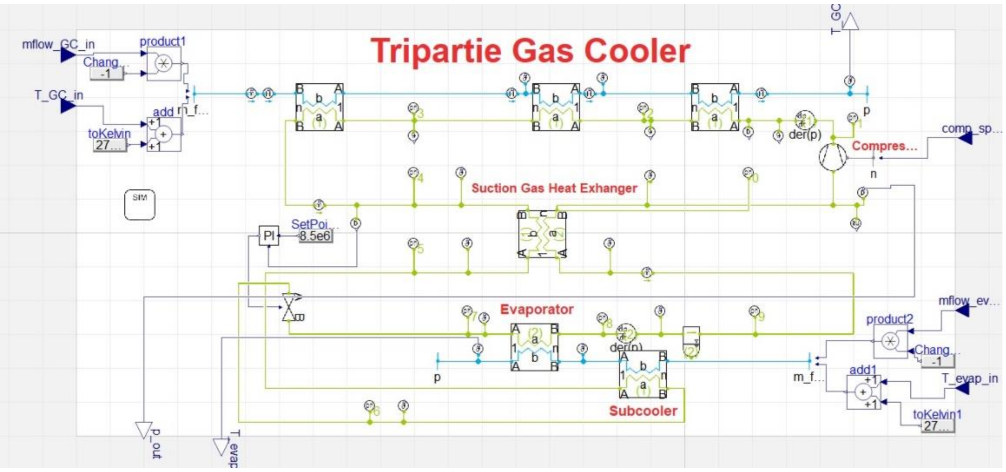

Figure 7. Shows the trans critical CO_2 heat pump modeled.

The model for the TES shown in Figure.8 was developed using components of the Buildings library. The model uses the stratified storage tank model, which implements several volumes that exchange heat among themselves and with the ambient via conduction. Each layer volume contains a fluid port that may be used to inject or withdraw water to or from the tank. Heat loss through the top and sides of the TES was modeled by assuming that the ambient temperature is kept at 19°C, the minimum acceptable indoor temperature according to Norwegian building regulations [32]. Insulation thickness and conductivity were assumed to be 200mm and 0.04 W/m-K, respectively. The TES height was kept at 2m. Hot fluid from the heat pump first passes through a backup heater in case the required temperature was not attained. It is then injected into the top layer of the tank. Relatively cold fluid is drawn from the bottom to manage the temperature inside the tank. Hot water from the top and the middle layers are withdrawn to provide the energy required for DHW heating and SH, respectively. The rate of withdrawal of water is controlled by the thermal demand model component.

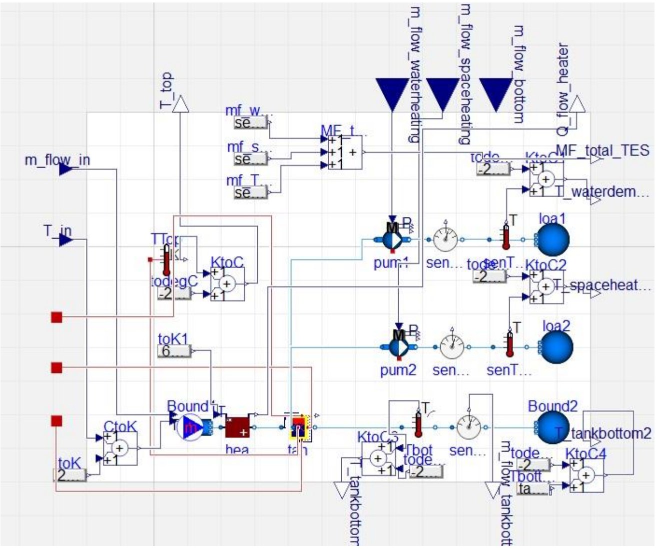

Figure.8 TES component made in Dymola.

Thermal energy demand shown in Figure.9 was represented by a pipe, which features a heat port. The heat port is connected to demand information, which could either be obtained from measurements or simulations. The flow of hot fluid coming from the TES is controlled by indicating the expected temperature of the fluid after it has undergone heat exchange with the distribution system. This model is a simplification of how the heat demand is being met by the system.

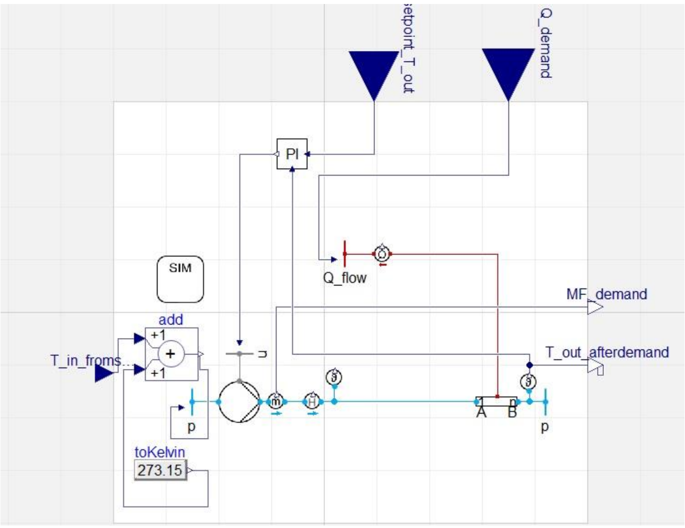

Figure. 9 Model of thermal energy demand made in Dymola.

Table 3 displays the assumptions and configurations employed in the modeling approach. These choices were primarily based on the work of J. Stene in "Residential CO2 Heat Pump Systems for Combined Space Heating and Hot Water Heating" [25], where an actual real-world prototype was constructed. As Stene's data is also utilized for calibration in this thesis, it is logical to strive for emulation of his real-life system as closely as feasible. Additional information was sourced from the Norwegian department [32] responsible for building quality standards, which provide the minimum safe conditions.

Table. 3 Shows the assumption and settings made in the modeling approach.

Assumption/Setting	Value	Source
Steady operating conditions are achieved	-	-
Teat or pressure losses within transfer between components are negligible	-	-
Target temperature can be achieved	-	-
Heat exchanger mas	2.5kg-18kg	[25]
Heat exchanger insulation thickness	10-25mm	[25]
Heat exchanger conductivity	0.032 W/m-K	[25]
No heat exchanger pressure loss	-	-
Compressor displacement	3.33e-6 m^3	[25]
Compressor max speed	120 Hz	[25]
TES insulation thickness	200mm	[25]
TES conductivity	0.04 W/m-K	[25]
TES height	2 m	[25]
TES ambient temperature	19°C	[32]

3.2 Performance metrics

3.2.1 Seasonal performance factor

Seasonal performance factor is defined as the ratio of the annual heat supply from the heat pump system and the total energy supplied. It depends on several factors, which are listed below [25]:

- Annual space heating demands, the maximum heat loads, and load variation over the year
- The sizing of heat pump in relation to maximum load, and the requirements for supplementary heating by a peak load system
- The COP at varying operating conditions.
- The variation in outside temperature for the heating system throughout the heating season.
- Energy consumption of pumps and auxiliary equipment
- The control system

3.2.2 Annual cost and Levelized cost of energy

Annual cost is a common performance metric used in business to assess how well an investment performs. It represents the total amount of money spent over the course of a year to operate and maintain the investment, including the initial cost spread over the lifetime of the investment. Usually, an investor would seek a return on investment too, to cover opportunity cost. The higher the risk taken would normally demand a higher return to be an attractive investment. Table 4 shows the parameters we need to define to determine annual cost.

Table. 4 Shows the parameters needed to be defined to determine annual cost [33].

Lifetime	25 years
Initial cost	5490 USD
Annual maintenance cost (AM)	0, for simplicity
Salvage value	0, for simplicity
Average/estimated cost of electricity during lifetime	Will vary depending on operating conditions
Interest rate/MARR	2%
Annual heating provided by heat pump	Will vary depending on operating conditions
Annual electricity usage by heat pump in kWh	Will vary depending on operating conditions

The initial cost was found using a table that is based on cost correlation, therefore if the size of the components is known. initial cost can roughly be calculated [33]. The lifetime is set to 25 years and interest rate is set to 2%. This is an optimistic view. Lifespan is on the long side especially since the focus of this thesis is on the residential side where current traditional heat pump doesn't have that long of a lifespan. An interest rate of 2% in today current economic climate would also be very favorable. There reason these parameters were chosen was to give the technology the best chance of being competitive, by showcasing a best-case scenario.

To make the present(P) initial set up cost into an annuitized cost (Ac) we translate a stream of equal annuities to some fixed point in the future N years away, given a specific interest rate i. The fixed point will in our case be the lifetime of the project [34].

$$Ac = P\frac{i(1+i)^N}{(1+i)^N - 1}$$

Equation 4

Then to make the future salvage value(F) into an annuitized value (Av) translate the future salvage value into a stream of equal annuities given a specific amount of years N and interest rate i[34].

$$Av = F\frac{i}{(1+i)^N - 1}$$

Equation 5

Then calculate how big electricity cost (EC) is each year by multiplying kWh used by the kWh price. Next calculate how much electricity saved (ES) is by the heat pump by taking the heating provide minus the electricity used and multiplying it with the electricity price. From here annual cost is found.

$$Anual\ cost = Av + Es - Ac - Ec$$

Equation 6

From here it follows that Levelized cost of energy is found (LCOE).

$$LCOE = \frac{Anual\ cost}{Total\ energy\ provied\ in\ one\ year\ in\ kWh}$$

Equation 7

3.3 Calibrations

The heat pump was calibrated using parameters listed in Table 5, where T_E is evaporator inlet temperature, P_{GC} is high side pressure, Q_{TOT} is total thermal energy output, T_{SH} is temperature over space heating part, Q_{SH} is thermal output of space heating part, T_{DHW} is temperature over domestic how water part, Q_{DHW-R} thermal output of domestic hot water and P_C is power consumed by compressor. The calibration data comes from the work of J. Stene in "Residential CO2 Heat Pump Systems for Combined Space Heating and Hot Water Heating" [25].

Table 5. Calibration parameters

T_E	P_{GC}	Q_{TOT}	T_{SH}	Q_{SH}	T_{DHW}	Q_{DHW-R}	P_C	COP
-5.1 °C	85 bars	6907 Watts	30.1-35.1 °C	2942 Watts	7.0-59.8 °C	2357 Watts	1775 Watts	3.89

Then the calibrated model is compared to the real-world prototype [25] at different P_{GC} shown in table 6. The percentage error achieved is generally satisfactory, especially in the median region. In the higher and lower part of the table the error percentage is relatively high, but in this type of analysis it is acceptable.

Table 6. Calibrated model under different operating pressures

P_{GC} (bar)	Real world prototype result (COP)	Model calibrated for 85 bar result (COP)	Percentage error
75.50	2.93	3.28	11.9%
80.30	3.67	3.88	5.7%
89.80	3.70	3.78	2.2%
95.05	3.47	3.64	4.9%
99.85	3.22	3.52	9.3%

4.0 Results

4.1 Baseline parameterization

The baseline parameters for the systems are listed in table 7.

Table 7. Baseline parameters of the system.

T_I (temperature at inlet)	M_I (mass flow at inlet)	TES upper temperature	High side pressure	Return temperature from space heating
0 °C	0.4 kg/s	65 °C	85 bar	25 °C
Range of change	Range of change	Range of change	Range of change	Range of change
-10 °C to 10 °C	0.1 kg/s to 1kg/s	60 °C to 80 °C	85 bar to 105 bar	25 °C to 40 °C

Then to study how the system behaves under changing operating conditions only one parameter is changed at a time.

4.2 Performance evaluation

To assess the results of the system it is useful to compare the results with the expected outcomes from the calibration section. Baseline parameterization was used except for parameter T_I being 3 °C and high side pressure which was varied to correspond to the data in the calibration section. The purpose of utilizing a different T_I than the baseline was to maintain the same level of T_E as employed during the calibration phase, and due to the sub cooler, a T_I of 3 °C will give a T_E of roughly -5.1 °C. The results are listed in Table 8.

Table 8. Modeled system compared to real world protype.

High side pressure in bar	COP of system	Real world prototype result (COP)	Percentage error
75.50	2.31	2.93	21.2%
80.30	2.68	3.67	27.0%
89.80	3.39	3.70	8.4%
95.05	3.44	3.47	0.9%
99.85	3.33	3.22	3.3%

4.3 Effect of changing parameters

Figures 10-19 show the variation of performance metrics running the system under baseline while changing one parameter at a time.

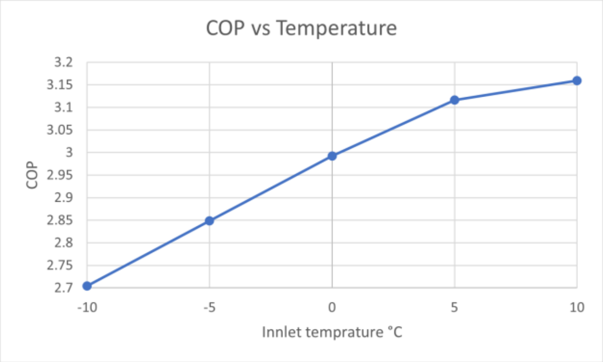

Figure. 10 COP vs Inlet temperature

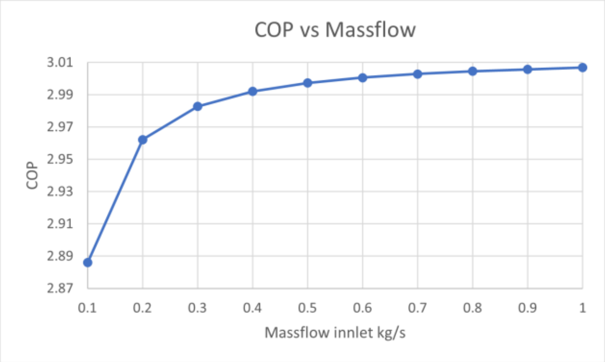

Figure.11 COP vs Mass flow at inlet

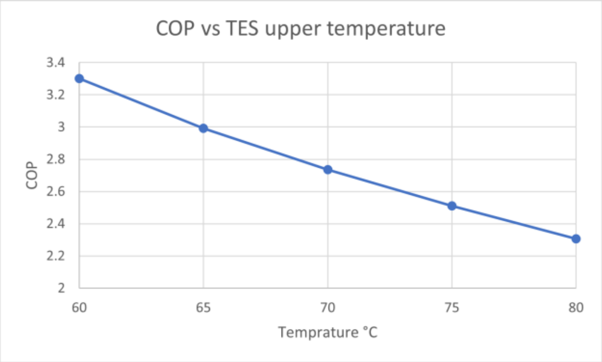

Figure. 12 COP vs TES upper temperature

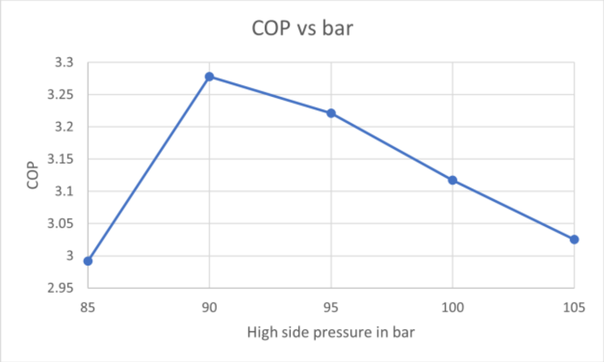

Figure.13 COP vs High side pressure

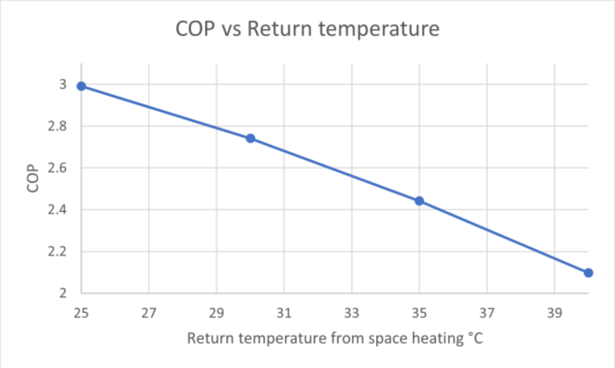

Figure. 14 COP vs Return temperature

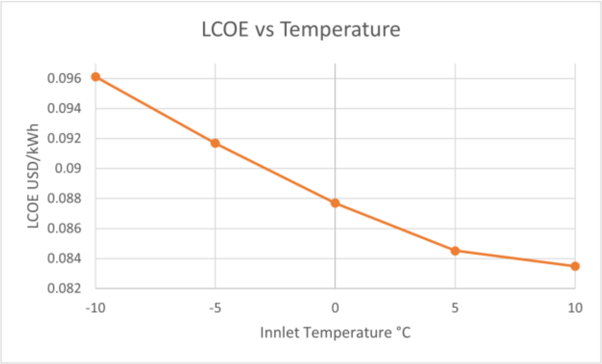

Figure. 15 LCOE vs Inlet temperature

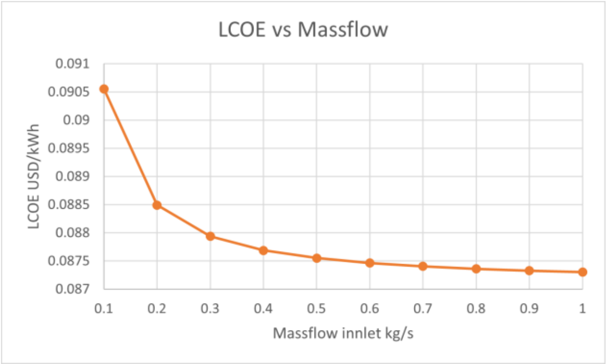

Figure.16 LCOE vs Mass flow at inlet

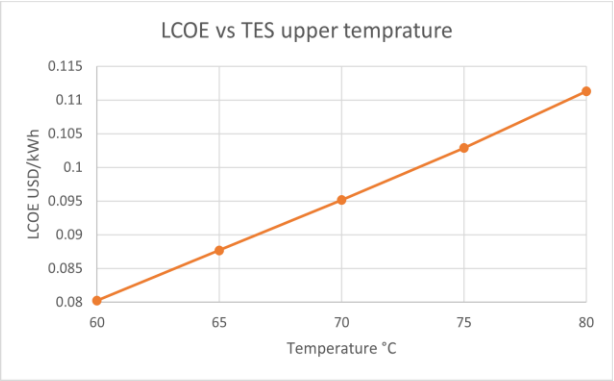

Figure. 17 LCOE vs TES upper temperature

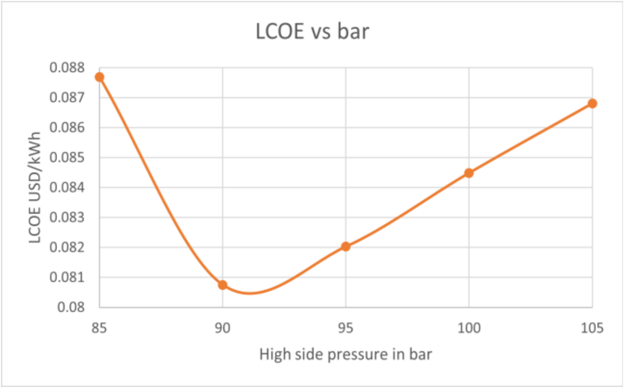

Figure.18 LCOE vs High side pressure

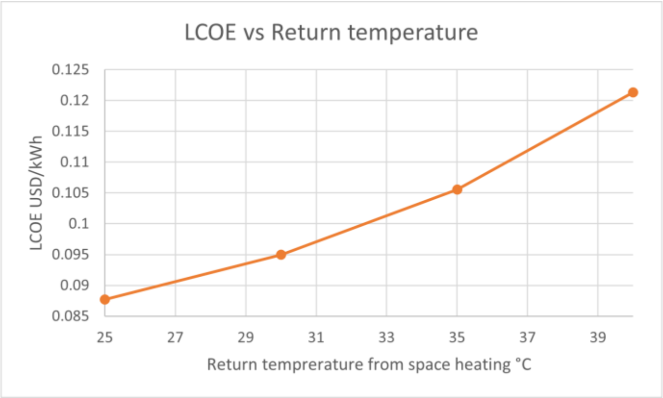

Figure. 19 LCOE vs Return temperature

5.0 Discussion

5.1 Validity evaluation

The COP of the system exhibits good correlation with the real-world prototype, except for the lower pressures where the error percentage is relatively large. However, these pressures are typically not considered effective operating ranges for trans-critical heat pumps. At normal operating ranges above 85 bar, the error percentage appears acceptable. However, the low-range discrepancies are due to the system's inability to satisfy heating demand at lower pressures, which causes the compressor to operate at maximum speed and consume a lot of electricity while delivering minimal heating gain, thereby affecting the COP at these pressure ranges. The system also shows common trends with the heat pump mentioned in typical performance (2.2.2). This in conjunction with the calibration performance evaluation shows that the system behaves as it should.

5.2 Optimal parameters

Optimal performance in a trans-critical CO_2 energy system is achieved at higher inlet temperatures, but the performance gain becomes progressively smaller as the temperature increases. This underscores the importance of determining the appropriate operating range during the system's design phase. In our case, the calibration is set to 3°C. However, for much higher temperatures, heat pumps that utilize different working fluids may prove to be more beneficial.

The mass flow performance consistently improves across the parameter interval, but beyond 0.4 kg/s, the rate of improvement begins to diminish. Therefore, in situations where accommodating higher mass flow rates would result in higher initial costs or more maintenance issues, a reasonable compromise could be to settle at a mass flow rate of 0.4 kg/s.

As the temperature in the TES increases, its performance experiences a decline in efficiency. However, to use the system for domestic water heating, a temperature of 60°C is necessary as this is the typical temperature for a conventional hot water heater. There may be other justifications for employing a higher storage temperature. For instance, if access to low-cost electricity is only available during specific periods of the day, a higher temperature would permit greater energy storage within the same space.

The high side pressure performance has its peak close to 90 bar. This will be the optimal pressure for the system. Going higher also avoids higher costs related to higher pressures, as it could require more robust components to handle the increased pressure over its lifetime.

The performance of the return temperature from space heating also demonstrates a reduction in efficiency with higher temperatures. Nevertheless, even at 25°C, there is still a significant amount of thermal energy present in the air that could be utilized. However, the temperature might not be sufficiently high to warrant the installation of an additional heat exchanger in the system. Therefore, by raising the temperature, all the energy can be more effectively harnessed, and if another heat exchanger were to be added, it could lead to an increase in COP. However, as that is not an option in this work 25°C is the optimal temperature.

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6.0 Conclusion

6.1 Conclusion

The aim of this thesis was to examine the performance of a CO2 heat pump under various operating conditions. To accomplish this, a basic energy system was developed using Dymola. The heat pump model was validated using a physical prototype, and a good level of agreement was observed between the model and the real-world system. Hence, it is reasonable to assume that the model is a reliable representation of the actual heat pump. The principal findings of this investigation are the optimum system parameters, which are presented in table 9.

Table 9. Optimal parameters of the system.

T_l (temperature at inlet)	M_l (mass flow at inlet)	TES upper temperature	High side pressure	Return temperature from space heating
10 °C	0.4 kg/s	60 °C	90 bar	25 °C

This system has a COP of 4.15 or in a more relative term 39% better than the baseline system. It also has an improved LCOE of the same degree. This, however, leads to the limitations of this study. The limitations are mostly related to how static the system is. An example of this is for instance demand and how it relates to LCOE. Throughout a day heating needs for both water and space will probably not stay constant, and it will not stay constant trough a year. In this model, however demand is constant day and night, this will artificially lower LCOE as the initial cost is spread out on more kWh. This was, however, not always the intention of this work, the plan was to use real weather and demand data. This was not obtainable in the end due to a mixture of time constraints in finding a new solution and the technical constraints. The technical constraint arose from the protype that the model was calibrated. The inlet temperature in the protype was relatively low and therefor when simulations were run with temperatures above 20ish degree the model could not reach high enough temperature for the TES which caused the compressor to spin at max value consuming close to 2 kW while the heating demand might have only been 2 kW. Suggestion for future work could be the construction of an air-sourced CO_2 heat pump in a moderate climate where both cooling and heating are needed to obtain more data.

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