TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

Energy Economics Group

Master's Thesis

# Two-stage stochastic optimization of district energy systems: a case study from the United States

by

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11912008

for the achievement of the academic degree

Dipl.-Ing.

in the field of study Energy Engineering
at TU Wien

Vienna, March 2025

submitted at
Institute of Energy Systems and Electrical Drives

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## Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Wien, _____ _____

Date Signature

# Preamble

This master thesis forms the basis for a peer-reviewed paper which, at the time of this thesis completion, is under review with Elsevier's journal Energy Conversion and Management (manuscript number ECM-D-25-01805; submitted 10 February 2025).

The submitted paper is entitled:

> *Optimizing district energy systems under uncertainty: Insights from a case study from Washington D.C., USA*

The contributors and authors of the paper under review are Sebastian Zwickl-Bernhard (lead author), Felix Bauer and myself (all three affiliated with the Energy Economics Group, Technische Universität Wien) and Nicholas Long, Whitney Trainor-Guitton and Juliet G. Simpson (all three affiliated with the National Renewable Energy Laboratory, Golden, CO, USA). The findings of the US case study were presented and critically discussed by Felix Bauer at the Smart Energy Systems Conference in Aalborg, Denmark, providing valuable insights and fostering an engaging exchange with experts in the field.

The fundamental framework and methodological approach of this work were developed collaboratively as part of a joint effort with Felix Bauer. Based on this foundation, two distinct case studies were conducted: Felix Bauer was responsible for the Norweign case study, while I (Simon Jordan) focused on the US-American case study. Therefore, some images and text passages are similar respectively equal between these two master's theses.

# Abstract

To achieve climate neutrality, diverse policy measurements and incentives have to be realized. Various sectors have to adapt towards a sustainable and carbon-neutral future. One of these sectors which has to reduce emissions is space heating and cooling. Especially in rural areas, people are dependent on regional and individual solutions. But also bigger cities often lack of a common district heating and cooling infrastructure. In this thesis, a two-stage stochastic optimization model is developed to get robust and cost-optimal investment decisions. Different heating, cooling and storage options are modeled, making a broad portfolio available. As future developments are hard to predict, different scenarios are introduced to cope with energy price changes, demand fluctuations and policy adaptions. The results are based on a US-American case study in Washington D.C. for a small district of 35 buildings. This case study will help to gain insights on how beneficial a common thermal energy supply will be compared to individual solutions. The optimal solution of the model will give a trend on promising technologies as well as technology correlations.

# Contents

# 1 Problem formulation and research questions

Reducing $CO_2$ emissions has become a critical aspect of policy makers to achieve national climate goals. Therefore, a higher share of carbon-neutral technologies and supply chains is important. Kuntuarova et al., Guericke et al. [1, 2] have identified district heating (DH) systems as a major component for mitigating greenhouse gas emissions. One possibility in providing thermal energy demand by low-carbon generation units is the transition towards electrification. Renewable electricity supply on the other hand faces the challenge of volatile generation, which is described by Salvestroni et al. [3]. Therefore new concepts must be introduced to combine technologies and minimize challenges. Sector-coupling is a key method to compensate disadvantages between energy sectors. Kozarcanin et al. [4] identified space heating as very important in sector-coupled energy systems. This approach enables a broad spectrum of energy supply for different kinds of loads. Furthermore, thermal energy storages can be implemented to increase the flexibility of the coupled system, as described by Fry et al. [5]. By using thermal energy storages electric energy can be stored in a different medium and the energy generation can be shifted from expensive production hours to cheap ones.

At the moment especially in rural areas district energy systems (DES) are not available, but also cities often lack of a common DES. Therefore, a lot of individual solutions are in use, mostly gas powered ones. This is not only a problem, in fact it is an opportunity where this thesis focus on. [1]

The transition from individual gas-dominated heating systems to carbon-neutral electrified district heating solutions is a critical aspect of the ongoing transformation towards a more sustainable future. Traditionally, gas has been the dominant energy source for heating in many regions, providing reliable and cost-effective solutions. However, with the growing emphasis on decarbonization and reducing greenhouse gas emissions, there is an increasing shift toward electrified heating systems, such as heat pumps, electric boilers and geothermal generation units, which offer more sustainable alternatives by leveraging renewable energy sources. As described by Berrill et al. [6], in addition to electrification, renovations are also mandatory to achieve rapid decarbonization.

[1] The work conducted here contributes to the ongoing ERA-Net project FLXenabler, which aims to develop an implementable modeling framework to demonstrate the impact of sector coupling and integration of geothermal resources, heat pumps, variable renewable resources, and thermal energy storage in accelerating the transition into a fully decarbonized energy system in Europe and the USA.

Furthermore, district cooling is gaining significant importance. Scoccimarro et al. [7] have identified that the rising global temperatures lead to an increasing number of cooling degree days. This means a significant cooling demand increment, which was analyzed by Staffell et al., Miranda et al. [8, 9]. Extreme weather conditions such as heatwaves will appear more often and are a serious problem especially in urban regions. Considering cooling aspects at the same time as heating gives even more sector-coupling options and makes the system more flexible.

Thermal energy storages are essential to improve flexibility and compensate the volatile behaviour of renewable energy sources. They play an important role in the energy transition process. Chavan et al., Christensen et al. [10, 11] highlight the importance of thermal energy storages in district energy systems.

Based on the gathered information, the core objective of this thesis focuses on the optimization of a cost-minimal system for district heating and cooling networks, incorporating various technologies and the additional implementation of energy storage systems. The goal is to design a system that not only minimizes costs, but also meets the growing demand for both heating and cooling in a sustainable and efficient way by considering uncertainties among future parameter developments.

The developed model is then applied on Washington D.C., as US-American case study. This case study is justified by the increasing efforts to achieve high levels of energy efficiency in commercial and residential buildings, as described by Cooper and Rajkovich [12].

Following research questions are defined, which will be answered by this thesis:

1. What investment strategy is suitable based on various technology options to cover a given demand by minimizing economic costs?
2. How robust is the cost-optimal solution regarding different scenarios and their dispatches?

First of all a fundamental overview about existing technologies and scientific knowledge will be given. Based on this comprehensive knowledge mathematical formulations are defined. These mathematical foundations have been modeled and implemented in Python. The results are based on the US-American case study and illustrate trends in technology selection and sector coupling. Finally, a brief outlook of future extensions and possible enhancements will be given.

# 2 Relevant literature

First of all the current state of the art has to be analyzed to build this thesis on existing scientific knowledge. Therefore, a fundamental modeling overview will be given followed by detailed information about the investigated technology options.

## 2.1 Modeling approaches

In this subsection, the background of the computational method of this study is examined. The first part focuses on the general optimization of district energy systems, while the second part explores the fundamentals of two-stage stochastic optimization. [2]

### 2.1.1 District energy system optimization

Optimization is essential in the energy sector, driving efficient resource allocation, reducing costs, and improving system reliability. A range of optimization techniques is applied to tackle challenges like energy generation scheduling, grid management, and investment strategies. While deterministic optimization models are widely used, relying on the assumption of perfect parameter knowledge, energy systems face considerable uncertainties. These include unpredictable demand shifts, fluctuating fuel prices, and the variability of renewable energy generation. To effectively address these uncertainties, more advanced optimization approaches are necessary.

Weber et al. [13] describes the optimization of district heating networks by integrating both operational and design aspects to minimize costs and improve energy efficiency. They introduce a mixed-integer linear programming (MILP) model that incorporates demand uncertainties and investment planning for infrastructure expansion. The results demonstrate significant cost savings and enhanced system flexibility, highlighting the importance of strategic planning in district heating networks.

Capone et al. [14] proposes a bi-level optimization framework combining a genetic algorithm for demand-side management with linear programming for production optimization, incorporating a physical model of the district heating network to account for thermal transients. The study considers both, cost minimization and $CO_2$ emissions reduction as objectives. Tran and Smith [15] integrates renewable energy sources, by considering uncertainty in

[2] The subsections 2.1, 2.1.1 and 2.1.2 were written in collaboration with Felix Bauer and appear identically in both of our master's theses.

energy demand and generation with a Monte Carlo approach to handle stochastic energy generation and consumption. In general, these optimizations have achieved significant cost reductions, while also substantially lowering $CO_2$ emissions.

### 2.1.2 Two-stage stochastic optimization

Two-stage stochastic optimization is a mathematical optimization method used for decision-making under uncertainty. In the first stage, strategic decisions are made. These long-term decisions give, for example, information about investment strategies. In the second stage, uncertainties like demand, market prices, and weather conditions are known. Based on the decisions of the first stage, the second stage is optimized. This method helps to make robust decisions by minimizing expected costs or risks in different scenarios.

Zhou et al. [16] developed a two-stage stochastic model for the optimal design of distributed energy systems under uncertainty of energy demand and supply. This model combines a genetic algorithm to optimize first-stage decisions and a Monte Carlo method to handle uncertainty in the second stage. It could be identified that the optimal solution under uncertainties does not differ much from the deterministic solution.

Schwarz et al. [17] focus on weather-related uncertainties in decentralized energy systems due to the expansion of renewable energy sources. Therefore a two-stage stochastic mixed-integer linear program (SMILP) is developed to optimize the investment and operation of a residential quarter's energy system. This paper proves, that thermal storage units are beneficial and reduce insufficient setup decisions.

Al-Lawati et al. [18] presents the challenge of decision-making for wind energy generators in energy markets. There, commitments must be made before accurate information on wind availability and market prices is available. All market options have to be considered, wherefore two decision-making frameworks for wind energy generators are implemented.A single-phase two-stage stochastic convex optimization model as well as a multi-phase two-stage stochastic model. The multi-phase approach increases the profit significantly in comparison to the single-phase.

Siddique et al. [19] analyzed dispatch strategies for large-scale heat pumps in a district heating system under a high share renewable of renewable energy sources by using a multistage stochastic optimization approach.

## 2.2 District heating and cooling supply

As explained in the problem formulation district heating and cooling grids are vital for decarbonization. In addition to ecological aspects, also ecnomic scalability is a key aspect. In densely populated areas a lot of customers can be supplied by a minimum of infrastructural costs. Wack et al. [20] stressed the importance of scalable district energy systems out. District heating and cooling systems developed a lot during the last decades. This evolution is characterized by Araner [21]. A graphical overview can be seen in Figure 2.1.

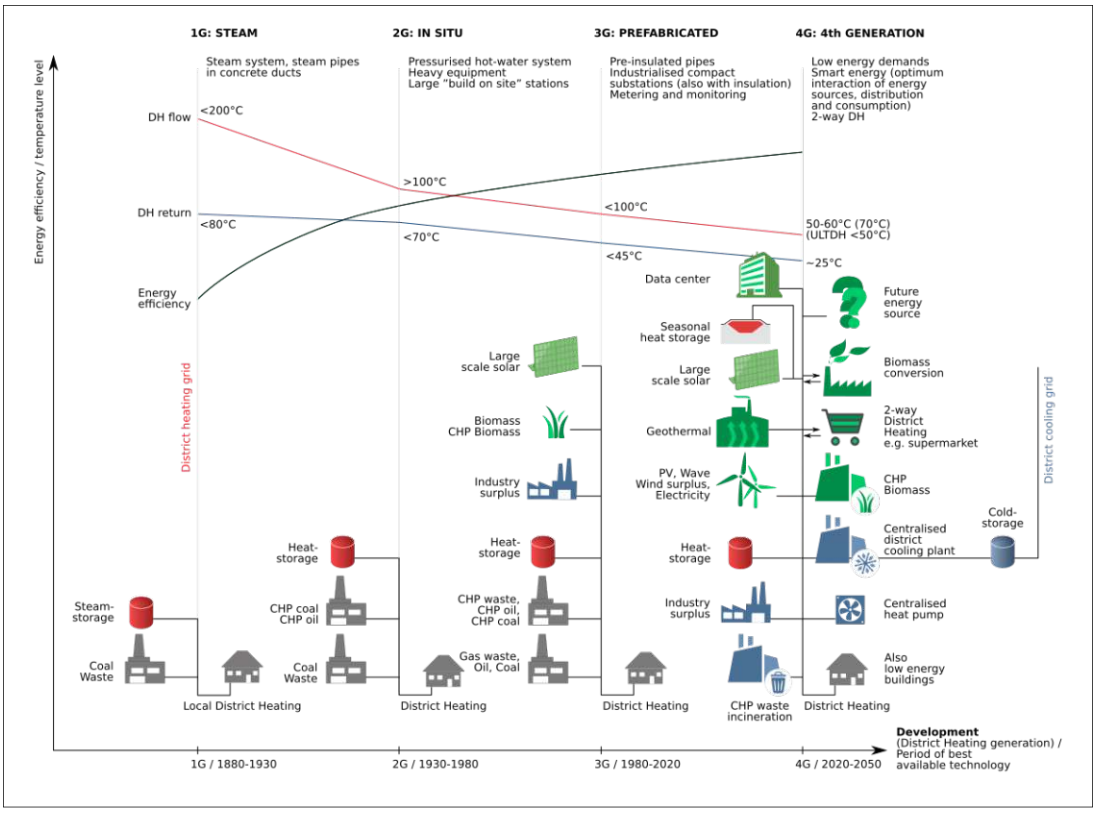


Figure 2.1: Evolution of district energy systems; Source: [22]

During the evolution of district energy systems, district heating supply and return temperatures continuously decreased, which leads to a higher system efficiency, as heat losses decline. On the other hand the distributed energy is reduced by lower operation temperatures. Throughout the evolution also the number of available technology options increased and a crossover between heating and cooling is possible. Also cold storages are intended, which leads to energy savings described by Anderson et al. [23].

## 2.3 Supply and storage technologies

In this section different heating, cooling and storage technologies are investigated. These technologies will be described by their functionality, key parameters and economic scalability. This knowledge is important, as the mathematical formulations of the model are based on this.

### 2.3.1 Heating generation

In total, eight heating generation technologies have been reviewed. Differences and similarities were elaborated by gathering the relevant literature.

#### Electric boiler (EB)

Electric boilers use electricity to generate thermal heat energy. This heating process is done with a high grade of efficiency. Soysal et al. [24] highlighted the advantages of electric boilers in district heating systems. Apart from their cheap upfront investment costs, they also offer a high flexibility potential, which is needed in times of demand peaks.

#### Heat pump (HP)

Heat pumps use electricity as well as electric boilers to provide thermal energy. In contrast to the electric boiler, heat pumps on the one hand require higher upfront investments, but on the ohter hand they are much more efficient during operation. The so-called coefficient of performance (COP) of an air-sourced heat pump depends on the outside temperature. Barco-Burgos et al. [25] focused on the integration of high-temperature heat pumps in district heating and cooling networks and noted that most common district energy systems are third and fourth generation.

#### Geothermal (GT)

Geothermal generation units are also electricity-based and use thermal energy from deep soil layers. In comparison to air-sourced heat pumps, the energy source temperatures are much more stable. This means a better predictable energy outcome for this technology. Mostly the energy medium has to be heated up by an external heat pump, which depends on the grid temperature. Aljubran and Horne [26] investigated the techno-economic feasibility and power supply potential of enhanced geothermal systems across the USA. Their results show a significant improvement in the use of geothermal technologies.

### Deep geothermal (DGT)

Deep geothermal does not require an additional heat pump, as the temperatures in deeper layers are already high enough to feed the energy directly into the grid. This technology is highly dependent on the location, as sufficient potential does not exist everywhere.

### Solar thermal (ST)

Solar thermal uses the energy from solar radiation, but the temperature is not high enough to feed it directly into the grid. For this reason an additional heat pump has to be used like for geothermal. Gao et al. [27] made an economic and environmental analysis of solar district heating system with a large heat storage.

### Industrial excess heat (IEH)

Fritz et al. [28] see industrial excess heat as an important factor in decarbonization, while Chinese et al. [29] focus on the economic perspective. This technology provides thermal energy by using "waste" heat from industrial processes. Moreover, it is a technology with low investment and operating costs. However, industrial excess heat is also very dependent on the location, as there must be enough factories near to the district energy system.

### Waste incineration (WI)

Waste incineration generates thermal energy by burning waste. However, electricity is also produced at the same time. Waste as fuel for the power plant causes only little costs compared to the upfront investments. Fruergaard et al. [30] assess the importance of waste incineration in district heating networks, where the obstacles of the correct assessment mechanism are emphasized. Moreover Vares et al. [31] highlighted the potential of waste incineration for reducing greenhouse gas emissions.

### Combined heat and power (CHP)

Gas-fired combined heat and power plants are quite common in district heating systems, as Klaassen and Patel [32] stressed out. But they exhaust a lot of carbon emissions during operation. Without $CO_2$ taxation, gas-fired power plants would be highly beneficial, as they have low investment and fuel costs. Like waste incineration, thermal energy and electricity are the outputs of this power plant.

### 2.3.2 Heating storage

Next to heating generation technologies, also a storage is important for designing district heating systems. Therefore, a storage was investigated to store thermal heat energy.

#### Tank thermal energy storage (TTES)

Tank thermal energy storages can be installed at any location. This is a great advantage compared to other thermal energy storages. The hot water tank can be either buried underground or built above. This storage type can be characterized by moderate investment costs dealing with higher losses compared to other storages, according to Mangold and Deschaintre, Pourahmadiyan et al. [33, 34]. Storages can be used to compensate peak demands and shifting energy generation from cost-intensive hours to cheap ones.

### 2.3.3 Cooling generation

Three types of cooling generation technologies have been researched, while two types can be equipped with different extensions. This means a total portfolio of five technologies, where three technologies operate in heating and cooling energy systems, which enables a linkage between both thermal energy grids.

#### Air chiller (AC)

Air chillers are a cheap option to provide cold energy. In addition, they can be easily installed at different locations, but are not the ideal option for large district cooling systems. Especially in dry regions, with less water reservoirs, this technology is a suitable option. Apart from that also maintenance costs are very low. Chan et al. [35] presents a model on how to design air-cooled chillers.

#### Absorption cooling machine (AB)

The absorption cooling machine, also known as absorption chiller, uses excess heat to generate cold energy. This is a suitable option if there is a heat surplus in the system on the one hand and a high cooling demand on the other hand. Absorption cooling machines have high upfront investment costs, which is also described by Chorowski et al. [36]. Based on this technology, two possible extensions are possible. The first one is by using a cooling tower to dissipate heat. Cooling towers are the cheaper extension option. Petersen et al. [37] also describe the option of heat recovery. There, the thermal energy is heated up by a heat pump and fed back into the district heating system.

#### Compression cooling machine (CP)

Compression cooling machines stand out by their high efficiency at moderate investment costs. This technology operates with mechanical compression to provide cold energy. Kadam et al. [38] focus on a modeling approach for compression chillers. In addition for the compression cooling machine the same two extensions, as for the absorber, are possible. Compression cooling machines with cooling tower can also be labeled as water-cooled chillers. Compression cooling machines equipped with heat pumps are also known as heat recovery chillers and make a crossover between district heating and cooling possible.

### 2.3.4 Cooling storage

As for heating also for cooling, a storage is analyzed based on scientific literature.

#### Ice thermal energy storage (ITES)

Generally, increased flexibility is provided by introducing storage options. Ice thermal energy storages work with the phase change of water from liquid to solid. The advantages are similar to those of tank thermal energy storages. Reduced thermal energy costs, balance of energy supply and demand and shift of peak loads have been identified by Altuntas and Erdemir [39].

# 3 Methodology

This chapter focuses on the methodology of the developed model. Therefore, a general graphical representation will be provided to give insight about the architecture of the district heating and district cooling system. Apart from that, the mathematical formulation of each technology and the associated parameters will be discussed. In addition to the implemented technologies, also the defined scenarios will be highlighted in this chapter.

The main task of the model is to supply all customers at any time with the required thermal energy demand. This thermal energy demand is based on heat and cold load profiles of customers on an hourly bases. To provide thermal energy, the model can choose between different technology options. For the district heating system a technology portfolio of eight different power plants, such as geothermal, solarthermal or industrial excess heat, is introduced. In the district cooling portfolio five additional technologies are defined, at which three technologies operate in both thermal energy grids. In each thermal energy grid, also a storage option is available. As there are energy price and demand fluctuations over time, this is a valuable option to increase the flexibility of the system. Next to the increased flexibility, also the economical aspect is important. With the additional storage option the model can shift energy from cost-intensive production hours to cheaper ones, which leads to a more economical system.

All investigated technologies can be found in Table 3.1. There, the technology names and the corresponding abbreviations, which are used in this thesis, are given. Apart from that, also the technology output heat (H), cold (C) or a combination of both (H & C) is visualized. The key parameter of the technology shows dependencies and limitations. Some of the technologies are not able to feed in at the supply temperature. Therefore, these technologies need additional equipment to match the temperature of the grid. In the heating sector additional heat pumps are installed and for the cooling sector additional air chillers are used. The final column represents, if an external temperature lift is needed (Yes = Y) or if the generation temperature is high enough (No = N).

Both storage types need a temperature lift as well. This is because of the declining temperature within the storage over time. To feed the energy back into the grid, the temperature must meet the grid temperature. As there are high energy prices, when the storage is discharged, the temperature lift must occur at the charging phase. For this reason, the energy to store is overheated for the TTES and undercooled for the ITES.

| Technology | Abbreviation | Output | Key parameter | TL[a)] |
|---|---|---|---|---|
| *Electric boiler* | EB | H | Highly driven by low or negative electricity prices | N |
| *Heat pump* | HP | H | COP is a function of the ambient outside temperature, varying in accordance with external climatic conditions | N |
| *Geothermal* | GT | H | Geothermal potential driven | Y |
| *Deep geothermal* | DGT | H | Deep geothermal potential driven | N |
| *Solar thermal* | ST | H | Strongly influenced by solar irradiance | Y |
| *Industrial excess heat* | IEH | H | Dependent on the generation profile of the waste heat plant | N |
| *Combined heat amd power* | CHP | H | Natrual gas and electricity price driven | N |
| *Waste incineration* | WI | H | Limitation of residents per area | N |
| *Air Chiller* | AC | C | EER is a function of the ambient outside temperature, varying in accordance with external climatic conditions | N |
| *Absorber + Cooling tower* | AB_CT | C | Dependent on the generation profile of the waste heat plant | N |
| *Absorber + Heat pump* | AB_HP | H & C | Dependent on the generation profile of the waste heat plant, simultaneous to heating and cooling demand | Y |
| *Compression + Cooling tower* | CP_CT | C | Driven by cooling demand | N |
| *Compression + Heat pump* | CP_HP | H & C | Simultaniously driven by both cooling and heating | Y |
| *Tank thermal energy storage* | TTES | H | Surplus energy in the grid or low electricity prices | Y |
| *Ice thermal energy storage* | ITES | C | Surplus energy in the grid or low electricity prices | Y |

Table 3.1: Overview of the heating and cooling technology portfolio

[a)] TL. . . Temperature lift in order to match source and supply temperatures.

In Figure 3.1 the schematic of the district heating (DH) and district cooling (DC) system is displayed. There the different technologies are visualized as rectangles. It can be seen, that most technologies only operate in one thermal energy grid and three can operate in both. The arrows indicate the flow direction of the thermal energy and the storages are represented as well. This also means, that the two storages TTES and ITES operate bidirectional, depending if they are in charging or discharging mode. At this point also some limitations of the developed model have to be stressed out. First of all, this thesis focuses on providing energy for the customers in suitable amounts, whereas the energy distribution is not considered. This leads to the fact that the grid infrastructure, like piplines and pumps, is not modeled. Therefore, the physical flow dynamics and the grid losses are not quantified in the result section. Furthermore, it has to be said that the technologies in the figure represent the sum of the technology branch and not a specific power plant.

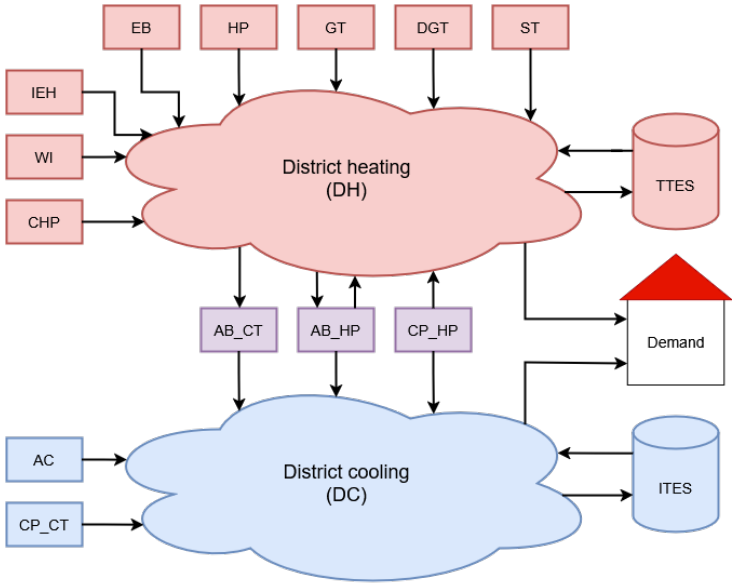


Figure 3.1: Schematic of the DH/DC architecture

In addition to the task of finding an investment strategy to cover demand at any time, there is also a second major issue that must be addressed. The developed model also has to detect the most cost-effective solution. To achieve this goal, a two-stage stochastic optimization model is developed. This model is able to find the most economical investment strategy by meeting the demand. This two-stage stochastic optimization model not only shows the best investment strategy over time, but also shows the dispatch of the different technologies. Moreover by considering different scenarios, the robustness of the solution is significantly increased.

The input data and the outputs are visualized schematically in Figure 3.2. Some input parameters are constant, like temperature levels of the grid and waste price, whereas the demand and electricity price change on an hourly bases. Additionally it has to be mentioned, that lifetimes of the technology investments are not considered, as the simulation horizon is only 26 years. Furthermore, also the run-up times during operation are not implemented in the model. There is also the limitation, that the demand always has to be met. Penalties for not supplying customers are no possible option.

The optimization model converges, based on the input parameters and constraints, towards a cost-optimal technology portfolio. Furthermore, it gives insight on the use of the technologies, by deriving the dispatch.

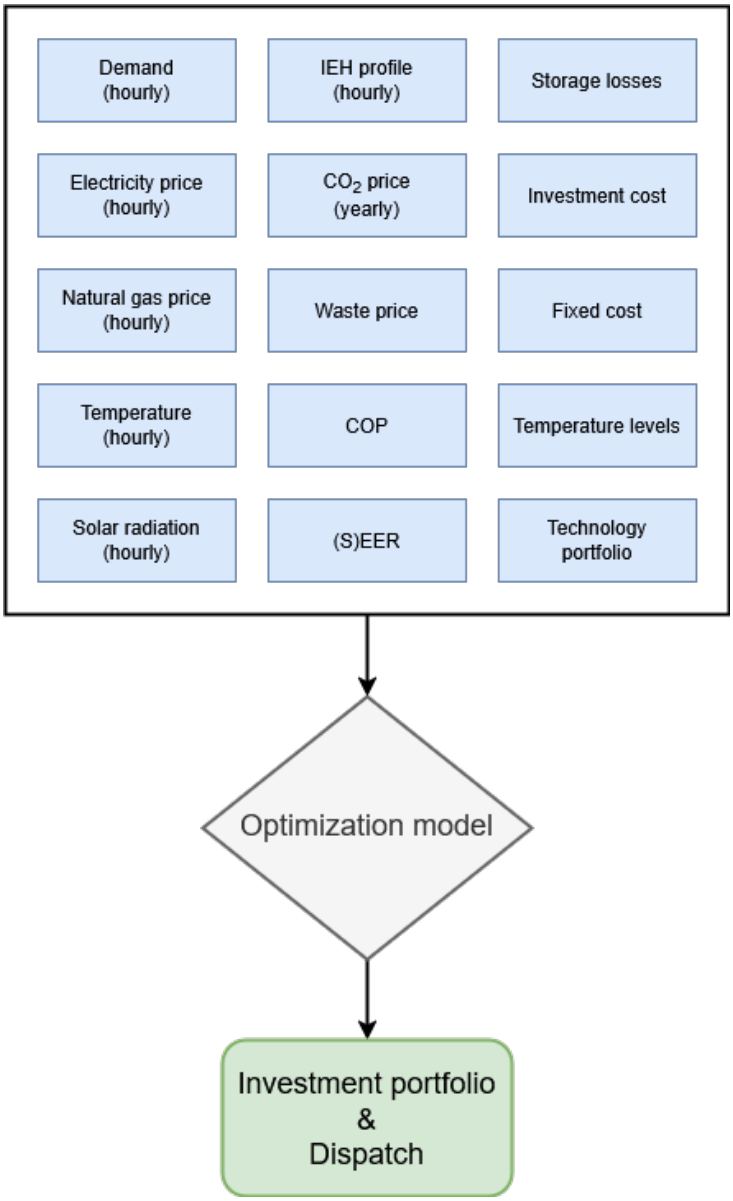


Figure 3.2: Schematic of the model workflow

The described model was developed in Python, by using Pyomo to implement the functionality of the model, where every fifth year, starting from 2025, is simulated. This is due to a reduction of computation time, as only minor changes occur within one year. All technologies are defined by constraints and their regarding efficiency and cost parameters. The mathematical formulation of the constraints can be found in the following section 3.1. The most important paramters will be discussed in section 3.2. Apart from that, also different scenarios are defined in section 3.3.

## 3.1 Mathematical formulation

In this chapter the mathematical formulation of the technology portfolios are presented. Furthermore, also the objective function and the demand balance constraints are introduced. The model is developed as two-stage optimization approach, which finds the optimal investment strategy as well as the dispatch of the invested technologies. The optimization problem is defined as cost-minimization and considers different external parameters. Energy prices for electricity and gas are used as well as the outside temperature and the solar radiation. Apart from that, also carbon emission costs are taken into account. The optimization model optimizes the heating and cooling side at the same time, as there are combined technologies between both grids. In Table 3.2 the convention of the upcoming mathematical descriptions are shown, just as indices and variable declarations.

| Type | Description | Unit |
|---|---|---|
| Sets and indices | | |
| $t \in \mathcal{T}$ | Set of technology, index by $t$ | |
| $s \in \mathcal{S}$ | Set of scenarios, index by $s$ | |
| $y \in \mathcal{Y}$ | Set of years, index by $y$ | |
| $h \in \mathcal{H}$ | Set of hours, index by $h$ | |
| Decision variables | | |
| $q^{sup,heat}_{t,s,y,h}$ | Heat energy feed in per technology, scenario, year and hour | MWh |
| $q^{\text{con, elec}}_{t,s,y,h}$ | Electricity input per technology, scenario, year and hour | MWh |
| $\bar{q}^{\text{cap}}_{t,y}$ | Installed technology capacity per technology and year | MW |
| $k^{sto,heat}_{t,s,y,h}$ | Storage capacity per technology, scenario, year and hour | MWh |
| $c^{\text{inv}}_{t,y}$ | Investment costs per technology and year | \$ |
| $c^{\text{fix}}_{t,y}$ | Fixed costs per technology and year | \$ |
| $c^{\text{var}}_{t,s,y,h}$ | Variable costs per technology, scenario, year and hour | \$ |
| $P^{elec}_{s,y,h}$ | Electricity price per scenario, year and hour | \$/MWh |
| Parameters | | |
| $COP^{HP}_{t}$ | Coefficient of performance of technology | |
| $EER_t$ | Energy efficiency ratio of technology | |
| $SEER_t$ | Seasonal energy efficiency ratio of technology | |
| $\lambda^{losses}_{t}$ | Energy losses of technology | |
| $\eta_t$ | Efficiency of technology | |

Table 3.2: Overview mathematical convention

### 3.1.1 Objective function

The target of the models's objective function is to minimize all occuring costs. Furthermore, also the two stages of the model can be seen in this equation. The first stage is strategic regarding to the investement strategy. Whereas, the second stage is operational to determine the dispatch based on the invested technology portfolio. This equation considers different scenarios, which is why a robust investment decision is made for all scenarios and only the dispatch differs.

$$\underset{x}{minimize} \sum_{t} \sum_{y} \left\{ \underbrace{\left(c_{t,y}^{inv} + c_{t,y}^{fix}\right)}_{\text{1st stage}} + \sum_{s} \sum_{h} \underbrace{p_s \times c_{t,s,y,h}^{var}}_{\text{2nd stage}} \right\} \tag{1}$$

### 3.1.2 Heating and cooling demands balance constraint

Next to the objective function, also the demand balance equations are mandatory. In equation (2) it is defined, that the sum of the generated thermal energy has to meet the demand. This is valid for both, heating and cooling. It also has to be mentioned, that the demand may vary between different scenarios.

$$\begin{aligned} \sum_{t} q_{t,s,y,h}^{sup,heat} &= q_{s,y,h}^{dem,heat} \quad &: \forall s, y, h \\ \sum_{t} q_{t,s,y,h}^{sup,cold} &= q_{s,y,h}^{dem,cold} \quad &: \forall s, y, h \end{aligned} \tag{2}$$

### 3.1.3 Heating supply constraints

In this section, the constraints of the eight heating generation technologies are formulated.

#### Electric boiler (EB)

The electric boiler is the first technology to be investigated. This technology uses electricity to convert energy into thermal energy. Furthermore, it is very cheap but not that efficient, in contrast to heat pumps.

In equation (3) the maximum capacity $\bar{q}_{eb,y}^{cap}$ of the technology is set by the maximum heat supplied $q_{eb,s,y,h}^{sup,heat}$. This is necessary to determine the new installed capacity and the corresponding investment costs.

$$q^{sup,heat}_{eb,s,y,h} \leq \bar{q}^{cap}_{eb,y} \quad : \forall s, y, h \tag{3}$$

In equation (4) the consumption of electricity $q^{con,elec}_{eb,s,y,h}$ is calculated by the efficiency of the electric boiler $\eta_{eb}$ and the thermal energy provided $q^{sup,heat}_{eb,s,y,h}$.

$$q^{sup,heat}_{eb,s,y,h} = \eta_{eb} \times q^{con,elec}_{eb,s,y,h} \quad : \forall s, y, h \tag{4}$$

The constraint in equation (5) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{eb,y}$.

$$\bar{q}^{cap}_{eb,y} = \begin{cases} \bar{q}^{cap}_{eb,y-1} + \Delta\bar{q}^{cap}_{eb,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{eb,y} & (\text{else}) \end{cases} \tag{5}$$

In equation (6) the newly installed capacity $\Delta\bar{q}^{cap}_{eb,y}$ is used to calculate the investment costs $c^{inv}_{eb,y}$ by the specific investment costs $C^{inv}_{eb,y}$.

$$c^{inv}_{eb,y} = C^{inv}_{eb,y} \times \Delta\bar{q}^{cap}_{eb,y} \quad : \forall y \tag{6}$$

Equation (7) calculates the fixed costs $c^{fix}_{eb,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{eb,y} = C^{fix}_{eb,y} \times \bar{q}^{cap}_{eb,y} \quad : \forall y \tag{7}$$

The last economic equation is represented by the constraint of the variable costs. In equation (8) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{eb,s,y,h}$.

$$c^{var}_{eb,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{eb,s,y,h} \quad : \forall s, y, h \tag{8}$$

### Heat pump (HP)

From a mathematical point of view, the heat pump is very similar to the electric boiler. This technology also converts electric energy into thermal energy. But in contrast to the electric boiler, the air-sourced heat pump is much more efficient at higher dedicated costs. The so-called coefficient of performance (COP) is dependent on the outside temperature, which changes hourly.

In equation (9) the maximum capacity $\bar{q}^{cap}_{hp,y}$ of the technology is set by the maximum heat supplied $q^{sup,heat}_{hp,s,y,h}$.

$$q^{sup,heat}_{hp,s,y,h} \leq \bar{q}^{cap}_{hp,y} \quad : \forall s, y, h \tag{9}$$

In equation (10) the consumption of electricity $q^{con,elec}_{hp,s,y,h}$ is calculated by the coefficient of performance of the heat pump $COP_{hp,y,h}$ and the thermal energy provided $q^{sup,heat}_{hp,s,y,h}$.

$$q^{sup,heat}_{hp,s,y,h} = COP_{hp,y,h} \times q^{con,elec}_{hp,s,y,h} \quad : \forall s, y, h \tag{10}$$

The constraint in equation (11) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{hp,y}$.

$$\bar{q}^{cap}_{hp,y} = \begin{cases} \bar{q}^{cap}_{hp,y-1} + \Delta\bar{q}^{cap}_{hp,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{hp,y} & (\text{else}) \end{cases} \tag{11}$$

In equation (12) the newly installed capacity $\Delta\bar{q}^{cap}_{hp,y}$ is used to calculate the investment costs $c^{inv}_{hp,y}$ by the specific investment costs $C^{inv}_{hp,y}$.

$$c^{inv}_{hp,y} = C^{inv}_{hp,y} \times \Delta\bar{q}^{cap}_{hp,y} \quad : \forall y \tag{12}$$

Equation (13) calculates the fixed costs $c^{fix}_{hp,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{hp,y} = C^{fix}_{hp,y} \times \bar{q}^{cap}_{hp,y} \quad : \forall y \tag{13}$$

In equation (14) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{hp,s,y,h}$.

$$c^{var}_{hp,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{hp,s,y,h} \quad : \forall s, y, h \tag{14}$$

### Geothermal (GT)

In addition, geothermal energy generation is key technology for a sustainable energy supply. This technology uses thermal energy from the soil, which means a more stable temperature compared to the air-sourced heat pump. The temperature is still not high enough to feed it directly into the grid, which is why the increase in temperature is performed by an external heat pump.

In equation (15) the maximum capacity $\bar{q}^{cap}_{gt,y}$ of the technology is set by the maximum heat supplied $q^{sup,heat}_{gt,s,y,h}$.

$$q^{sup,heat}_{gt,s,y,h} \leq \bar{q}^{cap}_{gt,y} \quad : \forall s, y, h \tag{15}$$

In equation (16) the consumption of electricity $q^{con,elec}_{gt,s,y,h}$ is calculated by the coefficient of performance of the additional heat pump $COP^{hp}_{gt}$ and the thermal energy provided $q^{sup,heat}_{gt,s,y,h}$. The COP does not change on an hourly bases, instead it is set to an average value as the ground temperature varies little.

$$q^{sup,heat}_{gt,s,y,h} = COP^{hp}_{gt} \times q^{con,elec}_{gt,s,y,h} \quad : \forall s, y, h \tag{16}$$

The constraint in equation (17) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{gt,y}$.

$$\bar{q}^{cap}_{gt,y} = \begin{cases} \bar{q}^{cap}_{gt,y-1} + \Delta\bar{q}^{cap}_{gt,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{gt,y} & (\text{else}) \end{cases} \tag{17}$$

In equation (18) the newly installed capacity $\Delta\bar{q}^{cap}_{gt,y}$ is used to calculate the investment costs $c^{inv}_{gt,y}$ by the specific investment costs of geothermal $C^{inv}_{gt,y}$ and the additional heat pump $C^{inv}_{hp,y}$.

$$c^{inv}_{gt,y} = \left(C^{inv}_{gt,y} + C^{inv}_{hp,y}\right) \times \Delta\bar{q}^{cap}_{gt,y} \quad : \forall y \tag{18}$$

Equation (19) calculates the fixed costs $c^{fix}_{gt,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{gt,y} = C^{fix}_{gt,y} \times \bar{q}^{cap}_{gt,y} \quad : \forall y \tag{19}$$

In equation (20) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{gt,s,y,h}$.

$$c^{var}_{gt,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{gt,s,y,h} \quad : \forall s, y, h \tag{20}$$

### Deep geothermal (DGT)

Apart from classic geothermal generation units at a depth of a few hundred meters, deep geothermal generation is also considered, operating at depths of several kilometers. This technology uses thermal energy from the soil as well, but the extracted energy is already at the temperature level of the district heating grid. Therefore, no additional heat pump is needed.

In equation (21) the maximum capacity $\bar{q}^{cap}_{dgt,y}$ of the technology is set by the maximum heat supplied $q^{sup,heat}_{dgt,s,y,h}$.

$$q^{sup,heat}_{dgt,s,y,h} \leq \bar{q}^{cap}_{dgt,y} \quad : \forall s, y, h \tag{21}$$

In equation (22) the consumption of electricity $q^{con,elec}_{dgt,s,y,h}$ is calculated. Here the electricity is only needed for running the pumping equipment, where the corresponding share is necessary $f^{share,elec}_{dgt}$.

$$q^{sup,heat}_{dgt,s,y,h} = f^{share,elec}_{dgt} \times q^{con,elec}_{dgt,s,y,h} \quad : \forall s, y, h \tag{22}$$

The constraint in equation (23) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{dgt,y}$.

$$\bar{q}^{cap}_{dgt,y} = \begin{cases} \bar{q}^{cap}_{dgt,y-1} + \Delta\bar{q}^{cap}_{dgt,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{dgt,y} & (\text{else}) \end{cases} \tag{23}$$

In equation (24) the newly installed capacity $\Delta\bar{q}^{cap}_{dgt,y}$ is used to calculate the investment costs $c^{inv}_{dgt,y}$ by the specific investment costs $C^{inv}_{dgt,y}$.

$$c^{inv}_{dgt,y} = C^{inv}_{dgt,y} \times \Delta\bar{q}^{cap}_{dgt,y} \quad : \forall y \tag{24}$$

Equation (25) calculates the fixed costs $c^{fix}_{dgt,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{dgt,y} = C^{fix}_{dgt,y} \times \bar{q}^{cap}_{dgt,y} \quad : \forall y \tag{25}$$

In equation (26) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{dgt,s,y,h}$.

$$c^{var}_{dgt,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{dgt,s,y,h} \quad : \forall s, y, h \tag{26}$$

### Solar thermal (ST)

Next to extracting energy from the soil, energy can also be converted from solar radiation. But here, also an additional heat pump has to be installed, to lift the temperature. This renewable form of energy generation is only available, when enough solar radition is transmitted during the day.

In equation (27) the maximum capacity $\bar{q}^{cap}_{st,y}$ of the technology is set by the maximum heat supplied $q^{sup,heat}_{st,s,y,h}$.

$$q^{sup,heat}_{st,s,y,h} \leq \bar{q}^{cap}_{st,y} \quad : \forall s, y, h \tag{27}$$

In equation (28) the solar radiation profile $p^{radiation}_{st,y,h}$ is used together with the efficiency $\eta_{st}$ of the solar thermal generation unit to identify the hourly energy output of this technology.

$$q^{sup,heat}_{st,s,y,h} = p^{radiation}_{st,y,h} \times \eta_{st} \quad : \forall s, y, h \tag{28}$$

In equation (29) the consumption of electricity $q^{con,elec}_{st,s,y,h}$ is calculated by the coefficient of performance of the additional heat pump $COP^{hp}_{st}$ and the thermal energy provided $q^{sup,heat}_{st,s,y,h}$. The COP does not change on an hourly bases, instead it is set to an average value as the solar radiation temperature varies little.

$$q^{sup,heat}_{st,s,y,h} = COP^{hp}_{st} \times q^{con,elec}_{st,s,y,h} \quad : \forall s, y, h \tag{29}$$

The constraint in equation (30) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{st,y}$.

$$\bar{q}^{cap}_{st,y} = \begin{cases} \bar{q}^{cap}_{st,y-1} + \Delta\bar{q}^{cap}_{st,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{st,y} & (\text{else}) \end{cases} \tag{30}$$

In equation (31) the newly installed capacity $\Delta\bar{q}^{cap}_{st,y}$ is used to calculate the investment costs $c^{inv}_{st,y}$ by the specific investment costs of solar thermal $C^{inv}_{st,y}$ and the additional heat pump $C^{inv}_{hp,y}$.

$$c^{inv}_{st,y} = \left(C^{inv}_{st,y} + C^{inv}_{hp,y}\right) \times \Delta\bar{q}^{cap}_{st,y} \quad : \forall y \tag{31}$$

Equation (32) calculates the fixed costs $c^{fix}_{st,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{st,y} = C^{fix}_{st,y} \times \bar{q}^{cap}_{st,y} \quad : \forall y \tag{32}$$

In equation (33) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{st,s,y,h}$.

$$c^{var}_{st,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{st,s,y,h} \quad : \forall s, y, h \tag{33}$$

### Industrial excess heat (IEH)

Another possibility of supplying customers with thermal energy is the use of industrial excess heat. There, different industrial factories provide and sell excess heat of their processes. It is assumed, that the temperature of the excess heat is high enough to feed the heat directly into the grid, which means that no additional heat pump is needed to increase the temperature.

In equation (34) the maximum capacity $\bar{q}^{cap}_{ieh,y}$ of the technology is set by the maximum heat supplied $q^{sup,heat}_{ieh,s,y,h}$.

$$q^{sup,heat}_{ieh,s,y,h} \leq \bar{q}^{cap}_{ieh,y} \quad : \forall s, y, h \tag{34}$$

In equation (35) the industrial excess heat profile $p^{radiation}_{ieh,y,h}$ is used to limit the supply of this technology.

$$q^{sup,heat}_{ieh,s,y,h} \leq p^{in}_{ieh,y,h} \quad : \forall s, y, h \tag{35}$$

In equation (36) the electricity consumption $^{con,elec}_{ieh,s,y,h}$ is calculated by the electricity share $f^{share,elec}_{ieh}$ and the thermal energy provided $q^{sup,heat}_{ieh,s,y,h}$.

$$q^{sup,heat}_{ieh,s,y,h} = \frac{^{con,elec}_{ieh,s,y,h}}{f^{share,elec}_{ieh}} \quad : \forall s, y, h \tag{36}$$

The constraint in equation (37) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{ieh,y}$.

$$\bar{q}^{cap}_{ieh,y} = \begin{cases} \bar{q}^{cap}_{ieh,y-1} + \Delta\bar{q}^{cap}_{ieh,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{ieh,y} & (\text{else}) \end{cases} \tag{37}$$

In equation (38) the newly installed capacity $\Delta\bar{q}^{cap}_{ieh,y}$ is used to calculate the investment costs $c^{inv}_{ieh,y}$ by the specific investment costs $C^{inv}_{ieh,y}$.

$$c^{inv}_{ieh,y} = C^{inv}_{ieh,y} \times \Delta\bar{q}^{cap}_{ieh,y} \quad : \forall y \tag{38}$$

Equation (39) calculates the fixed costs $c^{fix}_{ieh,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{ieh,y} = C^{fix}_{ieh,y} \times \bar{q}^{cap}_{ieh,y} \quad : \forall y \tag{39}$$

In equation (40) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{ieh,s,y,h}$ and the costs for the industrial excess heat.

$$c^{var}_{ieh,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{ieh,s,y,h} + P^{heat}_{ieh} \times q^{sup,heat}_{ieh,s,y,h} \quad : \forall s, y, h \tag{40}$$

### Waste incineration (WI)

The next investigated technology is waste incineration. This technology does not only generate thermal energy, but also electricity which has to be considered. The output heat is also high enough, so that an additional heat pump is not necessary.

In equation (41) the maximum capacity $\bar{q}^{cap}_{wi,y}$ of the technology is set by the sum of the maximum heat $q^{sup,heat}_{wi,s,y,h}$ and electricity supplied $q^{sup,elec}_{wi,s,y,h}$.

$$q^{sup,heat}_{wi,s,y,h} + q^{sup,elec}_{wi,s,y,h} \leq \bar{q}^{cap}_{wi,y} \quad : \forall s, y, h \tag{41}$$

In equation (42) the waste amount $q^{con,waste}_{wi,s,y,h}$ is used together with the efficiency $\eta_{wi}$ of the waste incineration unit, calorific value of waste $h^{waste}_{wi}$ and heat share $f^{share,heat}_{wi}$ to identify the hourly heat output of this technology.

$$q^{sup,heat}_{wi,s,y,h} = q^{con,waste}_{wi,s,y,h} \times \eta_{wi} \times h^{waste}_{wi} \times f^{share,heat}_{wi} \quad : \forall s, y, h \tag{42}$$

In equation (43) the waste amount $q^{con,waste}_{wi,s,y,h}$ is used together with the efficiency $\eta_{wi}$ of the waste incineration unit, calorific value of waste $h^{waste}_{wi}$ and heat share $f^{share,elec}_{wi}$ to identify the hourly electricity output of this technology.

$$q^{sup,elec}_{wi,s,y,h} = q^{con,waste}_{wi,s,y,h} \times \eta_{wi} \times h^{waste}_{wi} \times f^{share,elec}_{wi} \quad : \forall s, y, h \tag{43}$$

The constraint in equation (44) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{wi,y}$.

$$\bar{q}^{cap}_{wi,y} = \begin{cases} \bar{q}^{cap}_{wi,y-1} + \Delta\bar{q}^{cap}_{wi,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{wi,y} & (\text{else}) \end{cases} \tag{44}$$

In equation (45) the newly installed capacity $\Delta\bar{q}^{cap}_{wi,y}$ is used to calculate the investment costs $c^{inv}_{wi,y}$ by the specific investment costs $C^{inv}_{wi,y}$.

$$c^{inv}_{wi,y} = C^{inv}_{wi,y} \times \Delta\bar{q}^{cap}_{wi,y} \quad : \forall y \tag{45}$$

Equation (46) calculates the fixed costs $c^{fix}_{wi,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{wi,y} = C^{fix}_{wi,y} \times \bar{q}^{cap}_{wi,y} \quad : \forall y \tag{46}$$

In equation (47) the variable costs are calculated by the waste price $P^{waste}_{wi}$ times the waste consumption $q^{con,waste}_{ieh,s,y,h}$ and the costs for the produced carbon emissions. The achieved revenue for selling electricity has to be substracted from the costs.

$$
\begin{aligned}
c^{var}_{wi,s,y,h} = & P^{waste}_{wi} \times q^{con,waste}_{wi,s,y,h} \\
& + q^{con,waste}_{wi,s,y,h} \times C^{CO_2}_{s,y} \times f^{share,CO_2}_{wi} \quad : \forall s, y, h \\
& - q^{sup,elec}_{wi,s,y,h} \times P^{elec}_{s,y,h}
\end{aligned} \tag{47}
$$

### Combined heat and power (CHP)

Combined heat and power plants also generate thermal energy and electricity simultaneously. A temperature lift is not needed for this technology, as the heat can be fed directly into the grid.

In equation (48) the maximum capacity $\bar{q}^{cap}_{chp,y}$ of the technology is set by the sum of the maximum heat $q^{sup,heat}_{chp,s,y,h}$ and electricity supplied $q^{sup,elec}_{chp,s,y,h}$.

$$
q^{sup,heat}_{chp,s,y,h} + q^{sup,elec}_{chp,s,y,h} \leq \bar{q}^{cap}_{chp,y} \quad : \forall s, y, h \tag{48}
$$

In equation (49) the gas amount $q^{gas}_{chp,s,y,h}$ is used together with the efficiency $\eta_{chp}$ of the combined heat and power plant as well as the heat share $f^{share,heat}_{chp}$ to identify the hourly heat energy output from this technology.

$$
q^{sup,heat}_{chp,s,y,h} = q^{gas}_{chp,s,y,h} \times \eta_{chp} \times f^{share,heat}_{chp} \quad : \forall s, y, h \tag{49}
$$

In equation (50) the gas amount $q^{con,gas}_{chp,s,y,h}$ is used together with the efficiency $\eta_{chp}$ of the combined heat and power plant as well as the electricity share $f^{share,elec}_{chp}$ to identify the hourly electricity output from this technology.

$$
q^{sup,elec}_{chp,s,y,h} = q^{con,gas}_{chp,s,y,h} \times \eta_{chp} \times f^{share,elec}_{chp} \quad : \forall s, y, h \tag{50}
$$

The constraint in equation (51) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{chp,y}$.

$$\bar{q}^{cap}_{chp,y} = \begin{cases} \bar{q}^{cap}_{chp,y-1} + \Delta\bar{q}^{cap}_{chp,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{chp,y} & (\text{else}) \end{cases} \tag{51}$$

In equation (52) the newly installed capacity $\Delta\bar{q}^{cap}_{chp,y}$ is used to calculate the investment costs $c^{inv}_{chp,y}$ by the specific investment costs $C^{inv}_{chp,y}$.

$$c^{inv}_{chp,y} = C^{inv}_{chp,y} \times \Delta\bar{q}^{cap}_{chp,y} \quad : \forall y \tag{52}$$

Equation (53) calculates the fixed costs $c^{fix}_{chp,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{chp,y} = C^{fix}_{chp,y} \times \bar{q}^{cap}_{chp,y} \quad : \forall y \tag{53}$$

In equation (54) the variable costs are calculated by the gas price $P^{gas}_{s,y,h}$ times the gas consumption $q^{con,gas}_{chp,s,y,h}$ and the costs for the produced carbon emissions. The achieved revenue for selling electricity has to be substracted from the costs.

$$\begin{aligned} c^{var}_{chp,s,y,h} = {} & P^{gas}_{chp,s,y,h} \times q^{con,gas}_{chp,s,y,h} \\ & + \frac{q^{con,gas}_{chp,s,y,h}}{h^{gas}_{chp}} \times C^{CO_2}_{s,y} \times f^{share,CO_2}_{chp} \quad : \forall s, y, h \\ & - q^{sup,elec}_{chp,s,y,h} \times P^{elec}_{s,y,h} \end{aligned} \tag{54}$$

### 3.1.4 Heating storage constraints

This section shows the mathematical approach of formulating a simplified thermal energy storage.

#### Tank thermal energy storage (TTES)

To increase the flexibility of the model storages are important. This component makes it possible to shift energy from expensive production hours to cheap ones. Therefore a heat pump is needed to overheat the thermal energy, so that it can be directly fed back into the grid. In the district heating system a tank thermal energy storage is available in the

portfolio. The tank thermal energy storage is a bidirectional element, which means that the energy flow turns during operation.

In equation (55) the maximum storage capacity of the heat pump $\bar{q}^{cap}_{ttes,y}$ is set by the maximum heat stored $q^{sto,heat}_{ttes,s,y,h}$.

$$q^{sto,heat}_{ttes,s,y,h} \leq \bar{q}^{cap}_{ttes,y} \quad : \forall s, y, h \tag{55}$$

In equation (56) the maximum capacity $\bar{q}^{cap}_{ttes,y}$ of the storage is set by the maximum state of charge $k^{sto,heat}_{ttes,s,y,h}$.

$$k^{sto,heat}_{ttes,s,y,h} \leq \bar{k}^{cap}_{ttes,y} \quad : \forall s, y, h \tag{56}$$

The so-called state of charge $k^{sto,heat}_{ttes,s,y,h}$ is modeled in equation (57). It is set to an initial state based on a factor. During operation the state of charge is dependent on the previous state considering losses as well as the charged and discharged energy considering the efficiency.

$$k^{sto,heat}_{ttes,s,y,h} = \begin{cases} \bar{k}^{cap}_{ttes,y-1} \times \lambda^{losses}_{ttes} + \\ q^{sto,heat}_{ttes,s,y,h} \times \eta_{ttes} - \\ \frac{q^{sup,heat}_{ttes,s,y,h}}{\eta_{ttes}} \end{cases} \quad : \forall s, y, h \quad (\text{if } y \neq y_0)$$
$$\bar{k}^{cap}_{ttes,y_0} \times f^{init}_{ttes} \qquad (\text{else}) \tag{57}$$

In equation (58) the consumption of electricity $q^{con,elec}_{ttes,s,y,h}$ is calculated by the coefficient of performance of the additional heat pump $COP^{hp}_{ttes}$ and the thermal energy stored $q^{sup,heat}_{ttes,s,y,h}$. The COP does not change on an hourly bases, instead it is set to an average value as the grid temperature varies little.

$$q^{sto,heat}_{ttes,s,y,h} = q^{con,elec}_{ttes,s,y,h} \times COP^{hp}_{ttes} \quad : \forall s, y, h \tag{58}$$

The constraint in equation (59) defines the capacity expansion of the heat pump, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{ttes,y}$.

$$\bar{q}^{cap}_{ttes,y} = \begin{cases} \bar{q}^{cap}_{ttes,y-1} + \Delta\bar{q}^{cap}_{ttes,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{ttes,y} & (\text{else}) \end{cases} \tag{59}$$

The constraint in equation (60) defines the storage capacity expansion, by adding the newly installed capacity $\Delta\bar{k}^{cap}_{ttes,y}$.

$$\bar{k}^{cap}_{ttes,y} = \begin{cases} \bar{k}^{cap}_{ttes,y-1} + \Delta\bar{k}^{cap}_{ttes,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{k}^{cap}_{ttes,y} & (\text{else}) \end{cases} \tag{60}$$

In equation (61) the newly installed capacity $\Delta\bar{k}^{cap}_{ttes,y}$ is used to calculate the investment costs $c^{inv}_{ttes,y}$ by the specific investment costs of the storage $C^{inv}_{ttes,y}$ and the additional heat pump $C^{inv}_{hp,y}$.

$$c^{inv}_{ttes,y} = C^{inv}_{hp,y} \times \Delta\bar{q}^{cap}_{ttes,y} + C^{inv}_{ttes,y} \times \Delta\bar{k}^{cap}_{ttes,y} \quad : \forall y \tag{61}$$

Equation (62) calculates the fixed costs $c^{fix}_{ttes,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{ttes,y} = C^{fix}_{ttes,y} \times \bar{q}^{cap}_{ttes,y} \quad : \forall y \tag{62}$$

In equation (63) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the electricity consumption $q^{con,elec}_{ttes,s,y,h}$ and the charging/discharging costs.

$$c^{var}_{ttes,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{ttes,s,y,h} + (q^{sup,heat}_{ttes,s,y,h} + q^{sto,heat}_{ttes,s,y,h}) \times C^{cha,dis}_{ttes} \quad : \forall s, y, h \tag{63}$$

### 3.1.5 Cooling supply constraints

In total, five cooling technologies have been investigated, while three technologies operate in heating and cooling grids at the same time.

### Air chiller (AC)

The air chiller is the first cooling technology, which is defined and is the counterpart of the heat pump. This technology uses electricity to convert it into cold energy.

In equation (64) the maximum capacity $\bar{q}^{cap}_{ac,y}$ of the technology is set by the maximum cold supplied $q^{sup,cold}_{ac,s,y,h}$.

$$q^{sup,cold}_{ac,s,y,h} \leq \bar{q}^{cap}_{ac,y} \quad : \forall s, y, h \tag{64}$$

In equation (65) the consumption of electricity $q^{con,elec}_{ac,s,y,h}$ is calculated by the energy efficiency ratio of the air chiller $EER_{ac,y,h}$ and the thermal energy provided $q^{sup,cold}_{ac,s,y,h}$.

$$q^{sup,cold}_{ac,s,y,h} = EER_{ac,y,h} \times q^{con,elec}_{ac,s,y,h} \quad : \forall s, y, h \tag{65}$$

The constraint in equation (66) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{ac,y}$.

$$\bar{q}^{cap}_{ac,y} = \begin{cases} \bar{q}^{cap}_{ac,y-1} + \Delta\bar{q}^{cap}_{ac,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{ac,y} & (\text{else}) \end{cases} \tag{66}$$

In equation (67) the newly installed capacity $\Delta\bar{q}^{cap}_{ac,y}$ is used to calculate the investment costs $c^{inv}_{ac,y}$ by the specific investment costs $C^{inv}_{ac,y}$.

$$c^{inv}_{ac,y} = C^{inv}_{ac,y} \times \Delta\bar{q}^{cap}_{ac,y} \quad : \forall y \tag{67}$$

Equation (68) calculates the fixed costs $c^{fix}_{ac,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{ac,y} = C^{fix}_{ac,y} \times \bar{q}^{cap}_{ac,y} \quad : \forall y \tag{68}$$

In equation (69) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{ac,s,y,h}$.

$$c^{var}_{ac,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{ac,s,y,h} \quad : \forall s, y, h \tag{69}$$

### Absorption cooling machine with cooling tower (AB_CT)

The absorption cooling machine operates in the district heating and cooling grid. This generation unit uses cheap heat and converts it into cold. Here, the remaining heat is dissipated via a cooling tower.

In equation (70) the maximum capacity $\bar{q}^{cap}_{ab\_ct,y}$ of the technology is set by the maximum cold supplied $q^{sup,cold}_{ab\_ct,s,y,h}$.

$$q^{sup,cold}_{ab\_ct,s,y,h} \leq \bar{q}^{cap}_{ab\_ct,y} \quad : \forall s, y, h \tag{70}$$

Equation (71) calculates the thermal cold energy provided $q^{sup,cold}_{ab\_ct,s,y,h}$ as multiplication between the energy efficiency ratio of the absorber $EER_{ab}$ and the extracted heat energy $q^{ext,heat}_{ab\_ct,s,y,h}$.

$$q^{sup,cold}_{ab\_ct,s,y,h} = EER_{ab} \times q^{ext,heat}_{ab\_ct,s,y,h} \quad : \forall s, y, h \tag{71}$$

In equation (72) the consumption of electricity $q^{con,elec}_{ab\_ct,s,y,h}$ is calculated by the thermal heat energy extracted $q^{ext,heat}_{ab\_ct,s,y,h}$, the thermal cold energy provided $q^{sup,cold}_{ab\_ct,s,y,h}$ and the corresponding factors.

$$q^{con,elec}_{ab\_ct,s,y,h} = q^{ext,heat}_{ab\_ct,s,y,h} \times f^{share,heat}_{ab\_ct} + q^{sup,cold}_{ab\_ct,s,y,h} \times f^{share,cold}_{ab\_ct} \quad : \forall s, y, h \tag{72}$$

The constraint in equation (73) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{ab\_ct,y}$.

$$\bar{q}^{cap}_{ab\_ct,y} = \begin{cases} \bar{q}^{cap}_{ab\_ct,y-1} + \Delta\bar{q}^{cap}_{ab\_ct,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{ab\_ct,y} & (\text{else}) \end{cases} \tag{73}$$

In equation (74) the newly installed capacity $\Delta\bar{q}^{cap}_{ab\_ct,y}$ is used to calculate the investment costs $c^{inv}_{ab\_ct,y}$ by the specific investment costs of the absorber $C^{inv}_{ab,y}$ and the cooling tower $C^{inv}_{ct,y}$.

$$c^{inv}_{ab\_ct,y} = \left(C^{inv}_{ab,y} + C^{inv}_{ct,y} \times \left(1 + \frac{1}{EER_{ab}}\right)\right) \times \Delta\bar{q}^{cap}_{ab\_ct,y} \quad : \forall y \tag{74}$$

Equation (75) calculates the fixed costs $c^{fix}_{ab\_ct,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{ab\_ct,y} = C^{fix}_{ab\_ct,y} \times \bar{q}^{cap}_{ab\_ct,y} \quad : \forall y \tag{75}$$

In equation (76) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{ab\_ct,s,y,h}$.

$$c^{var}_{ab\_ct,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{ab\_ct,s,y,h} \quad : \forall s, y, h \tag{76}$$

### Absorption cooling machine with heat pump (AB_HP)

The difference to this technology type is the way, how heat is dissipated. Here, the heat is recovered with an additional heat pump and fed back into the district heating grid.

In equation (77) the maximum capacity $\bar{q}^{cap}_{ab\_hp,y}$ of the technology is set by the maximum cold supplied $q^{sup,cold}_{ab\_hp,s,y,h}$.

$$q^{sup,cold}_{ab\_hp,s,y,h} \leq \bar{q}^{cap}_{ab\_hp,y} \quad : \forall s, y, h \tag{77}$$

Equation (78) calculates the thermal cold energy provided $q^{sup,cold}_{ab\_hp,s,y,h}$ as multiplication between the energy efficiency ratio of the absorber $EER_{ab}$ and the extracted heat energy $q^{ext,heat}_{ab\_hp,s,y,h}$.

$$q^{sup,cold}_{ab\_hp,s,y,h} = EER_{ab} \times q^{ext,heat}_{ab\_hp,s,y,h} \quad : \forall s, y, h \tag{78}$$

In equation (79) the consumption of electricity $q^{con,elec}_{ab,s,y,h}$ is calculated by the thermal heat energy provided $q^{ext,heat}_{ab\_hp,s,y,h}$, the thermal cold energy provided $q^{sup,cold}_{ab\_hp,s,y,h}$, the coefficient of performance $COP^{hp}_{ab}$ and the corresponding factors.

$$q^{con,elec}_{ab\_hp,s,y,h} = q^{ext,heat}_{ab\_hp,s,y,h} \times f^{share,heat}_{ab\_ct} + \frac{q^{ext,heat}_{ab\_hp,s,y,h} + q^{sup,cold}_{ab\_hp,s,y,h}}{COP^{hp}_{ab}} \quad : \forall s, y, h \tag{79}$$

The constraint in equation (80) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{ab\_hp,y}$.

$$\bar{q}^{cap}_{ab\_hp,y} = \begin{cases} \bar{q}^{cap}_{ab\_hp,y-1} + \Delta\bar{q}^{cap}_{ab\_hp,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{ab\_hp,y} & (\text{else}) \end{cases} \tag{80}$$

In equation (81) the newly installed capacity $\Delta\bar{q}^{cap}_{ab\_hp,y}$ is used to calculate the investment costs $c^{inv}_{ab\_hp,y}$ by the specific investment costs of the absorber $C^{inv}_{ab,y}$ and the heat pump $C^{inv}_{hp,y}$.

$$c^{inv}_{ab\_hp,y} = \left(C^{inv}_{ab,y} + C^{inv}_{hp,y} \times \left(1 + \frac{1}{EER_{ab}}\right)\right) \times \Delta\bar{q}^{cap}_{ab\_hp,y} \quad : \forall y \tag{81}$$

Equation (82) calculates the fixed costs $c^{fix}_{ab\_hp,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{ab\_hp,y} = C^{fix}_{ab\_hp,y} \times \bar{q}^{cap}_{ab\_hp,y} \quad : \forall y \tag{82}$$

In equation (83) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{ab\_hp,s,y,h}$.

$$c^{var}_{ab\_hp,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{ab\_hp,s,y,h} \quad : \forall s, y, h \tag{83}$$

#### Compression cooling machine with cooling tower (CP_CT)

The compression cooling machine operates only in the district cooling system, like the air chiller. This generation unit uses electricity and converts it to cold by a mechani-

cal compression process. The remaining heat of the process is exhausted via a cooling tower.

In equation (84) the maximum capacity $\bar{q}^{cap}_{cp\_ct,y}$ of the technology is set by the maximum cold supplied $q^{sup,cold}_{cp\_ct,s,y,h}$.

$$q^{sup,cool}_{cp\_ct,s,y,h} \leq \bar{q}^{cap}_{cp\_ct,y} \quad : \forall s, y, h \tag{84}$$

In equation (85) the consumption of electricity $q^{con,elec}_{cp\_ct,s,y,h}$ is calculated by the thermal cold energy provided $q^{sup,cold}_{cp\_ct,s,y,h}$, the seasonal energy efficiency ratio of the compressor $SEER_{cp}$ and the corresponding factors.

$$q^{con,elec}_{cp\_ct,s,y,h} = \frac{q^{sup,cold}_{cp\_ct,s,y,h}}{SEER_{cp}} + q^{sup,cold}_{cp\_ct,s,y,h} \times \left(1 + \frac{1}{SEER_{cp}}\right) \times f^{share,cold}_{cp\_ct} \quad : \forall s, y, h \tag{85}$$

The constraint in equation (86) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{cp\_ct,y}$.

$$\bar{q}^{cap}_{cp\_ct,y} = \begin{cases} \bar{q}^{cap}_{cp\_ct,y-1} + \Delta\bar{q}^{cap}_{cp\_ct,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{cp\_ct,y} & (\text{else}) \end{cases} \tag{86}$$

In equation (87) the newly installed capacity $\Delta\bar{q}^{cap}_{cp\_ct,y}$ is used to calculate the investment costs $c^{inv}_{cp\_ct,y}$ by the specific investment costs of the compressor $C^{inv}_{cp,y}$ and the cooling tower $C^{inv}_{ct,y}$.

$$c^{inv}_{cp\_ct,y} = \left(C^{inv}_{cp,y} + C^{inv}_{ct,y}\right) \times \Delta\bar{q}^{cap}_{cp\_ct,y} \quad : \forall y \tag{87}$$

Equation (88) calculates the fixed costs $c^{fix}_{cp\_ct,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{cp\_ct,y} = C^{fix}_{cp\_ct,y} \times \bar{q}^{cap}_{cp\_ct,y} \quad : \forall y \tag{88}$$

In equation (89) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{cp\_ct,s,y,h}$.

$$c^{var}_{cp\_ct,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{cp\_ct,s,y,h} \quad : \forall s, y, h \tag{89}$$

### Compression cooling machine with heat pump (CP_HP)

This technology operates again in both district thermal energy systems. It differs from the previous technology in the way, how heat is dissipated. Here, the heat is recovered with an additional heat pump and fed back into the district heating grid.

In equation (90) the maximum capacity $\bar{q}^{cap}_{cp\_hp,y}$ of the technology is set by the maximum cold supplied $q^{sup,cold}_{cp\_hp,s,y,h}$.

$$q^{sup,cold}_{cp\_hp,s,y,h} \leq \bar{q}^{cap}_{cp\_hp,y} \quad : \forall s, y, h \tag{90}$$

Equation (91) calculates the thermal heat energy provided $q^{sup,heat}_{cp\_hp,s,y,h}$ based on the thermal cold energy provided $q^{sup,cold}_{cp\_hp,s,y,h}$ and the seasonal energy efficiency ratio of the compressor $SEER_{cp}$.

$$q^{sup,heat}_{cp\_hp,s,y,h} = q^{sup,cold}_{cp\_hp,s,y,h} + \frac{q^{sup,cold}_{cp\_hp,s,y,h}}{SEER_{cp}} \quad : \forall s, y, h \tag{91}$$

In equation (92) the consumption of electricity $q^{con,elec}_{cp\_hp,s,y,h}$ is calculated by the thermal cold energy provided $q^{sup,cold}_{cp\_hp,s,y,h}$, the seasonal energy efficiency ratio of the compressor $SEER_{cp}$ and the coefficient of performance $COP^{hp}_{cp}$.

$$q^{con,elec}_{cp\_hp,s,y,h} = \frac{q^{sup,cold}_{cp\_hp,s,y,h}}{SEER_{cp}} + \frac{q^{sup,heat}_{cp\_hp,s,y,h}}{COP^{hp}_{cp}} \quad : \forall s, y, h \tag{92}$$

The constraint in equation (93) defines the capacity expansion, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{cp\_hp,y}$.

$$\bar{q}^{cap}_{cp\_hp,y} = \begin{cases} \bar{q}^{cap}_{cp\_hp,y-1} + \Delta\bar{q}^{cap}_{cp\_hp,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{cp\_hp,y} & (\text{else}) \end{cases} \tag{93}$$

In equation (94) the newly installed capacity $\Delta\bar{q}^{cap}_{cp\_hp,y}$ is used to calculate the investment costs $c^{inv}_{cp\_hp,y}$ by the specific investment costs of the absorber $C^{inv}_{cp,y}$ and the heat pump $C^{inv}_{hp,y}$.

$$c^{inv}_{cp\_hp,y} = \left(C^{inv}_{cp,y} + C^{inv}_{hp,y} \times \left(1 + \frac{1}{SEER_{cp}}\right)\right) \times \Delta\bar{q}^{cap}_{cp\_hp,y} \quad : \forall y \tag{94}$$

Equation (95) calculates the fixed costs $c^{fix}_{cp\_hp,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{cp\_hp,y} = C^{fix}_{cp\_hp,y} \times \bar{q}^{cap}_{cp\_hp,y} \quad : \forall y \tag{95}$$

In equation (96) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the needed electricity consumption $q^{con,elec}_{cp\_hp,s,y,h}$.

$$c^{var}_{cp\_hp,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{cp\_hp,s,y,h} \quad : \forall s, y, h \tag{96}$$

### 3.1.6 Cooling storage constraints

In addition to the heating sector, a cooling storage is described mathematically as well.

#### Ice thermal energy storage (ITES)

Also, for the district cooling system a storage type is defined. Therefore, ice thermal energy storages are introduced, which increase the flexibility also on the cooling side. In contrast to the tank thermal energy storage, here the counterpart of the heat pump, an air chiller, is used to undercool the stored energy. The ice thermal energy storage is also a bidirectional element, which means that the energy flow turns during operation.

In equation (97) the maximum storage capacity of the air chiller $\bar{q}^{cap}_{ites,y}$ is set by the maximum cold stored $q^{sto,cold}_{ites,s,y,h}$.

$$q^{sto,cold}_{ites,s,y,h} \leq \bar{q}^{cap}_{ites,y} \quad : \forall s, y, h \tag{97}$$

In equation (98) the maximum capacity $\bar{q}^{cap}_{ites,y}$ of the storage is set by the maximum state of charge $k^{sto,cold}_{ites,s,y,h}$.

$$k^{sto,cold}_{ites,s,y,h} \leq \bar{k}^{cap}_{ites,y} \quad : \forall s, y, h \tag{98}$$

The state of charge $k^{sto,cold}_{ites,s,y,h}$ is modeled in equation (99). It is set to an initial state based on a factor. During operation the state of charge is dependent on the previous state considering losses as well as the charged and discharged energy considering the efficiency.

$$k^{sto,cold}_{ites,s,y,h} = \begin{cases} \bar{k}^{cap}_{ites,y-1} \times \lambda^{losses}_{ites} + \\ q^{sto,cold}_{ites,s,y,h} \times \eta_{ites} - \\ \frac{q^{sup,cold}_{ites,s,y,h}}{\eta_{ites}} \end{cases} : \forall s, y, h \quad (\text{if } y \neq y_0)$$
$$\bar{k}^{cap}_{ites,y_0} \times f^{init}_{ites} \qquad (\text{else}) \tag{99}$$

In equation (100) the consumption of electricity $q^{con,elec}_{ites,s,y,h}$ is calculated by the seasonal energy efficiency ratio of the additional air chiller $SEER^{ac}_{ites}$ and the thermal energy stored $q^{sup,cold}_{ites,s,y,h}$. The SEER does not change on an hourly bases, instead it is set to an average value as the grid temperature varies little.

$$q^{sto,cold}_{ites,s,y,h} = q^{con,elec}_{ites,s,y,h} \times SEER^{ac}_{ites} \quad : \forall s, y, h \tag{100}$$

The constraint in equation (101) defines the capacity expansion of the air chiller, by adding the newly installed capacity $\Delta\bar{q}^{cap}_{ites,y}$.

$$\bar{q}^{cap}_{ites,y} = \begin{cases} \bar{q}^{cap}_{ites,y-1} + \Delta\bar{q}^{cap}_{ites,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{q}^{cap}_{ites,y} & (\text{else}) \end{cases} \tag{101}$$

The constraint in equation (102) defines the storage capacity expansion, by adding the newly installed capacity $\Delta\bar{k}^{cap}_{ites,y}$.

$$\bar{k}^{cap}_{ites,y} = \begin{cases} \bar{k}^{cap}_{ites,y-1} + \Delta\bar{k}^{cap}_{ites,y} & : \forall y \quad (\text{if } y \neq y_0) \\ \Delta\bar{k}^{cap}_{ites,y} & (\text{else}) \end{cases} \tag{102}$$

In equation (103) the newly installed capacity $\Delta\bar{k}^{cap}_{ites,y}$ is used to calculate the investment costs $c^{inv}_{ites,y}$ by the specific investment costs of the storage $C^{inv}_{ites,y}$ and the additional air chiller $C^{inv}_{ac,y}$.

$$c^{inv}_{ites,y} = C^{inv}_{ac,y} \times \Delta\bar{q}^{cap}_{ites,y} + C^{inv}_{ites,y} \times \Delta\bar{k}^{cap}_{ites,y} \quad : \forall y \tag{103}$$

Equation (104) calculates the fixed costs $c^{fix}_{ites,y}$, which are typically 2 % of the investment costs.

$$c^{fix}_{ites,y} = C^{fix}_{ites,y} \times \bar{q}^{cap}_{ites,y} \quad : \forall y \tag{104}$$

In equation (105) the variable costs are calculated by the electricity price $P^{elec}_{s,y,h}$ times the electricity consumption $q^{con,elec}_{ites,s,y,h}$ and the charging/discharging costs.

$$c^{var}_{ites,s,y,h} = P^{elec}_{s,y,h} \times q^{con,elec}_{ites,s,y,h} + (q^{sup,cold}_{ites,s,y,h} + q^{sto,cold}_{ites,s,y,h}) \times C^{cha,dis}_{ttes} \quad : \forall s, y, h \tag{105}$$

## 3.2 Case study and data

The US-American case study is done for a small district in Washington D.C., the capital of the USA. In the observed area are 35 buildings located, with different heating and cooling demand profiles. At the moment every demand is covered individually by the houseowners, as there is no district heating or cooling system available. The task is to find a cost-optimal investment strategy to satisfy the energy demand of all buildings in the next 26 years starting in 2025. A 2D-map of all 35 buildings can be seen in Figure 3.3.

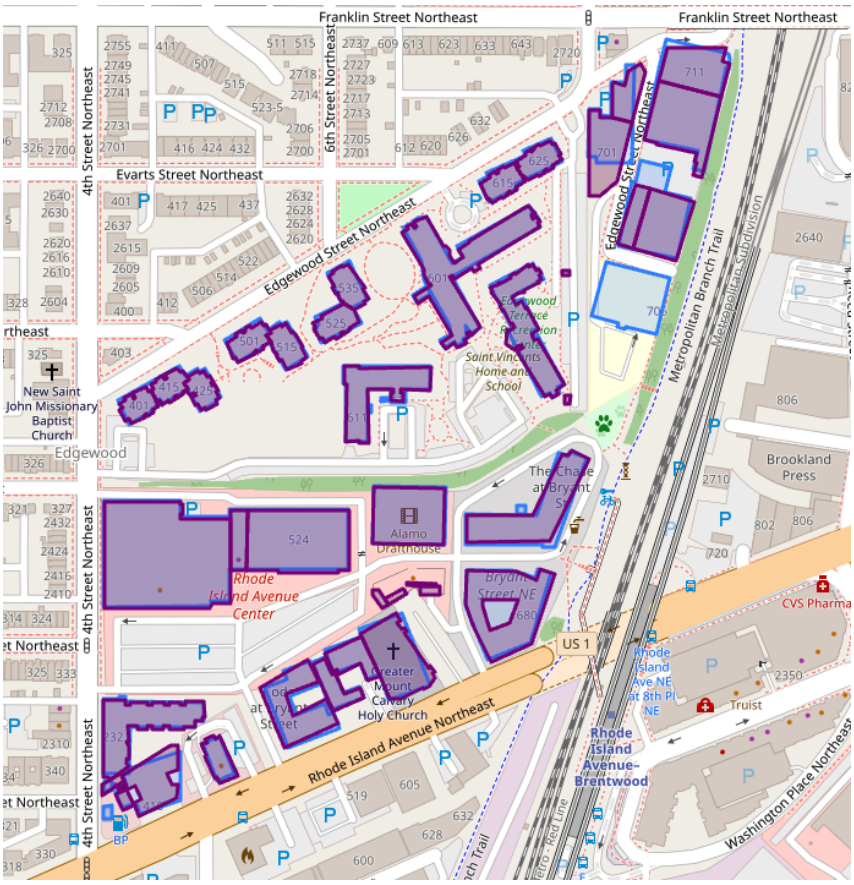


Figure 3.3: 2D-map of the 35 buildings

Additional details of the 35 buildings can be found in Table 3.3. Different building types are located in the investigated area like multifamily houses, offices and food services. Apart from that each building is indexed by an ID and the corresponding gross floor area is given. Furthermore, the Heating, Ventilation, Air Conditioning (HVAC) system type is listed.

| Building ID | Building Type | Gross Floor Area ($m^2$) | HVAC System Type |
|---|---|---|---|
| Building 1 | Service | 177 | PSZ-AC with gas coil |
| Building 2 | Food sales | 15 | PSZ-AC with gas coil |
| Building 3 | Food sales | 66 | PSZ-AC with gas coil |
| Building 4 | Multifamily | 13 541 | VAV chiller with gas boiler reheat |
| Building 5 | Multifamily | 2,245 | PSZ-AC with gas coil |
| Building 6 | Multifamily | 7,673 | PVAV with gas heat with electric reheat |
| Building 7 | Food service | 686 | PSZ-AC with gas coil |
| Building 8 | Multifamily | 7,330 | PVAV with gas heat with electric reheat |
| Building 9 | Service | 900 | PSZ-AC with gas coil |
| Building 10 | Office | 2,143 | PSZ-AC with gas coil |
| Building 11 | Religious worship | 5,955 | PSZ-AC with gas coil |
| Building 12 | Public assembly | 11,589 | PVAV with gas heat with electric reheat |
| Building 13 | Strip shopping mall | 932 | PSZ-AC with gas coil |
| Building 14 | Strip shopping mall | 5,631 | PSZ-AC with gas coil |
| Building 15 | Retail other than mall | 3,246 | PSZ-AC with gas coil |
| Building 16 | Multifamily | 8,762 | PVAV with gas heat with electric reheat |
| Building 17 | Multifamily | 15,705 | VAV chiller with gas boiler reheat |
| Building 18 | Multifamily | 2,262 | PSZ-AC with gas coil |
| Building 19 | Multifamily | 2,303 | PSZ-AC with gas coil |
| Building 20 | Multifamily | 17,411 | VAV chiller with gas boiler reheat |
| Building 21 | Multifamily | 2,659 | PSZ-AC with gas coil |
| Building 22 | Multifamily | 2,779 | PSZ-AC with gas coil |
| Building 23 | Multifamily | 2,706 | PSZ-AC with gas coil |
| Building 24 | Multifamily | 2,713 | PSZ-AC with gas coil |
| Building 25 | Multifamily | 17,916 | VAV chiller with gas boiler reheat |
| Building 26 | Education | 7,145 | PVAV with gas heat with electric reheat |
| Building 27 | Multifamily | 25,247 | VAV chiller with gas boiler reheat |
| Building 28 | Education | 1,870 | PSZ-AC with gas coil |
| Building 29 | Education | 5,066 | PSZ-AC with gas coil |
| Building 30 | Multifamily | 2,615 | PSZ-AC with gas coil |
| Building 31 | Multifamily | 2,747 | PSZ-AC with gas coil |
| Building 32 | Education | 1,621 | PSZ-AC with gas coil |
| Building 33 | Non-refrigerated warehouse | 3,771 | PSZ-AC with gas coil |
| Building 34 | Food service | 822 | PSZ-AC with gas coil |
| Building 35 | Non-refrigerated warehouse | 2,398 | PSZ-AC with gas coil |
| Totals | N/A | 190,661 | N/A |

Table 3.3: Information of the 35 buildings

It is assumed, that not all buildings are connected to the district heating and cooling grid at the same time. Instead three expansion phases were defined from 2025 to 2035. After this three stages of expansion the demand is at its maximum, except some demand fluctuations, which will be explained in the upcoming section.

The solution of the model is a cost-optimal investment strategy on which a 3rd generation district heating and cooling system can be created. The supply temperature for the district heating grid is 90 °C and the district cooling grid has an operating temperature of 7 °C. The used hourly electricity prices for the case study are from [40]. There, the real-time price for electricity was chosen for the PJM zone and increased by 2 % per year. The gas prices for the zone around Washington D.C. are from [41]. Other general parameters are the temperature curve over the year and the corresponding solar radiation. Both curves can be found on the Open-Meteo platform [42].

According to Aljubran and Horne [26] the area around Washington D.C. has not enough deep geothermal potential as the temperatures are to low. Therefore the maximmum capacity of the deep geothermal technology was limited to zero.

For the industrial excess heat profile, different energy-intensive production sites have been analyzed to generate a weekly recurring supply profile. A bakery, a chemical plant and a cement factory are assumed to create this general profile. As a matter of facts, industrial excess heat is a very suitable solution to cover heat demand. But the available heat demand has to be adapted to the enclosed district heating area. The limitation was chosen like in Vienna, where 19 % of the heating demand is covered by industrial excess heat.

Next to industrial excess heat, waste incineration has to be limited as well. There the amount of waste has to be adapted for the grid area. The available waste is based on the waste produced per person and scaled to an hourly maximum available waste amount, which can be burnt. This leads to a possible constant heat delivery.

Finally the specific investment cost of each technology is listed in Table 3.4. It is assumed that the investment costs decline over the years through the effect of technological learning. This effect differs between the technologies, which is why the learning rates are expressed as well. The specific investment costs are based on realized projects and validated by considering Billerbeck et al. [43] and Hatton et al. [44].

| Technology | Specific Investment Cost ($/MW) | Learning Rate (%) |
|---|---|---|
| **Heating Technology** | | |
| EB | 242,000 | 10 |
| HP | 755,876 | 25 |
| GT / HP | 25,397.9 / 755,876 | 30 / 25 |
| DGT | 3,399,000 | 30 |
| ST / HP | 356,760.8 / 755,876 | 20 / 25 |
| IEH | 324,500 | 15 |
| WI | 10,195,233.4 | 10 |
| CHP | 1,210,000 | 10 |
| **Cooling Technology** | | |
| AC | 405,156 | 25 |
| AB / CT | 966,532.6 / 396,000 | 25 / 25 |
| AB / HP | 966,532.6 / 755,876 | 25 / 25 |
| CP / CT | 458,033.4 / 396,000 | 25 / 25 |
| CP / HP | 458,033.4 / 755,876 | 25 / 25 |
| **Storage Technology** | | |
| TTES / HP | 2,600 / 755,876 | 25 / 25 |
| ITES / AC | 5,200 / 405,156 | 25 / 25 |

Table 3.4: Specific investment costs of the technology portfolios

## 3.3 Scenarios

As future developments are hard to predict, a lot of uncertainties would stick to the results. To reduce uncertainties and increase the robustness of the model, different scenarios are introduced. In Table 3.5 all existing scenarios are listed. In total, 16 scenarios are defined to represent different possible future developments. Each scenario is weighted by a self-defined probability and described by a key parameter. Furthermore, the affected years are given, where the input assumptions differ from the reference scenario.

The scenarios are categorized in four different groups. The markets-based group focuses on changes of the electricity price. Next to that group, the supply-side scenarios take resource changes into account. There the electricity price, gas price, specific investment costs and the $CO_2$ costs vary. The demand-side group considers fluctuations of the heating and cooling demand. These changes are based on possible climatic modifications and also affect electricity and gas prices. The last group is focussing on the regulatory framework, where $CO_2$ and investment costs change. These scenarios consider policy changes, which are stricter or more lenient.

Next to the different weighting of the scenarios, also the affected years differ. Some of the listed scenarios have a long-term impact and some are just temporary interferences. Based on these scenarios a robust investment strategy under consideration of the demand balance constraints has to be found.

| Group | Case | Key parameter | Input assumption | Affected years | Probability |
|---|---|---|---|---|---|
| | (1) *Reference (base)* | No alterations applied to the baseline scenario | - | - | 15 % |
| markets-based | (2) *High electricity prices* | Increased electricity price for all energy consumed | $1.2 \times P^{elec}_{s,y,h}$ | 2025 - 2050 | 3 % |
| markets-based | (3) *Low electricity prices* | Decreased electricity price for all energy consumed | $0.8 \times P^{elec}_{s,y,h}$ | 2025 - 2050 | 3 % |
| markets-based | (4) *Flexible energy market* | Electricity prices restricted to non-negative values due to high flexibility in the energy market | $P^{elec}_{s,y,h} \geq 0$ | 2025 - 2050 | 10 % |
| supply-side | (5) *Energy congestion* | Price increase for natural gas and electricity due to supply congestion | $1.1 \times P^{elec}_{s,y,h}$<br>$1.2 \times P^{gas}_{s,y,h}$ | 2035 - 2039 | 6 % |
| supply-side | (6) *Green friendly* | Elevated $CO_2$ prices coupled with financial incentives for RES investment | $0.8 \times C^{inv}_{t,y}$<br>$1.1 \times C^{CO_2}_{s,y}$ | 2025 - 2050 | 6 % |
| supply-side | (7) *Low gas demand* | The increase in $CO_2$ prices led to a reduction in natural gas demand, which subsequently caused a decline in gas prices | $1.25 \times C^{CO_2}_{s,y}$<br>$0.85 \times P^{elec}_{s,y,h}$<br>$0.95 \times P^{gas}_{s,y,h}$ | 2025 - 2050 | 6 % |
| supply-side | (8) *Natural gas friendly* | The reduction in natural gas prices, alongside the absence of $CO_2$ pricing, as a result of a political decisions | $0.85 \times P^{gas}_{s,y,h}$<br>$C^{CO_2}_{s,y} = 0$ | 2040 - 2044 | 3 % |
| demand-side | (9) *Cold winters* | Increased heat demand driven by colder-than-average winter conditions | $1.1 \times Q^{heat}_{s,y,h}$<br>$1.05 \times P^{elec}_{s,y,h}$<br>$1.1 \times P^{gas}_{s,y,h}$ | 2045 - 2050 | 9 % |
| demand-side | (10) *Hot summers* | Increased cooling demand resulting from higher-than-average summer temperatures | $1.1 \times Q^{cold}_{s,y,h}$<br>$1.1 \times P^{elec}_{s,y,h}$ | 2030 - 2034 | 9 % |
| demand-side | (11) *Warm summers* | Marginally increased cooling demand compared to typical conditions | $1.05 \times Q^{cold}_{s,y,h}$ | 2045 - 2050 | 3 % |
| demand-side | (12) *Moderate climate* | Milder summers and warmer winters result in reduced heating and cooling demand | $0.9 \times Q^{cold}_{s,y,h}$<br>$0.9 \times Q^{heat}_{s,y,h}$<br>$0.9 \times P^{elec}_{s,y,h}$<br>$0.8 \times P^{gas}_{s,y,h}$ | 2025 - 2050 | 3 % |
| regulatory framework | (13) *Zero $CO_2$ price* | The cost of $CO_2$ emissions is assumed to be zero, reflecting the current regulatory framework in the USA | $C^{CO_2}_{s,y} = 0$ | 2025 - 2050 | 3 % |
| regulatory framework | (14) *Delayed $CO_2$ pricing* | No $CO_2$ pricing is implemented until 2035, followed by the introduction of moderate carbon prices afterwards | $C^{CO_2}_{s,y} = 0$ | 2025 - 2034 | 9 % |
| regulatory framework | (15) *Ambitios $CO_2$ pricing* | Elevated $CO_2$ prices resulting from policy-driven regulatory changes | $1.25 \times C^{CO_2}_{s,y}$ | 2025 - 2050 | 6 % |
| regulatory framework | (16) *Expiring support RES* | Financial support for RES investment costs is available only until 2034. | $0.7 \times C^{inv}_{t,y}$ | 2025 - 2034 | 6 % |

Table 3.5: Overview of the 16 scenarios based on the variation of demand, energy prices and regulatory frameworks

# 4 Results and discussion

In this chapter the results of the developed model are analyzed for the US-American case study. Different findings will be presented and evaluated. Based on the results also conclusions about the available technologies are presented. Furthermore, the influence of storages and scenario-dependent dispatch differences are analyzed. Based on an hourly resolution, the results are visualized by plotly, a Python-based visualization tool. The results are splitted in two subsections, one for district heating and one for the district cooling system.

## 4.1 District heating

The first plot of the visualization describes the dispatch of the reference scenario in 2035. The cost-optimal investment portfolio is created by considering all 16 scenarios based on their weightings. In Figure 4.1 the dispatch of one year can be seen on an hourly resolution. According to the demand balance constraints, the demand has to be covered at any hour, by the sum of all technologies. It can be seen that the demand varies a lot throughout the year. In the summer months the heating demand is much lower than at the beginning and the end of the year. It is also visible that air-sourced heat pumps operate mainly in summer according to the higher outdoor temperatures, which influences the coefficient of performance.

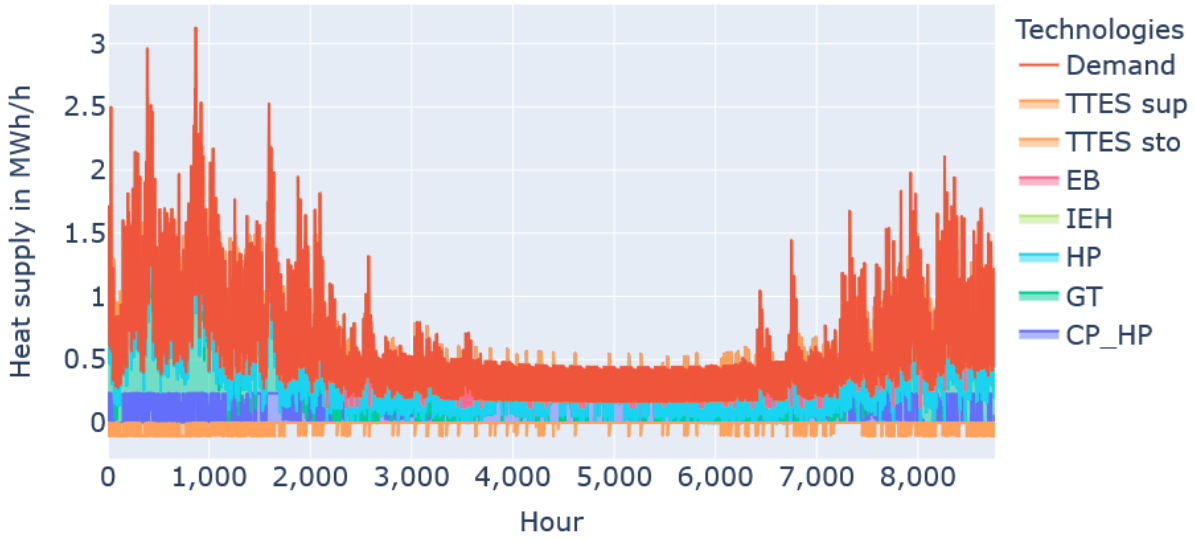


Figure 4.1: District heating load curve in 2035 (reference scenario)

To get a better insight, a winter week and a summer week are displayed. In Figure 4.2 the first week of the year is represented. It can be seen that most demand is covered by geothermal. This is a suitable technology in winter months, as the soil temperature is stable enough to maintain a constant COP for the additional heat pump. In constrast to geothermal generation units, heat pumps itself are not that used, as the outside temperature is low in winter, which means a worse COP. Next to them, industrial excess heat, a cheap source to provide heat, is used at its maximum capacity. The compression cooling machine with a heat pump provides heat in cases of high demand. To cover demand peaks, electric boilers and TTES are used.

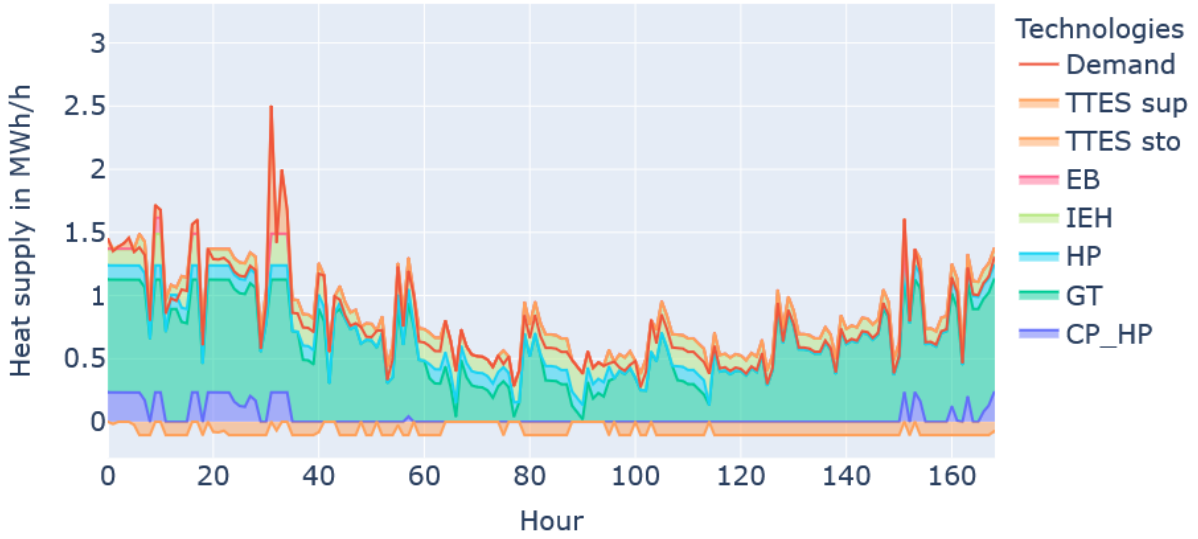


Figure 4.2: District heating load curve in winter 2035 (reference scenario)

The situation in winter differs a lot from a typical summer week. This situation is visualized in Figure 4.3. There the base load is mainly covered by the compression cooling machine with heat pump. This is because the cold demand is much higher in summer and therefore heat is generated additionally. Other used technologies are industrial excess heat, geothermal and heat pumps.

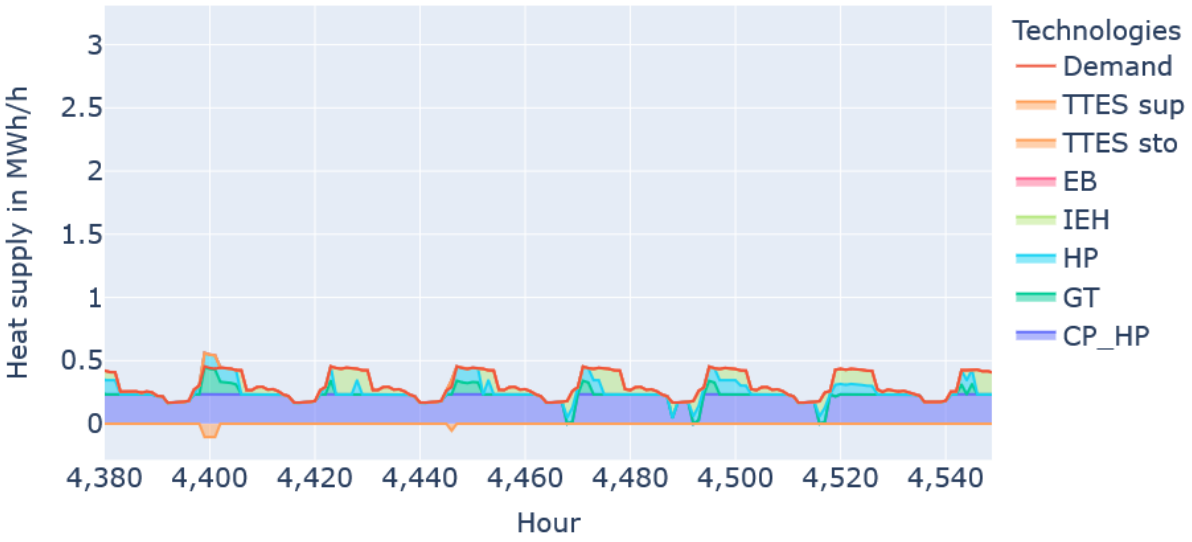


Figure 4.3: District heating load curve in summer 2035 (reference scenario)

The previous plots are generated for the reference scenario. But the dispatch differs between the scenarios. To illustrate possible differences, Figure 4.4 is introduced. There the dispatch differences are shown for geothermal between the reference senario and the scenario with no $CO_2$ costs. In most hours the heat generation of geothermal is much higher for scenarios with no carbon emission pricing. The differences are visualized through the shaded areas. Especially in winter the differences are a lot higher, as demand covering of geothermal takes mainly part at these months.

This situation can also be seen at other technologies. Figure 4.5 shows the situation for industrial excess heat. In constrast to geothermal, heat supply through industrial excess heat is much higher in most hours of the reference scenario. Without taxation of carbon emissions, a shift from industrial excess heat to geothermal can be seen. This leads to reduced costs, but increased carbon emissions.

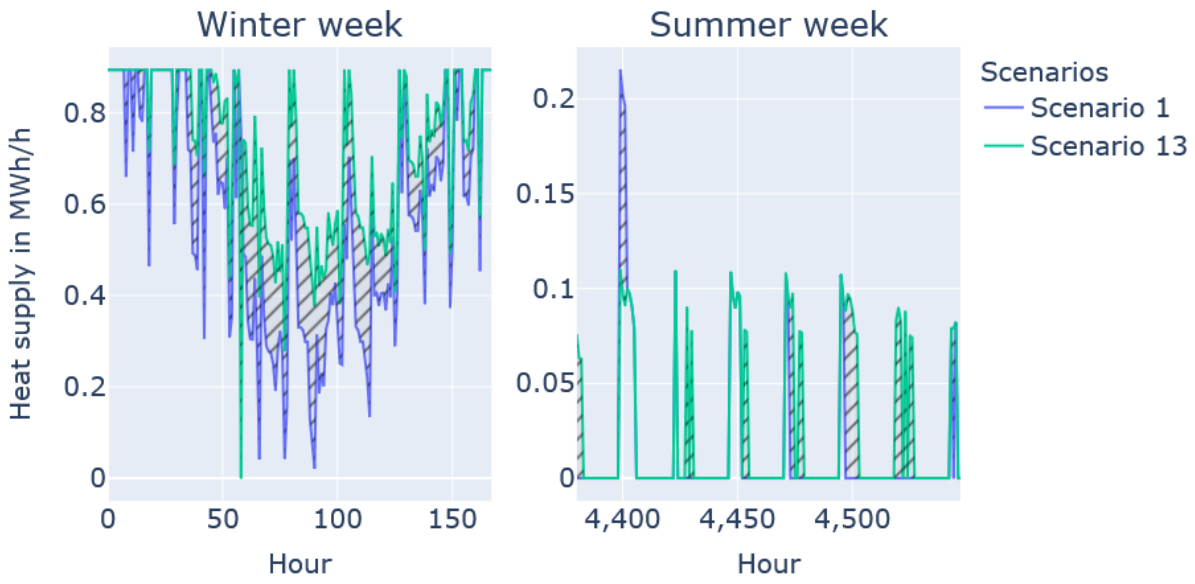


Figure 4.4: Dispatch differences of geothermal between scenarios 1 and 13

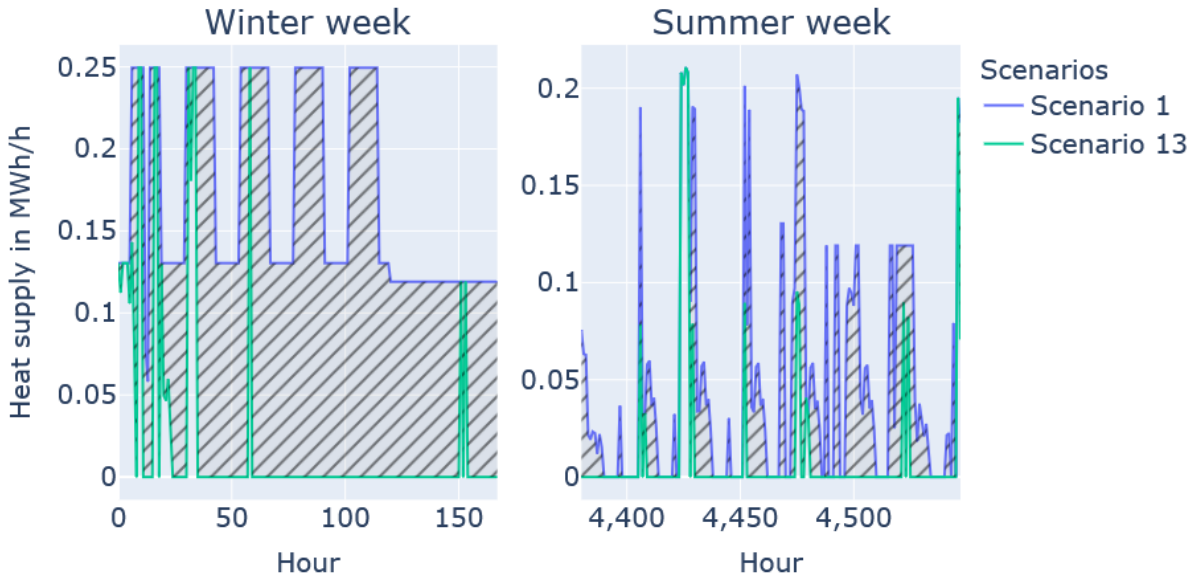


Figure 4.5: Dispatch differences of industrial excess heat between scenarios 1 and 13

Next to the dispatch and their differences within the scenarios, also the role of the storage is worth investigating it. This technology enables flexibility and makes it possible to shift energy delivery from cost-intensive production hours to cheap ones. Furthermore, the capacities of the generation technologies can be reduced to cover peak demands. In Figure 4.6 the state of charge of the tank thermal energy storage can be seen. There the curve gives insights when charging and discharging periods takes place. Especially in winter fluctuations can be seen to cover supply shortages.

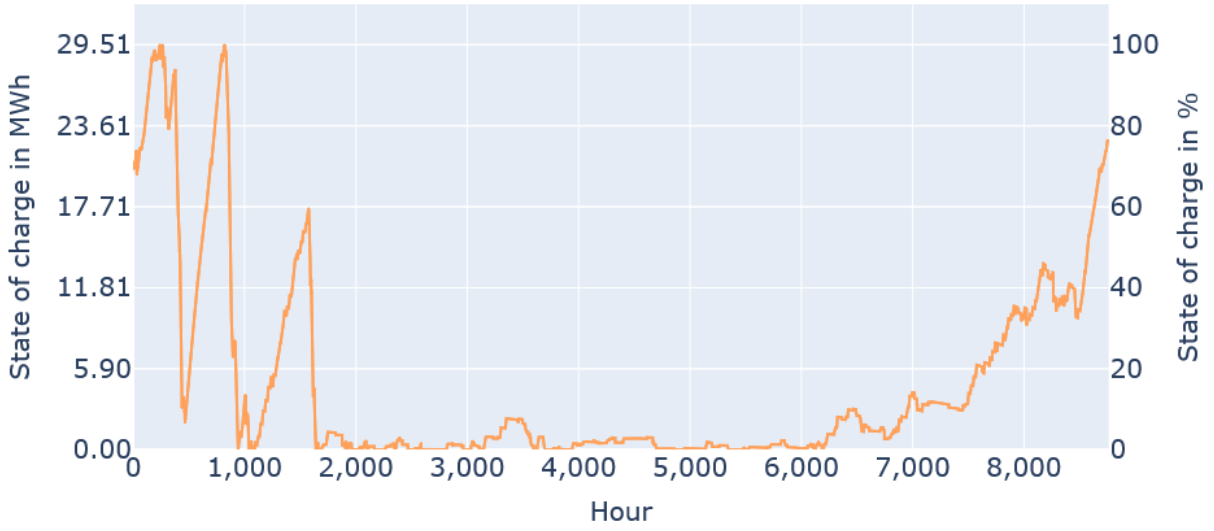


Figure 4.6: State of charge of the tank thermal energy storage in 2035

In Figure 4.7 the technology investments can be seen from 2025 to 2045. As the demand is expanded in the first three simulation years, most investments take place from 2025 to 2035. Investments in 2040 and 2045 are done because of fluctuations within the scenarios. On the left side investments in the heating technology portfolio are displayed and on the right side TTES investments are visualized. It can be seen that the complete potential of industrial excess heat is already built in 2025, as it is the cheapest solution for providing heat. Apart from that geothermal investments are mandatory in every expension phase. Electric boiler is only used to cover peaks. Furthermore, electric boilers are cheap as well, which is why they are built in 2045 as the simulation horizon ends in 2050. Heat pumps itself only play a minor role in this case study, but are essential to operate geothermal generation units.

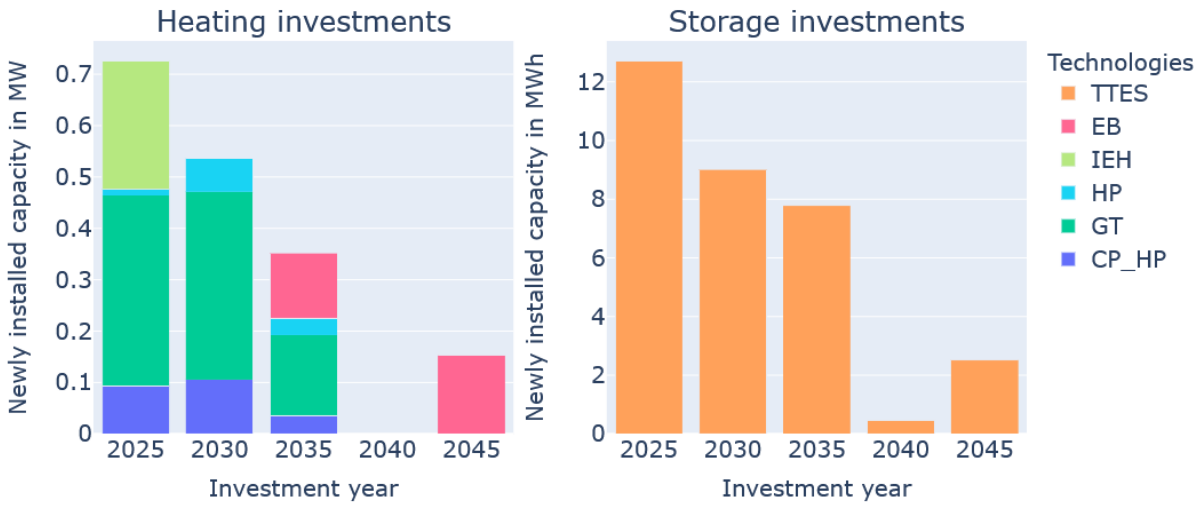


Figure 4.7: District heating investment strategy from 2025 to 2045

The so-called levelized costs of heating (LCOH) are an interesting output as well. As the demand profile of each building exists, the levelized costs of each building can be compared to the district heating solution of the model. The range of the LCOH are given by the different scenarios. This means, that scenarios with lower operational costs lead to lower LCOH. This is visualized in Figure 4.8. Each block represents one building and the horizontal band represents the district heating system. It can be seen, that five buildings have much higher LCOH compared to the others. This is because of the different individual heating systems. These five buildings are heated by electricity, while the others operate with gas. Furthermore, it is visible that in most cases the district heating system is much more cost-beneficial. Only in cases of no carbon emission pricing mechanism individual gas heating systems are cheaper. Another insight is that also the span of LCOH is much smaller in a district heating system. This is because of the robust scenario-based solution of the two-stage stochastic optimization.

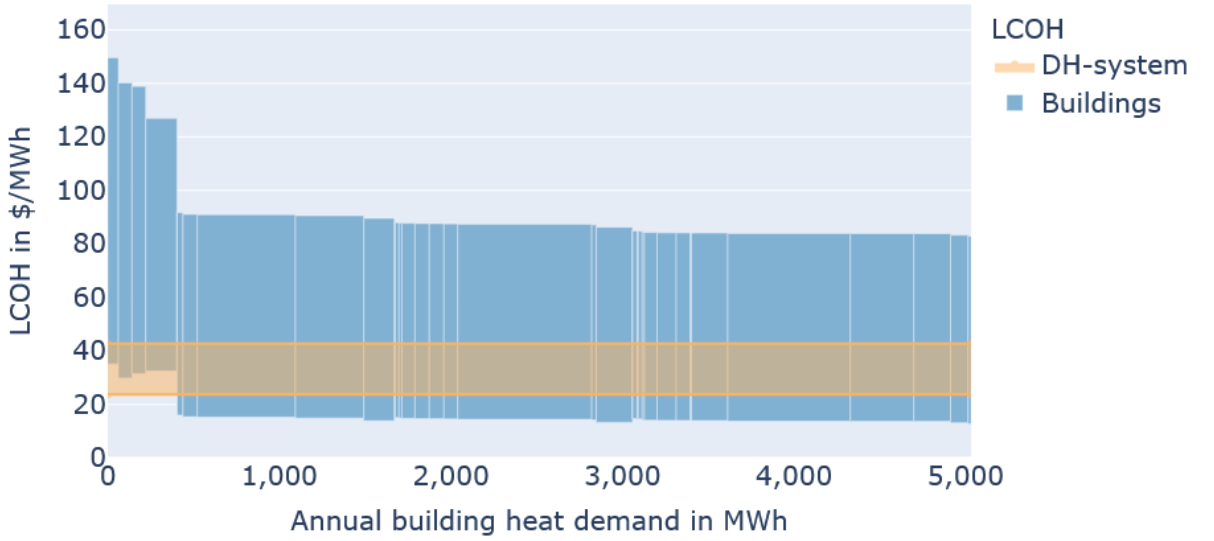


Figure 4.8: Levelized costs of heating

Finally, some reasons are discussed, why the model did not decide on other technologies. As there is not enough deep geothermal potential around the investigated location, this technoloy could not be chosen by the model. One technology that is not used, but could be used, is, for example, solar thermal. This technology has the huge disadvantage of time dependency, as the solar radiation indicates the energy output. Apart from that, also the high investment costs in combination with an additional heat pump makes other technology options much more attractive. Waste incineration was also not chosen, because of the high investment costs. Combined heat and power would be a suitable option in cases of no carbon emission taxation, which is only realized in one scenrio over the whole simulation horizon. Also the absorber options have too high investment costs compared to the other technologies.

## 4.2 District cooling

In the district cooling system also the dispatch of the reference scenario in 2035 will be analyzed. In Figure 4.9 the dispatch of one year can be seen on an hourly resolution. The demand has to be covered at any hour, by the sum of all technologies according to the demand balance constraints. In comparison to the dispatch of the district heating system, the demand is mainly required in summer. In the winter months only a fraction is needed. It is also visible that air chillers are used throughout the year, while others only operate temporary.

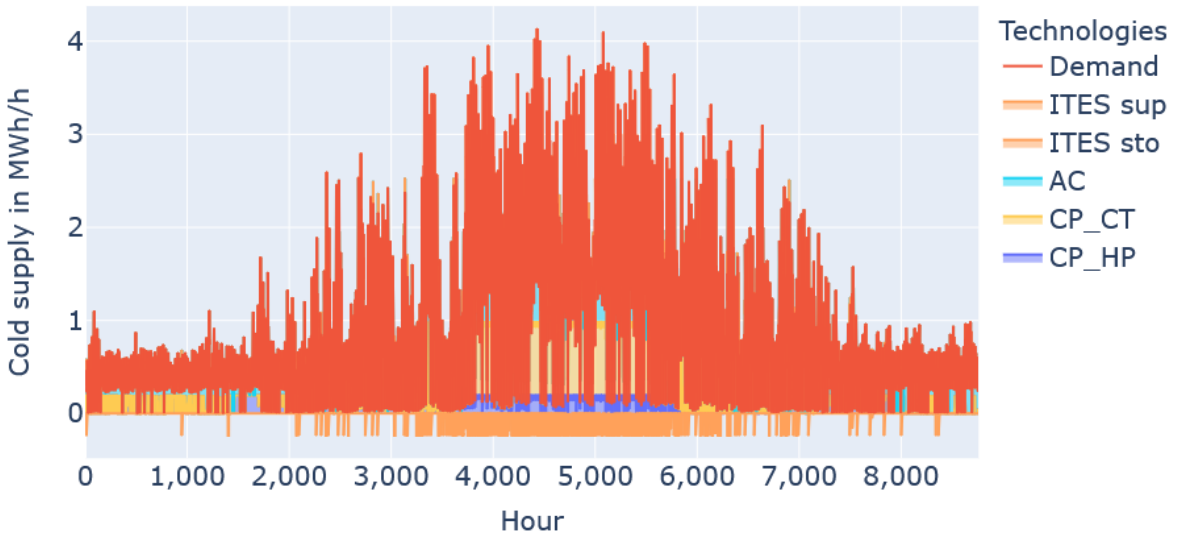


Figure 4.9: District cooling load curve in 2035 (reference scenario)

To understand the situation better, again a winter week and a summer week are displayed. In Figure 4.10 the first week of the year is represented. In winter most demand is covered by the air chiller. This is not suprising, as this technology is very scalable and cost-efficient. Next to the air chiller also the compression cooling machine is visible, which generated the heat contribution in Figure 4.2. The compression cooling machine with cooling tower is not that much used to cover cooling demand in winter. Also the ice thermal energy storage does not play an important role in typical winter weeks.

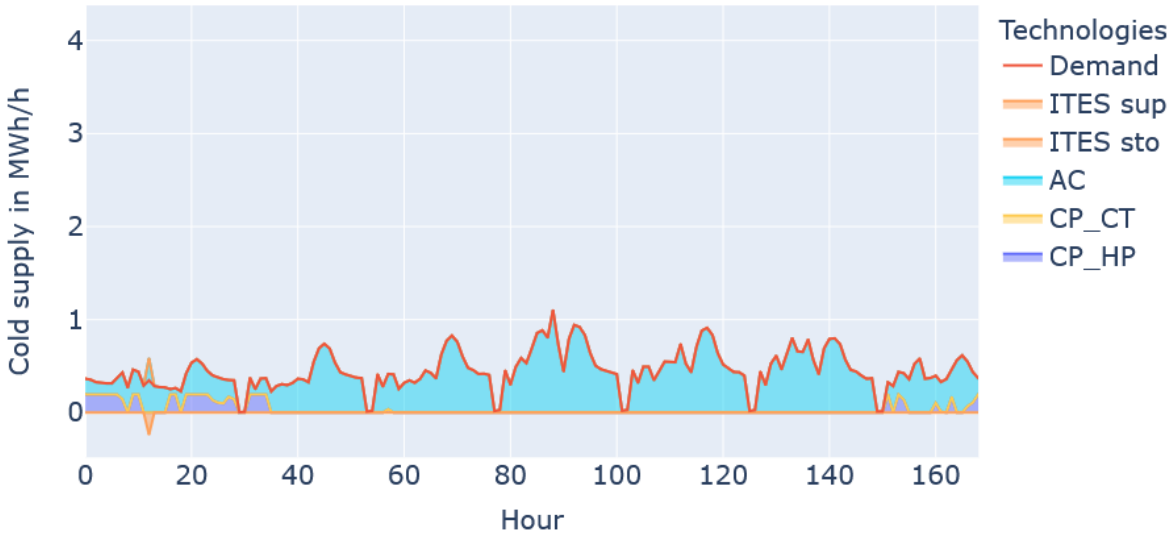


Figure 4.10: District cooling load curve in winter 2035 (reference scenario)

The situation in summer differs a lot from a typical winter week. This situation is visualized in Figure 4.11. It can be seen, that both compression technologies operate hardly constant, which generates a base load to cover the cooling demand. But also the air chiller covers a lot of the demand curve, while the ITES is used to compensate peak loads throughout the day. Absoprtion technologies are not used.

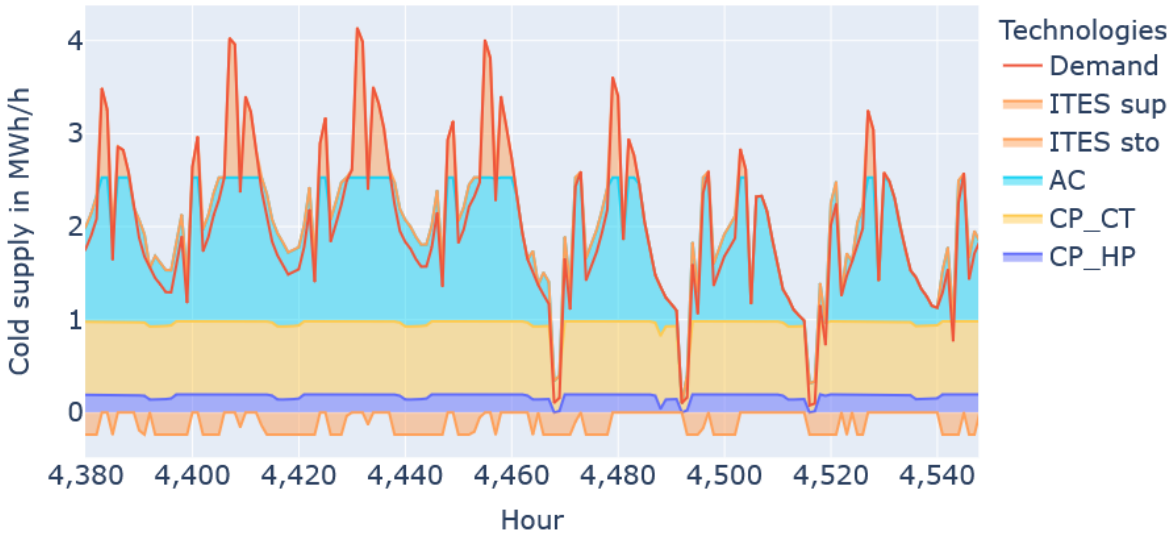


Figure 4.11: District cooling load curve in summer 2035 (reference scenario)

To illustrate possible dispatch differences between scenarios, Figure 4.12 is presented. There the dispatch differences are shown for the air chiller between the reference senario and the scenario with no $CO_2$ costs. The differences are visualized through the shaded areas. It can be seen in the summer and winter week that the dispatch does not vary a lot between these two different scenarios. This is the case because of the limited alternatives in the portfolio compared to the district heating system.

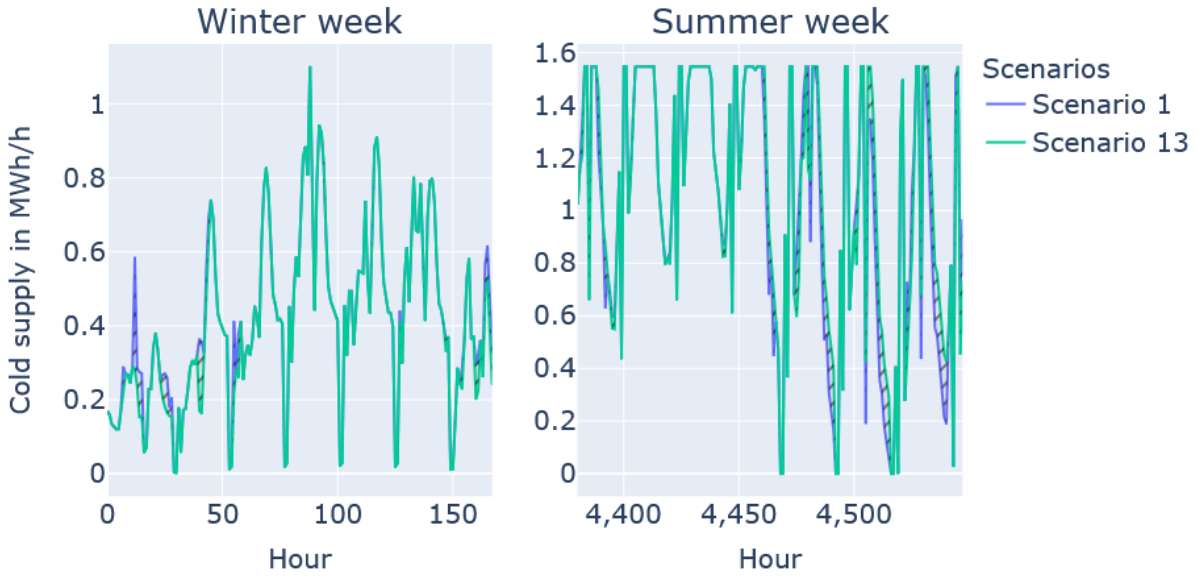


Figure 4.12: Dispatch differences of the air chiller between scenarios 1 and 13

The state of charge of the ice thermal energy storage is also analyzed. This storage type enables flexibiltiy in the district cooling system, where it shifts cold energy from cost-intensive production hours to cheap ones. In Figure 4.13 the state of charge of the ice thermal energy storage can be seen. It is visible that this storage operates mainly in the summer months, while it is mostly empty in winter.

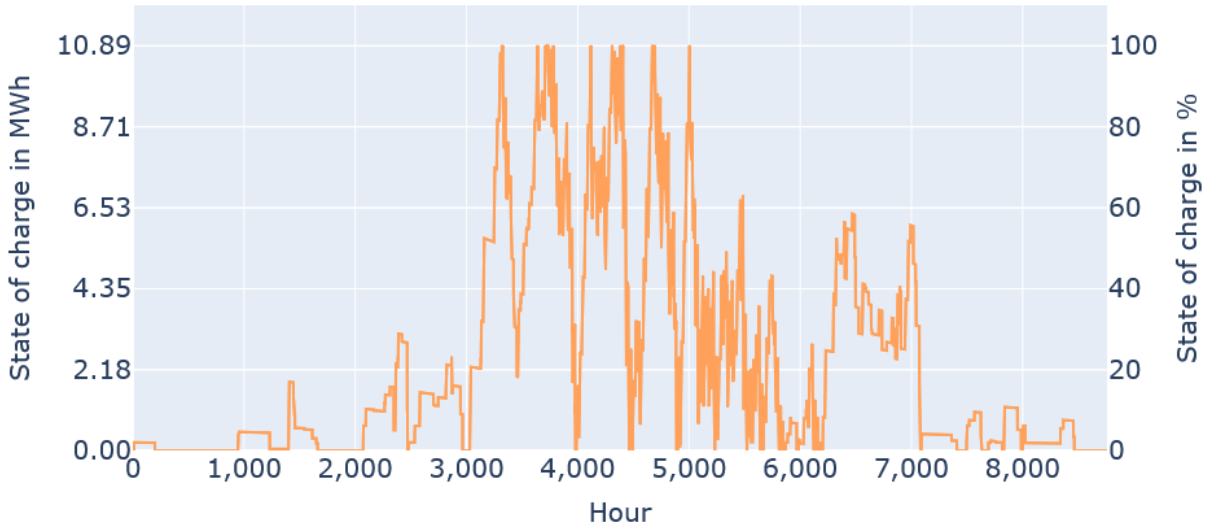


Figure 4.13: State of charge of the ice thermal energy storage in 2035

In Figure 4.14 the technology investments can be seen from 2025 to 2045. The three expension stages are from 2025 to 2035, while the new investment in 2045 is due to demand changes in the scenarios. On the left side investments in the cooling technology portfolio are displayed and on the right side ITES investments are visualized. It can be seen, that the model invests most in air chiller generation units, which is a cheap solution for covering cold demand. Next to that, also investments in compression cooling machines take place. Compressors with additional heat pumps are only used in a small amount, but on the other hand they can operate in both grids.

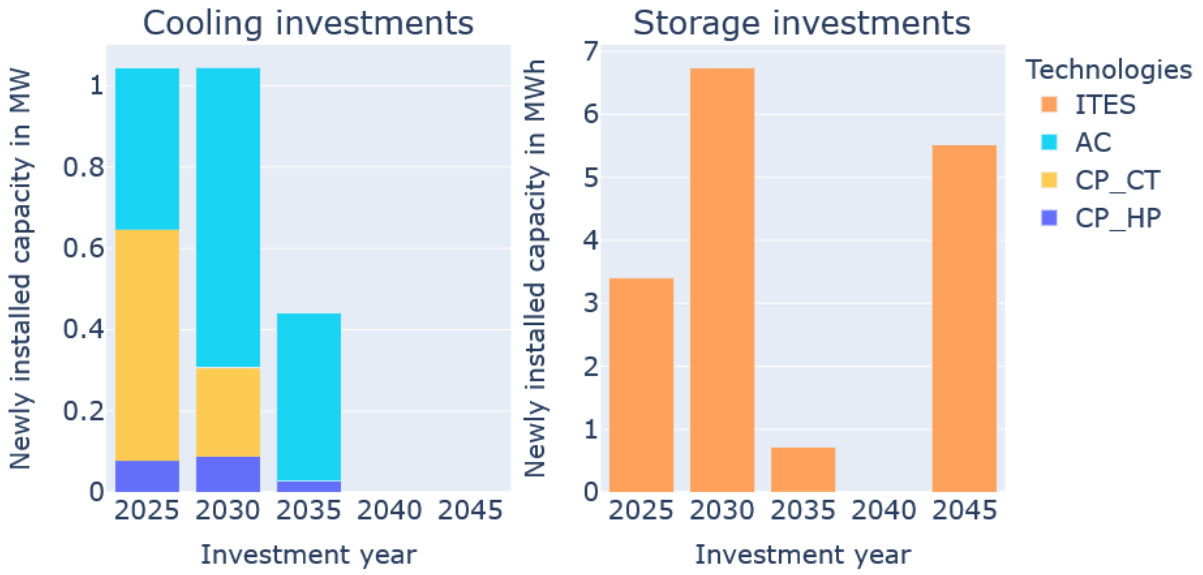


Figure 4.14: District cooling investment strategy from 2025 to 2045

Again the levelized costs of cooling (LCOC) are displayed in 4.15. There each building stands for one block and the span of a block represents the cost range of the different scenarios. Each scenario has a different cost structure, based on the common investment strategy. In contrast to the district heating system the available options are limited. This fact results in a wider band of the LCOC for the district cooling solution. It is also visible, that in the most cost-intensive scenarios some individual solutions are cheaper than the district cooling system, what was never the case for heating. For most buildings supplying through district cooling would be cost-beneficial, but not in every scenario. Especially when high $CO_2$ costs are assumed, a joint solution for all buildings is superior. But the band width is still smaller than the LCOC range of individual solutions, due to the model robustness.

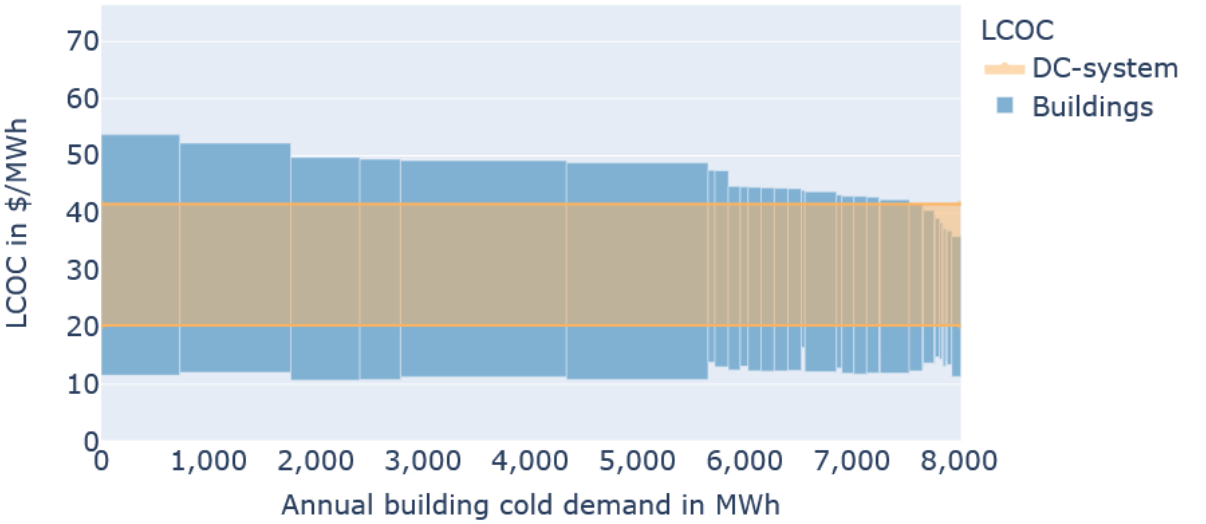


Figure 4.15: Levelized costs of cooling

Finally, some reasons are discussed for why the model did not decide on other technologies in the cooling sector. Apart from the chosen ones, only absortpion types could have been considered. These technologies need higher investment costs in comparison to the air chiller and compression technologies. The absorption cooling machine with cooling tower extracts heat from the district heating grid, which is not fed back in.

# 5 Conclusion and outlook

Individual heating and cooling solutions are widely used. But are often not the best option, whether from an economical or an ecological point of view. A common district heating and district cooling infrastructure is vital for future developments.

This thesis developed a two-stage stochastic optimization model to generate a suitable investment strategy for district heating and cooling based on a US-American case study. The focus was on the supply side and not on the distribution side, which is why the infrastructure has been neglected. Different technology options have been modeled and are based on real economic project parameters.

Future predictions are hard to make. This is why the solution has to be robust towards uncertainties. The two-stage stochastic approach was chosen to consider different versions of the future. In total 16 scenarios have been defined and implemented. The scenarios focus on different future developments, like energy prices, demand fluctuations and policy changes. With this wide spectrum a comprehensive investment portfolio was found for this case study. The research questions were formulated to give a brighter understanding and knowledge, about finding an cost-optimal investment strategy and how robust this optimum is regarding different scenarios and their dispatch.

By analyzing the results some key findings were discovered. Not only the specific investment costs are crucial, but also the different characteristics of the technologies with their strengths and weaknesses. The cots-optimal technology portfolio in this case study for district heating consists mainly of geothermal, industrial excess heat and a tank thermal enrgy storage. Geothermal generation units have the big advantage of stable underground temperature levels. But also investments in heat pumps were made. Industrial excess heat was built at its maximum right in the first investment year. This shows that “waste” heat from other industrial processes are not only low-carbon, but also economical reasonable. Electric boilers were mainly used to compensate peak demands and demands on a little simulation horizon. Shifting thermal heat energy with the tank thermal energy storage was also a key factor to reduce total costs.

The available technology portfolio for the cooling sector was smaller than for heating. It could be seen that next to cheap air chillers also compression cooling machines have their application in the developed system. Especially the compression cooling machine with heat pump is an interesting case, where a crossover between heating and cooling grid takes place. The ice thermal energy storage brings the same advantages for cooling as TTES does for heating.

Some technologies of the heating and cooling technology portfolio were not chosen due to their limitations or cost-intensive energy generation. With the calculation of the levelized costs for heating and cooling it could also been proved, that considering different scenarios brings a much more stable and robust economical band width than individual solutions. The dispatch can vary a lot between different scenarios, but the changes of the total levelized costs are limited.

In this thesis also some limitations and assumptions have been made. First of all, building the infrastructure was not part of the thesis and therefore possible limitations and costs have to be considered seperatly. Also lifetime and reinvestments were not considered as the planning and operation horizon were only simulated for 26 years. Furthermore, also some restrictions have been made for industrial excess heat and waste incineration.

Apart from this case study, Felix Bauer analyzed this modeling approach for a Norweign case study. Based on the same model, but with different parameters, and with two other technologies available instead of geothermal technologies. Different parameters were not only set for the technologies, but also for the general conditions, like grid temperatures, energy prices and carbon emission costs. The scenarios and their weightings have been adapted as well. The trend of the investment strategy was similar compared to the US-American case study, except the restriction, that waste has to be burnt. The heat ouput of the waste incineration could be stored in another kind of storage, the so-called borehole thermal energy storage.

A future interesting aspect of the developed model will be an extension regarding electricity price forecasting. This approach is interesting to make the model even more beneficial than it is at the moment. This promising adaption for implementing forecasting will help to minimize economical risks due to electricity price fluctuations.

Other enhancements could be represented by implementing lifetime cycles of generation units and by expanding the simulation horizon. This would make reinvestments necessary to enable a long-term supply with even more decades. Another option is to consider distribution infrastructure, like pipelines and their geographical limitation. Apart from that, considering carbon capture and storage technologies may also be promising and would expand the current technology portfolio tremendous, compare Loschetter et al. [45].

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