DELFT UNIVERSITY OF TECHNOLOGY

COMPLEX SYSTEMS ENGINEERING AND MANAGEMENT
MASTER THESIS

An integrated modeling approach to provide flexibility and sustainability to the district heating system in South-Holland, the Netherlands.

Author: Eva Colussi
Student number: 4826302

Graduation committee:
Chair & First supervisor: Prof. Dr. Ir. Laurens de Vries, TU Delft
Second supervisor: Dr. Ir. Özge Okur, TU Delft
Advisor: MSc. Sugandha Chauhan, TU Delft
Advisor: MSc. Christian Doh Dinga, TU Delft
First external supervisor: Pieter Meijer, Eneco
Second external supervisor: Roald Arkesteijn, Eneco

February 15, 2024

To be defended in public on February 29, 2024

TU Delft Delft University of Technology

Acknowledgment

This thesis concludes my time as a master student in Complex Systems Engineering and Management at the Faculty of Technology, Policy, and Management. Looking back at the past 2,5 years at the TU Delft, I have enjoyed this interdisciplinary program enormously. By being able to follow numerous courses about current topics such as the energy transition, geopolitical dynamics, and socio-technology of energy systems, this program has always motivated me to learn more and dive deeper into the issues of our complex world. I have had the possibility to do a six-month exchange with the University of Bologna which has brought me even more academic insights, personal skills, and friends abroad. Being able to do this master thesis with the DEMOSES project in collaboration with Eneco has been the last, positive challenge of my master.

Without my internal and external supervisors and advisors, this master thesis would not have been possible. Therefore, I want to express my gratitude to my supervisors Laurens de Vries and Özge Okur for their relevant and honest feedback. Furthermore, I would like to thank Sugandha Chauhan for our weekly meetings. Besides being a listening ear during the tougher modeling period, these meetings helped me keep a structured workflow. I would also like to thank Christian Doh Dinga, who patiently helped me set up and develop the model. Next, I would like to thank Pieter Meijer, as my main supervisor at Eneco. I greatly appreciate our weekly meetings at the office. Besides helping me set up the research and answering all my questions about the district heating network, Pieter helped me numerous times with solving modeling bugs. I would like to thank Roald Arkesteijn, with whom I had biweekly meetings, discussing my research progress and just being a listening ear.

Lastly, I would like to thank the people in my personal life. I would like to thank my friends and flatmates, who have made me feel at home in Delft. They provided the welcome distraction from my thesis in the form of fun, sports, and music. I would like to thank my girlfriend for her endless support and understanding while also graduating this year. Lastly, I would like to thank my parents and my brother for their support and interest, and for believing in me as long as I can remember.

Eva Colussi
Delft, February 2024

Executive Summary

Problem indication

Climate change is widely acknowledged to be one of the key challenges of the 21st century (IPCC, 2022). One of the ways to mitigate global warming is the decarbonization of the energy system. In the European Union (EU), heating and cooling account for 50% of the total energy consumption and half of the carbon emissions, as 75% of the energy is still supplied by fossil fuels. On the national level, energy transition decision-makers are sailing in the dark. How can market parties optimize the mix of heat supply technologies, while responding to policies and network requirements? To adequately manage renewable energy on a large scale, flexibility measures need to be in place across all components of the system, from generation to distribution, to supply and demand. Considering the generation and distribution side of district heating networks (DHN), energy efficiency, power-to-heat (P2H) technologies, and energy storage are relevant. Energy efficiency measures generate flexibility services from an energy conservation standpoint. In the case of a system with multiple energy carriers, switching between these energy carriers results in high flexibility. P2H technologies can be implemented in the DHN such as heat pumps, electric boilers, and geothermal sources in combination with heat storage.

Research goal and question

This master thesis is part of the TU Delft research project "DEMOSES" (Designing and Modelling Future Systems of Energy Systems), which aims to couple existing energy models into integrated systems of models. As a result, market parties, energy infrastructure operators, and governments can make far-sighted, optimal decisions for an efficient energy transition in the Netherlands. The main research question entails: *How can the integration of heat storage and additional heat sources enhance the flexibility and long-term sustainability of the South-Holland DHN?*

This research is divided into three sub-questions, to finally answer the main research question. The sub-questions are:

1. What regulatory and policy frameworks are necessary to support the implementation of heat storage and additional heat sources within the South-Holland DHN, and how can they work as an incentive for sustainable and future-proof practices?

2. What are the requirements for a DHN model to facilitate informed investment decisions, considering factors such as growth, decarbonization, and changing heat demand patterns?

3. What effect does expanding the DHN with additional heat sources and heat storage have on the flexibility and sustainability of the DHN in South-Holland?

The approach of this research is to provide a more compatible model of the Eneco low-carbon heat network in the province of South-Holland. This project focuses on the rich case of this regional DHN, and how this network can be optimized in terms of operational cost, and investment planning. Employing a modeling approach, the impact of the DHN expansion is explored and analyzed.

Research method

For this master thesis, several research methods are used. For the first sub-question, international, national, and regional regulations, and policies on DHN are analyzed. For the second sub-question, an analysis is done of the current model of Eneco, and model requirements are defined for the new model. For the third sub-question, the new model is developed in Python, with the packages 'NetworkX' and 'Pyomo'. The new model economically optimizes the DHN of South-Holland, with a set of variables and constraints. Additional sources and storage are added to the network. A comparative analysis is done of different network expansion cases, based on the policy analysis.

Results & conclusions

The new DHN model of South-Holland economically optimizes the heat generation. The modular buildup of the model facilitates model expansion, using additional heat sources and heat storage. Furthermore, electricity, gas, and CO2 prices can be modified, as well as the heat demand. Varying prices, demand, and additional heat sources and storage provide a relevant insight into the flexibility of the DHN of South-Holland. The results indicate that the addition of renewable heat or P2H sources strongly decreases the total yearly costs of the network as well as the CO2 emissions. On the other hand, additional heat storage only provides increased flexibility, which, however, does not result in decreasing costs or CO2 emissions.

Looking ahead to 2030, with the projected electricity, gas, and CO2 prices as well as demand increase taken into account, the effect of additional sources on the network significantly reduces the yearly costs and CO2 emissions. Where heat storage can lead to an increase in CO2 emissions in a conventional network, in a DHN with geothermal sources, heat pumps, and e-boilers, heat storage can provide the necessary flexibility, as well as sustainability. Therefore, it can be concluded that expanding the DHN with additional sources and additional storage provides the needed flexibility and sustainability. Considering the projected electricity, gas, and CO2 prices for 2030, financial support should be provided to invest in heat sources, and heat storage in combination with heat sources to limit the costs and CO2 emissions of the DHN of South-Holland, and meet the heat demand.

Recommendations

From a policy perspective, the development of additional heat sources and heat storage faces obstacles. Further research is required on the proposal of the Collective Heat System Act and its impact on the investment climate, as well as on the flexibility and sustainability of DHN in the Netherlands. In terms of strategy, investment in additional heat sources such as geothermal sources, heat pumps, and e-boilers is recommended, in combination with heat storage. Besides the decrease in CO2 emissions of DHN, this would significantly decrease the total costs of the network, looking at the price and demand projections for 2030.

In terms of modeling DHN, further research can be done on combining constraints and optimization of different time frames, to consider long-term contract structures, long-term heat storage, as well as weather forecasts. Furthermore, low- and medium-temperature district heating can be considered, allowing different heat sources and heat storage to be added to the network. Lastly, this model can potentially be coupled with other energy system models in the DEMOSES research project, which can serve as a decision-support tool to make the Dutch energy system future-proof. This can be done by coupling heat, electricity, gas, and potentially hydrogen distribution grids, and studying how their interaction can provide increased flexibility and sustainability.

List of Figures

List of Tables

List of abbreviations and acronyms

AES Aggregated Energy Systems. 2

aFRR automatic Frequency Restoration Reserve. 39

AML algebraic modeling languages. 27

ATES Aquifer Thermal Energy Storage. 11, 12, 14, 39

CAPEX capital expenditure. vi, 38, 39

CHP Combined Heat and Power plants. 3, 18, 39, 47

CSV comma separated values. 24

DEMOSES Designing and modeling future systems of energy systems. iv, 6, 23, 24, 64

DHN District heating network. iii–vi, xi, xii, 1–15, 17–24, 26–29, 32, 33, 35, 37–42, 57–64, 69

DSO Distribution system operator. 7

ED Economic dispatch. 22

EG 'Energie-efficiëntie Glastuinbouw', a subsidy to enable investments in heat sources for the greenhouse industry. 9

EMS Energy Management Systems. 2

ESM Energy System Models. 2, 5

EU European Union. 1, 5, 8, 14

FCR Frequency Containment Reserve. 39

GLPK GNU Linear Programming Kit. 29

II3050 Integral Infrastructure Exploration 2030-2050. 1, 38–40

IWH Industrial Waste Heat in Rotterdam. 17, 18, 26, 32, 35, 45, 47–49, 53

KEV Dutch abbreviation for 'Klimaat en Energieverkenning', climate and energy exploration. 37–42, 54, 57, 60

LoN 'Leiding over Noord', dutch for connection over the north, a district heat network connection at the north side of Rotterdam. 15, 21

MES Multi-energy systems. xi, 2, 3

MILP Mixed integer linear programming. 16, 22, 24

MIP Mixed integer programming. 33

NetworkX NetworkX is a Python package for creating, manipulating, and studying the structure, dynamics, and functions of complex networks. 6

OPEX operating expenditure. vi, 38, 39

P2H Power-to-Heat. iii, iv, 3, 38, 39

PEF Primary Energy Factor. 9, 14

PTES Pit Thermal Energy Storage. 39

Pyomo Python Optimization Modeling Objects. 6, 27, 29

RED Renewable Energy Directive of the European Union (2023/2413). 8

RES Dutch abbreviation for 'Regionale Energie Strategie', the regional energy strategy. 10

SDE++ 'Stimulering Duurzame Energieproductie en Klimaattransitie', a subsidy for stimulating sustainable energy and climate transition. 9, 13

TES Thermal Energy Storage. 3

TSO Transmission system operator. 7, 10

TTES Tank Thermal Energy Storage. 39, 40

UC Unit commitment. 22, 27, 29, 30

WI Waste Incineration Rotterdam. 15, 17, 18, 26, 31, 32, 45, 47–49, 52, 53

WIS 'Warmtenetten Investeringssubsidie', a subsidy to enable investments in collective heat networks. 9

WLQ Warmtelinq, the district heat network connection between the cities of Rotterdam and Den Haag. v, vi, 14, 15, 21, 27, 35, 36, 47, 73

Nomenclature

$\delta_{u_{n,t},u_{n,t-1}}$ Krockener delta function (δ) to represent the condition that checks whether the change from $u_{n,t}$ to $u_{n,t-1}$ is equal to 1

ΔT Temperature difference of the water

η_n^{charge} Efficiency of charging the buffer in node n

$\eta_n^{\text{discharge}}$ Efficiency of discharging in node n

$\text{flow}_{(i,n),t}$ Flow through edge (i,n) to node n at timestep t

$\text{flow}_{(n,i),t}$ Flow through edge (n,i) from node n at timestep t

$\text{inflow}_{n,t}$ Inflow in node n at timestep t

$\text{outflow}_{n,t}$ Outflow from node n at timestep t

$B_{n,t}^{\text{charge}}$ Buffer consumption in node n at timestep t

$B_{n,t}^{\text{discharge}}$ Buffer production in node n at timestep t

B_n^{loss} Storage energy loss in node n

BL_n^{max} Maximum buffer content level in node n

$BL_{n,t}$ Buffer content level in node n at timestep t

$C_{n,t}^{\text{CO2}}$ Expenses on CO2 certificates of production unit n at timestep t

$C_{e,t}^{\text{edges}}$ Costs of transporting connection of edge e at timestep t

$C_{n,t}^{\text{elec}}$ Costs or revenues of a plant by the products m produced by the production unit n at timestep t

$C_{n,t}^{\text{gas}}$ Expenses on gas to run production unit n at timestep t

$C_{n,t}^{\text{nodes}}$ Costs of the operating heat supplying plant(s) in node n at timestep t

$C_{n,t}^{\text{SU}}$ Start-up cost of production unit n at timestep t

$C_{(i,n),t}^{\text{transport}}$ Cost to transport heat over a connecting line (i,n) at timestep t

$C_{n,t}^{var}$ Variable cost of production unit n at timestep t

c_p Specific heat capacity at constant pressure

C_m Costs of product m

C_r Costs of resource r

CF_n Cash flow of process n owned by actor k

$CL_{n,t}^{\text{CO2}}$ CO2 consumption needed to produce the heat of production unit n at timestep t

$CL_{n,t}^{\text{gas}}$ Gas consumption needed to produce the heat of production unit n at timestep t

CL_n Power (heat) consumption of node n

E_e^{loss} Heat loss through the edge (i,n) to node n

$EF_{i,n}^{\max}$ Maximum flow through edge e

m Mass of the hot water flow

P_n^{yearly} Total power (heat) produced by production unit n in one year (as contracted)

$PL_{n,t}^{\text{elec}}$ Electricity produced or consumed when generating the heat from production unit n at timestep t

PL_n Production level of process n

$PL_n^{\max}$ Maximum amount that can be produced by a power plant if it is turned on

$PL_n^{\min}$ Minimum amount that can be produced by a power plant if it is turned on

$PL_{n,t}$ Power (heat) generation of node n at timestep t

Q Energy in the form of heat (GJ)

r_n^{rated} Maximum power supplied by the buffer in node n per timestep

$r_{n,t}$ Power from the buffer that is exchanged in node n at timestep t

SU_n Startup costs of production unit n

$t^{\text{lookahead}}$ Look-ahead period

t^{opt} Optimization period

U_k Cash flow of actor k

$u_{n,t}$ Binary value which defines whether the production unit n runs or not at timestep t. If the plant is off, the value is 0, if the plant is on, the value is 1

var_n variable costs of production unit n

$\text{CO2}_{n,t}$ Amount of CO2 credits needed to produce the heat of node n at timestep t

$\text{elec}_{n,t}$ Amount of electricity produced by production unit n at timestep t

$\text{gas}_{n,t}$ Amount of gas needed to produce the heat of node n at timestep t

Contents

1 Introduction

1.1 Context

Climate change is widely acknowledged to be one of the key challenges of the 21st century (IPCC, 2022). One of the ways to mitigate global warming is the decarbonization of the energy system. With the rapid growth of renewables and the electrification of demand, the energy system is becoming increasingly integrated. Where the energy system was previously mostly limited to one energy carrier and one network level, it is becoming more complex from the technical, economic, and policy perspectives. This leaves market parties, network operators, and policy-makers in difficult positions. How can providers of energy infrastructures determine where, when, and how much to invest when demand will shift from natural gas to electricity, hydrogen, or heat networks? Answering these types of questions becomes increasingly difficult for market parties when deciding how to invest in renewable energy generation and storage. In turn, the network operators need to understand how the market develops and how other network operators decide when and where to invest. Furthermore, policymakers need to understand what impact new regulations have on the integrated energy system. Therefore, long-term planning of the energy transition is only possible if stakeholders jointly come to an integral understanding of the system (Moallemi & Malekpour, 2018).

In the European Union (EU), heating and cooling account for 50% of the total energy consumption and half of the carbon emissions, as 75% of the energy is still supplied by fossil fuels (Aunedi, Pantaleo, Kuriyan, Strbac, & Shah, 2020). In the Netherlands, more than 90% of the households are heated with natural gas or other fossil fuels (Ministerie van economische zaken, 2023a). Only 6% of the households in the Netherlands is connected to district heating, of which only 23% of the heat is waste heat from industry or generated by renewable sources (Billerbeck et al., 2024). To ensure the long-term sustainability of heating households in the Netherlands, CO2 emissions of the DHN should be reduced. On the national level, energy transition decision-makers are sailing in the dark. How can market parties optimize the mix of heat supply technologies, while responding to policies and network requirements?

To keep the rising temperature below limits as declared in the Paris Agreement, the Netherlands aims to be climate neutral in 2050. This requires a drastic rebuild of the energy system within less than 30 years, in which the district heating network (DHN) can play a significant role in reducing emissions in high-density areas (Capone, Guelpa, & Verda, 2021). To meet future energy and electricity demand and supply, the national infrastructure should be strongly adapted (TenneT, 2021a). An example of the potential of district heating can be found in South-Holland, a province in the Netherlands, which is densely populated. Industry in this area produces waste heat which is distributed through the DHN. This network is now extended to connect more high-density areas to this network. While this area is developing, the proposal of the Collective Heat System Act ('Wet Collectieve Warmte') has put constraints on private ownership of the network, as well as tariff regulations. To fully meet the future demand for heat in this region as well as the long-term sustainability goals, decisions need to be made regarding the operation of - and investment in - this network, while complying with the policies and regulations.

1.2 Knowledge gap identification

While scientific literature is abundant on the integration of DHN in the bigger energy system from the technical perspective, little research is done on the market side, and to an even smaller extent on market analysis of integrated systems. The Dutch government has declared the importance of multi-sectoral exploration of the energy system in the Dutch Climate Agreement, by the establishment of the Integral Infrastructure Exploration 2030-2050 (II3050). The II3050 report aims to provide insights into the possible development of the future energy system, with a chapter on heat infrastructure impact (Nikas et al., 2021; Rijksoverheid, 2019; TenneT, 2021b). However, interaction with the electricity market is not included in these network studies. Including market parties in the integration of the energy system will provide a more complete picture, and therefore result in improved decision-making by policymakers, business cases by market parties, and network reliability by network operators.

1.2.1 Energy System Models

Energy System Models (ESM) are fundamental to planning the energy transition and understanding the impacts of possible future pathways (Kühnbach, Guthoff, Bekk, & Eltrop, 2020). In essence, ESM generate insights and analysis on the supply and demand of energy to support policy-making. Thus far, multiple types of ESM exist with different levels of complexity, which are often reliant on the model coupling to achieve the desired ESM capabilities (Chang, Lund, Thellufsen, & Østergaard, 2023). Where Kühnbach et al. (2020) uses a multi-modeling approach to develop different energy scenarios with a multitude of stakeholders, Chang et al. (2023) emphasizes that with this approach 'gaps remain in establishing model links addressing the human and social dimensions'. These social dimensions become especially clear in a case-specific study on one part of the DHN of South-Holland by Oorschot (2020) with the introduction of the Heat Act. Each neighborhood has different characteristics in terms of building types, year of construction, isolation level, etc. This in turn results in different complications for each 'heat lot' in carrying out the heat transition (Oorschot, 2020).

1.2.2 District heating network models

District heating provides a convenient and efficient solution for both heating and cooling buildings in high-density areas. The heat that would otherwise be lost can be used without emitting more CO2 emissions (Capone et al., 2021). Previous research on DHN modeling focused on either the optimal mix of heat supply technologies in specific regions, with limited attention to the integration with the electricity network (Nami, Anvari-Moghaddam, & Arabkoohsar, 2020), or the heat and electricity network integration with a set mix of heat supply technologies Capone et al. (2021). The integration between DHN models with electricity models has been previously explored with electrical power flow models (Liu, Liu, Cai, & Jin, 2023). The developments in this field have resulted in an increasingly tight connection between heating and cooling systems and electricity networks. Therefore, the concept of Multi-Energy Systems (MES) has been coined, where the integration between thermal grids and electricity grids is an example of MES (Capone et al., 2021).

1.2.3 Multi-Energy Systems (MES)

In MES, also called Aggregated Energy Systems (AES), the potential lies in the possibility of converting one type of energy into another type. In the context of district heating, for example, heat-to-power or power-to-cool technologies can be used for the preferred form of energy distribution and storage. Thereby, reliability and efficiency are MES increased by providing a synergy between different energy carriers (Ayele, Mabrouk, Haurant, Laumert, & Lacarrière, 2019). Few research has been done in the direction of MES considering DHN. One example is the study done by Capone et al. (2021), which provided a tool methodology for a fictional small-scale multi-energy system including heat, cold, and electricity. This study concentrated on the one hand on demand-side management, and the other hand on production optimization. Another study conducted by Alavijeh, Steen, Norwood, Tuan, and Agathokleous (2020) focused on the combination of different local energy management systems (EMS) by investigating operation strategies that can be adopted to abate CO2 emissions in local multi-energy systems. Lastly, Alavijeh et al. (2020) combined optimal geographical placement of heat supply technologies with optimal electricity distribution. In existing research, it is acknowledged that carbon prices and strategies to mitigate CO2 emissions are to be taken into account. Therefore, considering future scenarios for various levels of emission reduction, carbon pricing, and fuel costs can lead to improved insights into the strategic planning and operation of MES (Alavijeh et al., 2020).

1.2.4 Strategic energy planning

Due to the decentralized nature of district heating, local circumstances play a significant part in the strategic planning of heating systems (CE Delft, 2022). Paardekooper, Lund, Thellufsen, Bertelsen, and Mathiesen (2022) distinguish 4 different heat sector types, based on 14 different district heating cases in the EU. These 4 types are (1) existing heat planning traditions, intending for more efficiency and integration; (2) existing heating infrastructure, planning to refit and upgrade both buildings and existing heating infrastructure; (3) existing gas infrastructure, requiring essential transition;

(4) and those without heat planning traditions (Paardekooper et al., 2022). This is why the expansion of the district heating network (DHN) of South-Holland is especially interesting: a transition is happening away from gas for heating and cooking to other, more sustainable means (type 3), and a functioning district heating network is present in the city of Rotterdam (type 2). Depending on the heat sector type, policy recommendations have been made according to the Energy Efficient First (EEF) principle. This principle entails that the most 'cost-efficient energy efficiency measures are taken in shaping energy policy and making investment decisions' (European Parliament, 2021). In practice, this principle is difficult to implement, as multiple stakeholders and decision-makers are usually involved (Yu, Mandel, Thomas, & Brugger, 2022). Yu et al. (2022) developed a decision-tree framework for this aim, while also emphasizing the need for more detail and precision to ensure the usefulness in each case.

1.2.5 Flexibility in a DHN

As suggested by the International Renewable Energy Agency, to adequately manage renewable energy on a large scale, flexibility measures need to be in place across all components of the system, from generation to distribution, to supply and demand (IRENA, 2018). Flexibility, as identified by Mugnini, Comodi, Salvi, and Arteconi (2021), can be provided to a DHN through (1) energy efficiency, (2) energy storage, (3), and control logic. From the generation and distribution side of a DHN, the first two means are relevant.

Firstly, energy efficiency measures provide flexibility services from an energy conservation standpoint. In the case of a system with multiple energy carriers, switching between these energy carriers results in high flexibility (Boldrini, Jiménez Navarro, Crijns-Graus, & van den Broek, 2022). Power-to-heat (P2H) technologies can be implemented in a DHN such as heat pumps, e-boilers, and combined heat and power plants (CHP) (Javanshir, Syri, Tervo, & Rosin, 2023a; Mugnini et al., 2021). Another constant source of heat that can be developed is geothermal heat. Therefore, the conversion of heat to power can provide the necessary flexibility by managing and mitigating temporal imbalances (Schmidt & Leitner, 2021). Heat that cannot be used in one hour, can be converted to electricity and sold to the market. In the next hour, when there is not enough heat provided by the geothermal plant, a heat pump or e-boiler can be used which converts electricity to heat. This way, heat can be stored as power, power can generate heat and different energy carriers can be used.

Secondly, for the second mean, energy storage can provide a decoupling of energy generation and demand, therefore adapting the supply curve. In a DHN, heat can be stored in a Thermal Energy Storage (TES). Currently, heat is already stored within the network itself with the distribution pipes. For short-term heat storage, buffers can be used. The P2H technologies can provide energy conversion between heat and electricity (Schmidt & Leitner, 2021). With the increasing amount of renewable energy generation, it is essential to study the impact of flexibility by switching between energy carriers, as well as flexibility by means of buffer capacity in a DHN.

In summary, state-of-the-art literature contains research on the technical and economic side of MES, as well as research on energy planning and investment approaches in the field of district heating. However, a knowledge gap exists in the interference of technical, economic, and policy issues. Therefore, this research focuses on the interplay between technology, policy, and managing the heat transition in the form of a DHN in South-Holland.

1.2.6 Main research question

The transition towards sustainable and flexible energy systems is a critical imperative in mitigating climate change and ensuring long-term energy security. In this context, the integration of heat storage and additional heat sources plays a pivotal role in enhancing the flexibility and sustainability of a DHN. Therefore, the main research question of this research entails: *How can the integration of heat storage and additional heat sources enhance the flexibility and long-term sustainability of the South-Holland DHN?*

1.2.7 Sub-questions

This research endeavors to investigate how the integration of heat storage and additional heat sources can enhance the flexibility and long-term sustainability of the South-Holland DHN. By exploring regulatory frameworks, modeling requirements, and identifying the impact of network expansion, this study aims to provide valuable insights for informed decision-making in the realm of energy infrastructure development. To achieve this overarching objective, the research is structured around three interconnected sub-questions, each addressing specific aspects of the integration of heat storage and additional heat sources within the South-Holland DHN:

1. What regulatory and policy frameworks are necessary to support the implementation of heat storage and additional heat sources within the South-Holland DHN, and how can they work as an incentive for sustainable and future-proof practices?
2. What are the requirements for a DHN model to facilitate informed investment decisions, considering factors such as growth, decarbonization, and changing heat demand patterns?
3. What effect does expanding the district heat network with additional heat sources and heat storage have on the flexibility and sustainability of the DHN, particularly in adapting to fluctuating heat demand and supply conditions?

The first sub-question delves into the regulatory and policy frameworks necessary to support the implementation of heat storage and additional heat sources in the DHN in South-Holland. By analyzing these frameworks, this study aims to understand their role as incentives for sustainable and future-proof practices.

The second sub-question focuses on identifying the requirements for a DHN model that facilitates informed investment decisions. Factors such as network growth, decarbonization goals, and changing heat demand patterns will be considered to ensure the model's effectiveness in guiding decision-making processes. For this aim, a DHN model is developed with the possibility of running different scenarios for potential policy developments concerning decarbonization and growth of the network, affecting and affected by changing heat demand patterns.

The third sub-question investigates the impact of expanding the DHN with additional heat sources and heat storage regarding the flexibility and sustainability of the network. By analyzing various scenarios, this study seeks to understand how the network adapts to fluctuating heat demand and supply conditions, thereby informing strategies for enhancing its sustainability and flexibility. By iterating between the model design and model performance, requirements for flexibility and sustainability of a DHN are identified. This provides insights into the potential heat storage options for different scenarios. Furthermore, potential additional heat sources and heat storage are incorporated into the model to analyze potential benefits and challenges to the network.

1.3 Research approach

An integral understanding of the system by the stakeholders is needed for long-term planning of the energy transition. The approach of this research is to provide a more compatible model of the Eneco low-carbon heat network in the province of South-Holland. This project focuses on the rich case of this regional DHN, and how this network can be optimized in terms of operational cost, and investment planning, taking regulations and policies of different governance levels into account. The focus of the current model is how the utilization of different sources of heat varies for different scenarios of decarbonization. Where planning of the DHN currently relies on assumptions and estimates about how to operate and where to invest, the aim of modeling this network is to mitigate these uncertainties. This is done by focusing on the interaction with the distribution of heat and electricity to study the interaction between these grids. The new model is used to study flexibility provision in integrated energy systems by using heat-electricity interaction. For Eneco, this can potentially provide insights into the impact of new low-carbon heat sources and energy storage.

Currently, there is a lack of understanding in terms of how flexibility and sustainability are taken into account in the operational and economic decisions of the DHN, and how these decisions are affected by policy. The functioning of a DHN within the socio-technical system can be better understood if additional flexibility options are provided to interact with the electricity distribution network. How does policy influence investment and operational decisions in the current DHN from the market party perspective? What interventions are needed to reduce uncertainty in the development of a DHN? Answers to these questions can potentially be provided by applying a modeling approach. With this approach, the impact of system interventions such as operational, economic, and policy 'buffers' can be analyzed and visualized. Modeling a DHN requires the adoption of a socio-technical systems view, as parts of the man-made world are modeled. The development, operation, and management of the technical network are modeled, which in turn affect the behavior of market parties, policy-makers, and customers. Therefore, the modeling approach is divided into 6 steps, adapted from the 10 practical steps for creating and using a model for a socio-technical system by Van Dam, Nikolic, and Lukszo (2012).

1. Analysis of existing model
2. Define model requirements
3. Model design
4. Software implementation of the model and validation
5. Model experimentation
6. Scenario analysis

The scope of this modeling approach is to provide a 'plug-and-play', user-friendly, model of the DHN of the Dutch province of South-Holland. This network consists of the existing DHN in Rotterdam with the planned connection to the area of the city of Den Haag. The current model is an economic optimization model, which optimizes the operations and costs of the DHN for each hour in a year. Additional constraints such as existing subsidies, stimulation mechanisms, and the merit order are implemented in the model. The model is continuous, as with each time step, parameters such as electricity prices, efficiency, and demand change.

The first step is the analysis of the existing model, to identify the model requirements and highlight important details that should be included in the model. The second step is to explore what level of detail of the local electricity distribution system and DHN is required, to achieve the desired extent of integration. The third step is the model design, based on the defined model requirements. The fourth step is the software implementation of the model while incorporating the requirements of the market party as well as the integration requirements of the previous step. As an Agile method is used, an iterative modeling approach is taken by iterating between steps 2, 3, and 4. The aim of this is to start with the smallest meaningful model that can provide results and to further build up from there. Model validation is done by comparing the modeling results to the current situation/reality, as well as to the output of the previous model. The next step entails running the model optimization for various scenarios based on policy projections. The last step aims to analyze these scenarios in terms of the impact of potential improved integration between the heat and electricity flexibility of the DHN of South-Holland.

Modeling the DHN of South-Holland with flexibility provision can potentially demonstrate trade-offs between operational, economic, and policy decisions in different scenarios. For example, optimal configurations of heat storage and additional heat sources can be researched, under different decarbonization scenarios. Essentially, modeling different scenarios can illuminate core uncertainties about possible future pathways and their consequences (Epstein, 2008). For private and public parties, energy models can be a useful tool that can provide perspective for action, provide financial and socio-economic understanding, transparency, and validity (Henrich, Hoppe, Diran, & Lukszo, 2021). In the process of simulating ESM, Chang et al. (2023) stresses that using scenarios to explore multiple economic assumptions or different policies can provide insights into technological and economic alternatives.

1.4 Methodology

The research methods to gather this data vary depending on the sub-question. The required data, research method, and tools used for each sub-question are summarized in table 1. The first sub-question requires an understanding of the regulation and policies on DHN in the EU, the Netherlands, and in South-Holland. To realize this, a policy analysis is carried out, by means of reviewing policy documents at national, regional, and local governance levels. Furthermore, a literature review regarding DHN policy is done to understand the background of DHN policy-making.

For the second sub-question, requirements for a DHN are studied. This requires a thorough review of the existing model through expert knowledge at Eneco. This is done by means of 3 interviews with experts of the Portfolio Optimization team, attending a deep-dive day organized by the Eneco Heat Desk, as well as 2 interviews with the fundamental analysis team at Eneco. Simultaneous to the analysis of the existing model by means of desk research of Linny-R and diving into the model specifics, uncertainties, gaps, and limitations to the model have been discussed on a weekly basis with Pieter Meijer from the Portfolio Optimization team of Eneco. To realize a complete understanding of the existing model and due to the lack of existing model documentation, the current model is documented. Moreover, possible requirements of the new model from the perspective of Eneco have been discussed in these meetings. Requirements of the model have been in turn proposed and discussed with two modeling experts of the DEMOSES research group. Furthermore, the model requirements are explored regarding integration with other energy system models. The model objective, constraints, and variables have been defined in collaboration with two advisors of the DEMOSES research group, to set up a conceptual model of a DHN model.

For the third sub-question, the network expansion cases and the model results are required. The model is developed based on the model requirements and the conceptual model from sub-question 2. The model is validated by comparing the results to the real-world data and the previous model. Model verification is done by changing variables in the model and analyzing the model behavior. Finally, model experimentation and network expansion are carried out to answer the third sub-question. Experimentation with price and demand variations, including projections of the development of DHN in the Netherlands are used to construct different price and demand scenarios. The network expansion cases follow from the policy analysis of the municipalities situated in the South-Holland DHN area. With this network and scenario input, the model is run, and the scenarios are analyzed. The model is built in Python using the packages NetworkX and Pyomo to build a modular optimization model. Excel is used to organize model input and output. The Python packages 'Matplotlib' and 'Pandas' are used to analyze and visualize the results. The model is developed and expanded taking an iterative approach in terms of design and implementing constraints.

Considering modeling the DHN of South-Holland, it is crucial to distinguish between the model and reality. A model is a simplification of reality, while the heat transition in the form of a DHN is regarded as a 'wicked problem' (Moallemi & Malekpour, 2018). Therefore, the feedback loop between the optimization and modeling of the DHN is crucial.

Table 1: Research data, methods and tools

Sub-question	Data required	Research method	Tools
1	Regulation and policies on DHN	Policy analysis	Literature review, policy documents review
2	Requirements of a DHN model	Current DHN model analysis, expert knowledge of Eneco, expert knowledge of DEMOSES project group	Current model documentation, conceptual modeling of a DHN
3	Configuration of heat sources and heat storage, scenario input, model output	Model development, validation, verification, experimentation, expansion	Python (NetworkX, Pyomo), Excel

1.5 Contributions

As the current model lacks the possibility to be coupled with models of different scales, sectors, and carriers, the approach is to adapt the DHN model for this aim. With this project, Eneco aims to get closer to reaching climate ambitions such as phasing out natural gas and accelerating sustainable heat. This MSc Thesis is part of a larger project, DEMOSES (TU Delft, 2021), that aims to couple existing energy models into integrated systems of models. As a result, market parties, energy infrastructure operators, and governments can make far-sighted, optimal decisions for an efficient energy transition in the Netherlands.

The relevant beneficiary from the results is Eneco, one of the consortium partners of the DEMOSES project. Policymakers, energy companies, and transmission- and distribution system operators (TSO & DSO) are beneficiaries, as the project provides a hands-on case study of the consequences of the investment choices, to support the energy transition. Furthermore, it provides insights into the dynamic interactions between the heat and electricity networks over time.

1.5.1 CoSEM relevance

This thesis is written as part of the master program *Complex Systems Engineering and Management*, which relates to innovations in complex socio-technical environments (TU Delft, n.d.-a). In this research project, the case addresses a regional heat grid, in which technical, institutional, and societal aspects are considered. Furthermore, this approach requires the interaction of technical systems (heat and electricity), law, and institutions, with a multitude of conflicting needs and interests in a highly uncertain environment. The DHN in South-Holland is not just a technical system, it is regulated by laws and institutions. The climate ambitions of the Dutch government and business cases of market parties illustrate these conflicting needs and interests.

1.6 Thesis outline

This thesis is divided into 5 chapters. The next chapter is a policy analysis focused on national, regional, and local policy on DHN. From this analysis, different model expansion cases are proposed. Chapter 3 is an analysis of the current DHN model of South-Holland in Linny-R, and the model conceptualization, formulation, verification, validation, and experimentation of the new DHN model. Chapter 4 provides the results of the cases for different price, demand, and network expansion scenarios. Chapter 5 discusses these results and provides an evaluation of the methodology and limitations. Chapter 6 draws conclusions by answering the research question and the sub-questions and provides recommendations in terms of policy, modeling, and further research.

2 Regulatory and policy analysis

In this section, the existing regulatory and policy frameworks on DHN are analyzed. This analysis is focused on the flexibility and sustainability of the DHN in South-Holland. As identified by Billerbeck et al. (2023), especially EU countries with an extensive support mechanism for district heating achieve high contributions of renewable energy and waste heat in district heating networks. Therefore, the focus of this analysis is on renewable energy targets and support mechanisms of district heating networks. Firstly, specific EU regulation on the heat transition is analyzed. Secondly, the Dutch national regulations for the development of DHN are explored, considering subsidy schemes and national laws regarding district heating. Thirdly, policies of the region of Rotterdam and Den Haag are analyzed, regarding the development of heat supply and demand in DHN. This is done on the regional scale and municipal scale. Specific targets and plans for the DHN in South-Holland are highlighted. Lastly, the strategy of Eneco is explored, concerning district heating. Possible network expansion cases of the DHN of South-Holland in terms of heat sources and heat storage will be based on national, regional, and local policy, as well as the possibilities discussed with Eneco.

2.1 EU regulation for sustainable heating and cooling

The Renewable Energy Directive (RED), revised in October 2023, states that until 2026, it is binding to increase the renewable energy for heating and cooling with 0.8%, and 1.1% from 2026 to 2030. Additional yearly targets are specified for each member state, as an 'indicative top-up'. For the Netherlands, this percentage is 1.1% until 2026, and 0.8% from 2026 to 2030 (European Union, 2023; PBL, 2023; PBL, TNO, CBS & RIVM, 2022). Therefore, the binding target value of the RED for the Netherlands is 1.9% of renewable energy growth for heating and cooling of households and buildings. How these targets for sustainable heating and cooling are planned to be met through DHN is further elaborated in the national, regional, and local policies. In terms of ownership of DHN, the proposal of the Collective Heat System Act aims to stimulate open access networks for third parties (CE Delft, 2022). It is however not required for the DHN market, unlike the gas and electricity market, to be unbundled (Billerbeck et al., 2024).

2.2 National regulation for DHN

2.2.1 Collective Heat System Act

To be able to reach climate neutrality, the Dutch government has stated that buildings and households in the Netherlands should be natural gas-free in 2050. This is in line with the national climate agreement. To enable this heat transition, the state has revised the national heat act, which has resulted in the proposal of the 'Collective Heat System Act' in November 2023, also known as the 'Warmtewet 2' (Ministerie van economische zaken, 2023a, 2023b). The proposal states that 2.6 million households should be connected to collective heat networks with sustainable heat sources in the following years. Furthermore, the goal is to 'increase public guidance in the implementation of this heat transition and thus contribute to affordability, sustainability and security of supply for all households and companies' (Ministerie van economische zaken, 2023b). The reasoning behind the proposal is that collective heating networks are vital infrastructures that are monopolistic in nature, which therefore require public ownership (Herreras Martinez et al., 2023). Possible arguments in favor of public ownership are affordability for the consumer, connecting different possible areas, and democratic representation in coordinating local projects. In the report of CE Delft (2022), the need for strong coordination of large projects of DHN expansion per neighborhood is stressed, in terms of supply and demand. On the other hand, possible arguments against public ownership are the lack of municipal expertise, costly and complex unbundled projects, unattractive business models for private parties, and therefore no guarantee for lowering costs for the consumer (Herreras Martinez et al., 2023; PBL, 2023; PwC, 2022). Furthermore, Lavrijssen and Vitéz (2021) argues that low-carbon heat networks require multiple smaller heat sources from different owners, which calls for regulation for third-party access (Billerbeck et al., 2024).

2.2.2 Guiding instruments

In December 2023, the Dutch government released a draft version of the 'National Energy System Plan' (Ministerie voor economische zaken en klimaat, 2023). This plan states the heat input as end use for the built environment will increase by 40% in 2030 compared to 2019. However, this heat can be sourced from both collective heat networks as well as individual electric or hybrid heat pumps, or other heat solutions. In the greenhouse industry, the plan states that the heat input will be more than doubled in 2030 compared to 2019. To realize this, the focus is on geothermal heat as well as industrial waste heat (Ministerie voor economische zaken en klimaat, 2023). Concrete national plans for the exploitation of the heat transition do not exist, as this is the formal responsibility of municipalities. However, certain national programs exist to support municipalities, such as the 'National Program Local Heat Transition', 'Natural Gas-free Neighborhoods Program', and the 'Heat Expertise Center' (NPLM, 2023). The NPLW supports municipalities with information, practical examples, and tools for the heat transition. Research by the NPLW indicated that municipalities recognize the potential of collective heating, however, short-term certainty and clarity are necessary regarding the frameworks of district heating from the Dutch state. This mainly concerns the ownership structure of collective heating, as well as consumption tariffs of collective heating (NPLM, 2023).

2.2.3 Financial instruments

Apart from the Collective Heat System Act, the Dutch government has some subsidies and programs in place to stimulate collective heat sources and networks. National financial instruments to realize sustainable heat sources consist of two subsidies regarding the collective aspect: the SDE++ (Stimulering Duurzame Energieproductie en Klimaattransitie', Dutch for stimulating sustainable energy production and climate transition) and the WIS ('Warmtenetten Investeringssubsidie', Dutch for collective heat networks investment subsidy). The SDE++ is the most important instrument and is divided into low- and high-temperature heat sources. The SDE++ aims to reduce the peak costs of collective heat sources. The WIS, implemented in 2023, aims to reduce the construction costs of collective heat networks (Ministerie van economische zaken, 2023b).

For the greenhouse industry areas of South-Holland, the EG ('Energie-efficiëntie Glastuinbouw', Dutch for energy efficient greenhouses) subsidy was implemented in October 2023 (RVO, 2023a). This subsidy provides a maximum of 20% of the investment in energy-efficiency measures. The case for which this subsidy is relevant for DHN is the connection to a collective heat network. Secondly, the pilot 'program natural gas-free neighborhoods', is a program which has designated 66 neighborhoods in the country as testing grounds for the heat transition. In the area of the DHN of this research, multiple neighborhoods are part of this pilot, among which the Havenbuurt in Berkel en Rodenrijs, Bospolder Tussendijken and Pendrecht in Rotterdam, Klapwijk in Pijnacker-Nootdorp, and Bouwlust/Vrederust in Den Haag. Municipalities are autonomous in deciding how to carry out this pilot program (Rijksoverheid, 2023). Thirdly, the Dutch government has stated that from 2026 onward, the replacement of a heating facility in households should be a sustainable heating method, such as a heat pump or a connection to a DHN.

Another instrument to stimulate the production of heat for a DHN in a sustainable fashion, is CO2 taxation. The Dutch Emission Authority has the responsibility to implement and collect this tax and ensure compliance (NEA, 2023). The tariff for emitting CO2 or other greenhouse gases is increasing each year until at least 2030. Furthermore, for each heat-producing unit, a PEF ('Primary Energy Factor') is assigned (Lente Akkoord, 2019). This factor is dependent on the energy performance of a producing unit. The PEF per supplied GJ of heat in 2022 for the DHN of Rotterdam is 0.27, for the DHN of Lansingerland the PEF is 0.32, while for the DHN of Den Haag this is 0.51 (Eneco, 2022; RVO, 2022). The PEF of Den Haag is higher as the majority of the heat is supplied by a gas-fired power station (54%), while in Rotterdam, the majority is provided by a waste incineration heat installation (70%).

Besides the existing financial instruments, proposals are present to directly subsidize infrastructure projects such as DHN and energy storage, to stimulate investments. Moreover, the proposals include subsidies to develop the expertise of DHN and strengthen the implementation capacity (PBL, 2023). The Netherlands Environmental Assessment Agency has indicated that how these national subsidies work together with regional and local policies is not clarified (PBL, 2023).

2.3 Regional policy for DHN

All the municipalities in South-Holland have a vision of what the heat transition should look like. Therefore, a collaboration between these municipalities and other stakeholders has been established in 2023 to align these visions. The main regional policy collaboration relevant to DHN is the 'regional energy strategy' of the region of Den Haag and Rotterdam. This is a regional collaboration between 21 municipalities, 4 water authorities, the province of South-Holland, the TSO, and other stakeholders. This collaboration has resulted in the RES 1.0, a report that elaborates on the regional energy strategy plans (Regio Rotterdam Den Haag, 2021). The high-density areas of Den Haag and Rotterdam and the greenhouse district in Lansingerland result in substantial heat demand. The RES stresses that the region should take advantage of the possible and already existing heat resources to meet this demand. Possible ways to retrieve heat for the DHN as discussed in the RES, next to the geothermal heat potential and waste heat from the Port of Rotterdam, are aqua thermal heat, solar thermal heat, and low-temperature heat storage (Regio Rotterdam Den Haag, 2021).

The heat transition visions have been analyzed by the region of Den Haag and Rotterdam and CE Delft (Regio Rotterdam Den Haag, 2023; Regio Rotterdam Den Haag & CE Delft, 2023). The progress report of the RES 1.0 concludes that a big role will potentially be played by collective, regional district heating. However, the RES concludes that municipalities in South-Holland, have not always provided a concise indication of the heat sources to be realized in this area. The regional policy does not specify specific plans or projects that are in the realization, planning, or exploration phase. Therefore, the vision of three municipalities which are relevant for the DHN as modeled for this research, are examined.

2.4 Local policy for DHN

In line with the National Climate Agreement, the municipalities are leading in the heat transition for the built environment (Rijksoverheid, 2019). Within the region of South-Holland, where the DHN network is situated, the two biggest cities and municipalities are Rotterdam, Den Haag, and Lansingerland. The municipality of Lansingerland consists of the towns Bergschenhoek, Bleiswijk, and Berkel en Rodenrijs, also abbreviated as the B-triangle. Both cities and the B-triangle have a vision of how the heat transition should look like. These visions are the first versions that provide an outlook of the heat transition until at least 2030. The visions are updated after 5 years.

Municipality of Rotterdam In the 'Rotterdamse Transitievisie Warmte' (Gemeente Rotterdam, 2021a), the municipality has determined a vision for the 'heat transition' in Rotterdam. The main aim of the heat transition is to move from using gas for heating towards more sustainable, regional sources. Possible sources mentioned in their vision are waste heat from industry, geothermal and aqua thermal sources, and sustainable electricity from solar and wind power. The municipality has estimated that the available waste heat from the port industry is almost twice as high as the future demand in the municipality. Currently, only a small part of this waste heat from the industry is used. The development of heat sources such as a geothermal source in the port of Rotterdam is in the exploration phase. Heat storage is not mentioned in the vision. In the Transitievisie Warmte, the municipality has determined which neighborhoods in the city have the potential to start the transition to become 'natural gas-free' before 2025. Overall, the municipality states to be 'natural gas-free' in 2050, which is a total of 236.000 households that are subject to the heat transition (Gemeente Rotterdam, 2021a). The municipality has determined the most economical and sustainable heating solution for the heat transition for each neighborhood in the 'WHAT-map' as shown in figure 1. 'LT/MT collectief' stands for low to medium collective heating, and 'MT/HT warmtenet' for medium to high-temperature district heating. This map indicates that the municipality focuses on the development of medium to high-temperature district heating (red) for the majority of the neighborhoods. When this heat transition will take place is indicated in the 'WHEN-map' of the municipality, as shown in figure 2. Blue indicates that they are working on the heat transition in these areas, dark green areas are advised to start the heat transition before 2025, light green areas are advised to start before 2030, and yellow areas are advised not to start the heat transition yet.

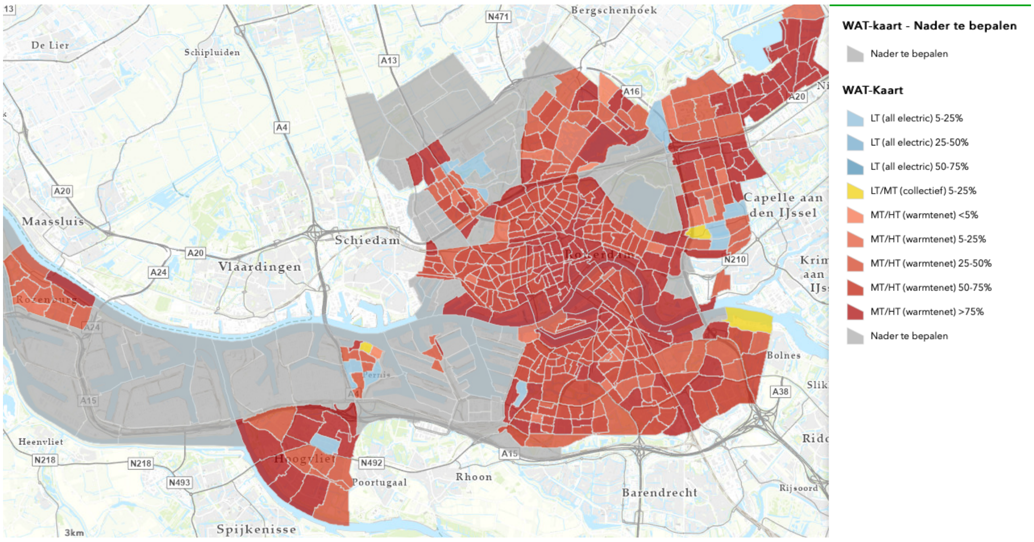


Figure 1: Map of the City of Rotterdam with alternative heating solutions per neighborhood (Gemeente Rotterdam, 2021a, 2021b).

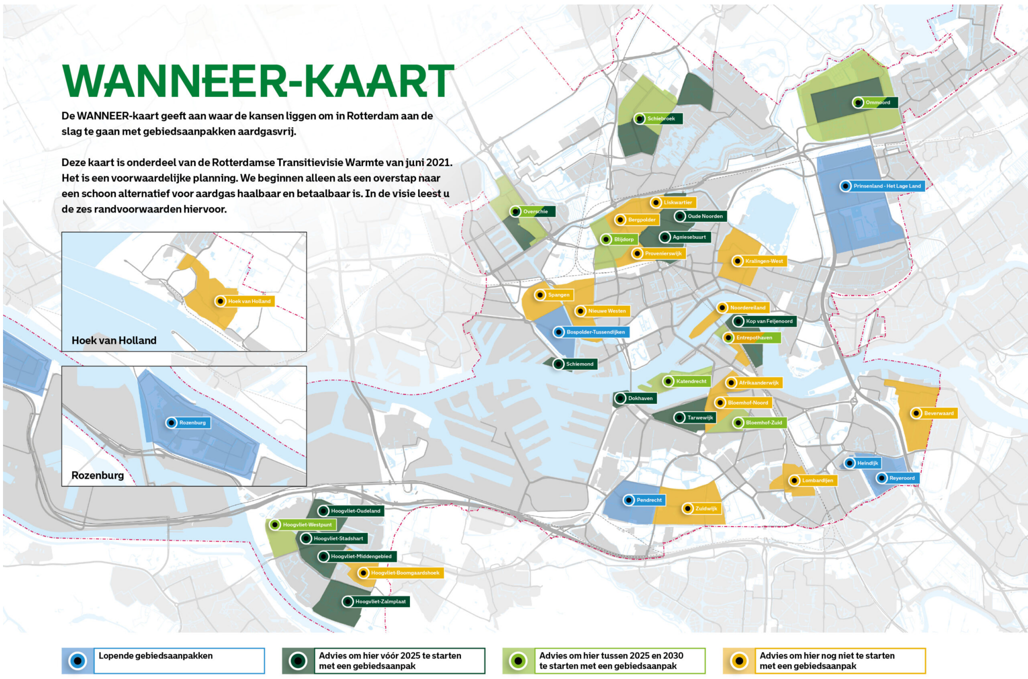


Figure 2: Map of the City of Rotterdam with indicating the phase of development of the heat transition (Gemeente Rotterdam, 2021a).

Municipality of Den Haag The municipality of Den Haag has reported their vision on the heat transition in the 'Transitievisie Warmte Den Haag' (Gemeente Den Haag, 2021). The geothermal source in Den Haag is the first geothermal source within a city in the Netherlands and operating since 2021 (Haagse Aardwarmte, 2023). Furthermore, some neighborhoods in the city are connected to low-temperature aquifer thermal energy storage (ATES). This is done by means of ground source heat pumps in combination with a water well of shallow depth (200-300 meters). The temperature of these sources is usually 25°C. One of the reasons for the low temperature is due to the prohibition of feeding in the water of a temperature above 30°C in the groundwater in the province of South-Holland (Ministerie van Verkeer en Waterstaat, 2008). The implementation of an e-boiler of 12 MW in the neighborhood 'Ypenburg' was realized in 2020 and provides heat to the DHN of Den Haag (RVO, 2023b). The municipality has determined the desired mix of heat sources for each neighborhood, before 2030 and 2040. This mix can consist of (hybrid) heat pumps and district heating network connections, as shown in figure 3. Blue areas are 'heat pump neighborhoods', dark green areas are 'district heating neighborhoods before 2030', light green areas are 'district heating neighborhoods after 2030', purple areas are a 'mix of heat pumps and district heating', yellow are 'hybrid heat pump neighborhoods', and for the brown areas, the heat transition mix is yet to be determined. Hybrid heat pumps serve as a 'transition heat source', which provides the flexibility to decide the ideal mix of sustainable heat sources until 2040. Potential local heat sources for the DHN are geothermal sources, aqua thermal sources, low-temperature ATES, and e-boilers. Other sources in the area that could potentially connect to the DHN are geothermal sources in the Westland area. In this area, multiple plans for geothermal sources are in further stages of development than in the cities of Den Haag or Rotterdam.

Currently, in the municipality of Den Haag, 3 additional search locations for geothermal heat are determined. 6 more areas are explored for this cause. 6 search locations are determined for low-temperature heat storage (Gemeente Den Haag, 2021). With these developments, the municipality of Den Haag plans to provide heating for 50.000 households, which is 20 % of the municipality, before 2035 (Gemeente Den Haag, 2023). Despite all plans, recent projects to expand the DHN in Den Haag have come to a standstill due to risks and uncertainty concerning the Collective Heat System Act (NRC, 2023).

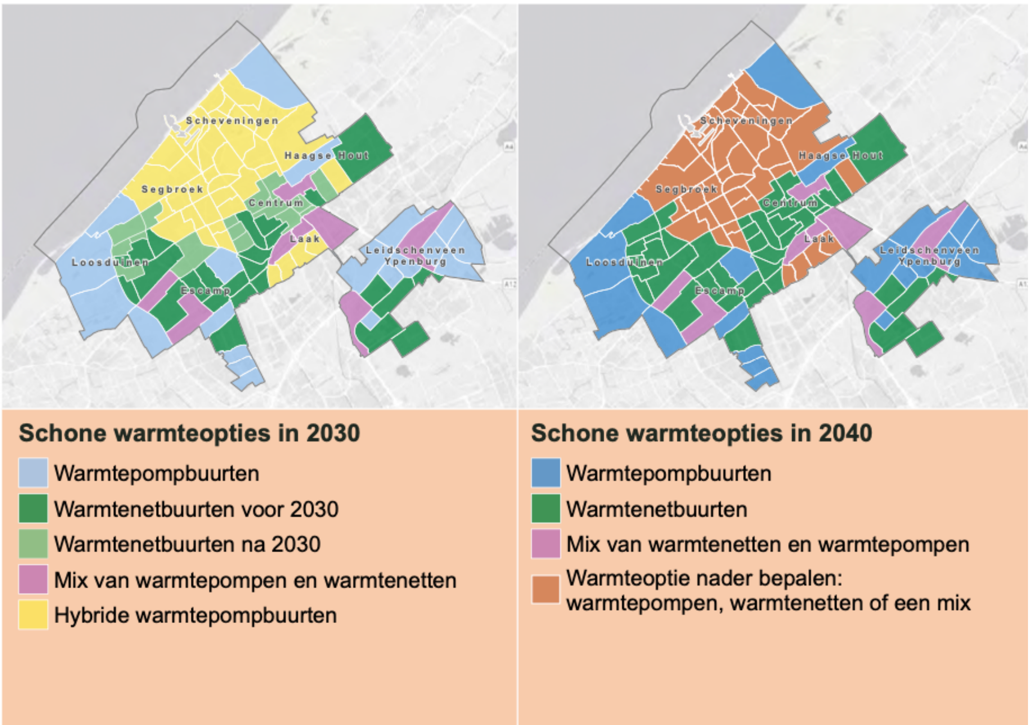


Figure 3: Map of the City of Den Haag with alternative heating solutions per neighborhood (Gemeente Den Haag, 2021).

Municipality of Lansingerland The municipality of Lansingerland consists of the villages of the B-triangle: Bleiswijk, Berkel en Rodenrijs, and Bergschenhoek. Similar to the Westland area, in the B-triangle region many greenhouses are located. Greenhouse companies in this area are mostly dependent on gas for heating. Therefore, geothermal heat can potentially deliver the desired heat in a natural gas-free future. Plans of the municipality of Lansingerland are described in the Transitievisie Warmte Lansingerland (Gemeente Lansingerland, 2019). In this vision, three neighborhoods have been discussed as front runners in the heat transition. For two of these neighborhoods, connection to the collective DHN is proposed. Furthermore, figure 4 shows the societal costs of heat transition options in the municipality of Lansingerland. Blue areas indicate potential all-electric heating solutions, red areas indicate that the societal benefits of the heat transition in the form of district heating or all-electric heating are lower than 10%. Light green areas show beneficial areas for district heating, dark green areas are existing district heating areas, orange areas are potential neighborhoods for innovation, green gas or hybrid solutions, and gray areas lack the data to provide the societal costs of heating solutions. Several neighborhoods could benefit from district heating connections. The possibilities for sustainable heat sources are explored, mainly in the form of geothermal heat. One geothermal source has been realized, another one is in development and two others are planned in this municipality. The existing heat sources and planned heat sources can provide heat to greenhouses, and potentially connect to the larger DHN of Rotterdam and Den Haag.

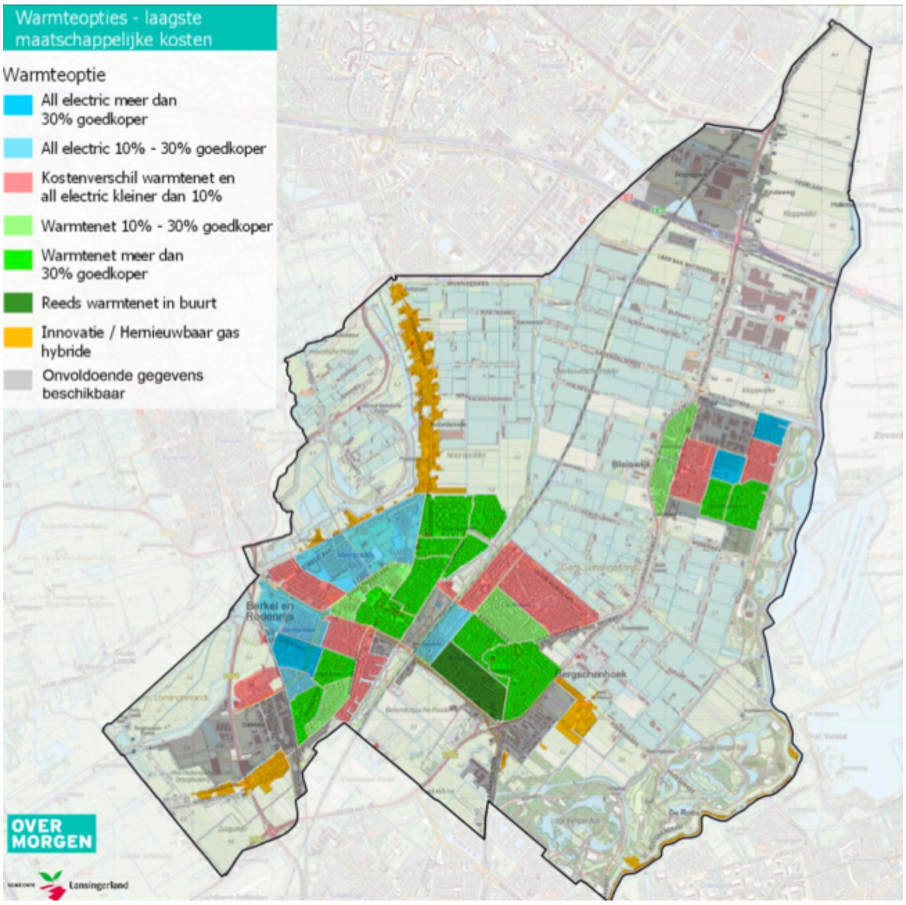


Figure 4: Map of the municipality of Lansingerland with alternative heating solutions per neighborhood, according to societal costs (Gemeente Lansingerland, 2019).

2.5 Strategy Eneco

With Eneco's One Planet Plan, the company aims to be climate-neutral in 2035. One of the steps to realizing this goal is connecting 300.000 households to district heating in Dutch urban areas in 2035 through geothermal-, aqua thermal and waste heat sources (Eneco, 2023). As stated in the Dutch Climate Agreement, the investment in new heat sources is partly subsidized through the SDE++. The SDE++ is a subsidy to stimulate sustainable energy production and climate transition, meant for non-profit organizations and companies to invest in large-scale sustainable energy generation or CO2 reduction (RVO, 2023c). With this, Eneco can reduce 70% of the average CO2 emissions of Eneco's DHN in 2030 compared to gas-powered DHN. With electrification, buffers, and the use of 'green' gas, Eneco is estimated to emit up to 0.08 Mton CO2 in 2035 compared to 0.1 Mton in 2020 (Eneco, 2023).

Considering the investment climate of DHN, the proposal of the Collective Heat System Act has resulted in the restraint of energy companies. In the long term, private owners of existing heating networks will be expropriated. With an investment horizon of 20 to 40 years for additional heat sources and heat storage, investing in DHN is not viable (Eneco, 2022; PwC, 2022).

2.6 Conclusion

Regulatory frameworks considering district heating networks are in place in the form of EU directives and the Dutch National Climate Agreement. National policy frameworks are present to support the local heat transition. Examples are financial instruments such as the 'SDE++' and 'EG' subsidy, as well as CO2 taxation and the PEF as a CO2 performance factor. Furthermore, the available subsidies on the national level are mainly concerned with heat production. National and regional programs aim to support the local heat transition, and the Collective Heat System Act has increased public guidance of local governments to realize the heat transition. This can be done by making plans, setting targets for these plans, and working together with other municipalities, district heating companies, housing associations, and citizens. However, municipalities and other stakeholders often lack specific knowledge on energy infrastructure and costs (CE Delft, 2022). On the other hand, this expertise is present at the energy companies. Therefore, collaboration between these stakeholders is crucial, as well as a coherent national subsidy scheme.

The main conditions of the three municipalities analyzed, are sustainability and affordability of the heat transition. The policy analysis of the municipalities leads to different possible district heating network plans, where the primary focus is on network expansion in the form of heat sources and heat storage. Regarding heat supply for the heat transition in the municipalities, it becomes clear that the focus is on sustainable heat sources. Heat storage is only mentioned in combination with low-temperature ATES. Regarding future heat demand in the municipalities, many potential areas for district heating are identified. From the perspective of Eneco, the PEF of the different parts of the DHN plays an important role in terms of where in the network new heat sources and heat storage are implemented. With the WLQ connection, the PEF of Den Haag will be reduced, however, the addition of new heat sources and storage should be considered.

2.7 Network expansion

To analyze the impact of additional heat sources and heat storage, several virtual assets are added to the network for this study. Firstly, regarding heat supply, additional sources in the form of geothermal energy will be considered in Den Haag, Rotterdam, and the B-triangle. Furthermore, heat pumps will be considered in Den Haag and Rotterdam, and e-boilers in Den Haag. Heat storage plans are mentioned in the visions of the municipalities, though clear plans are absent. Nonetheless, the effect of heat storage will be explored in Den Haag, Rotterdam, and the B-triangle, to explore the potential. Secondly, considering heat demand, the total heat demand of the municipalities is projected to increase. Despite the proposed targets for 2025, 2030, and 2040 to connect certain neighborhoods to district heating, heat demand increase in the coming years is difficult to estimate. The fact that heat visions are non-binding and alternative solutions for certain neighborhoods are incomplete, results in an uncertain investment climate for individual households and energy companies (CE Delft, 2022).

3 District heat network model

In this section, the current DHN of Eneco is documented and analyzed. This is carried out with the input of experts of the DHN and team meetings and presentations at Eneco, as well as a Linny-R model analysis. The geographical specification, model input, and output is specified. Secondly, a new DHN model is conceptualized, utilizing the existing model knowledge, as well as expert knowledge on optimization models of the DEMOSES research group. The model requirements, input, formulation, output, verification, and validation, and possible means of model expansion are specified.

3.1 Current model

The current DHN model covers the area of South-Holland district heating, including the WarmtelinQ (WLQ) and Leiding over Noord (LoN). The cities connected to the heat network are Rotterdam, Den Haag, as well as the region of Lansingerland (B-triangle). The network connects buildings (households, companies) to the waste heat of the Port of Rotterdam, waste incineration plants, and steam and gas turbines.

3.1.1 General operation & purpose

The DHN consists of three main components: production units, distribution pipes, and customers. The main purpose of a DHN is the production and distribution of heat to the customers. The heat is transferred through water, which is heated up by the production units and distributed through the pipes to be pumped, at a certain temperature to the customer substation. After the heat is consumed, water with a lower temperature flows back to the production units. Here, the water is reheated. The heat in GJ provided to a substation can be described as:

$$Q = \dot{m} * c_p * \Delta T \tag{1}$$

where:

Q = the energy in the form of heat,
$\dot{m}$ = the mass of the water flow through the substation,
c_p = the specific heat capacity at constant pressure, and
ΔT = the temperature difference of the water between the water arriving and leaving the consumer substation.

The exact meaning of the terms in the formulations for the decision variable, objective functions, and constraints that will be presented are listed in the nomenclature list.

3.1.2 Geographical specification

In the province of South-Holland, there are two heat grids in operation in the following cities: Den Haag and Rotterdam. Connecting these grids and expanding them can provide more flexibility to the DHN. The area of interest of the Eneco DHN model is South-Holland, with two main connections: 'WarmtelinQ' as depicted in figure 5 and 'Leiding over Noord' (LoN) 6 as shown in figure 5. The WLQ network connects the Port of Rotterdam with the city of Den Haag, with a few branches in between. In the current model, the link to the town of Ypenburg and the city of Leiden is not included. This is the case as these parts of the WLQ are still in the planning phase. The rest of the WLQ network is under construction. The LoN connects the waste incineration plant in Rotterdam (WI), through Vlaardingen and Schiedam, to the city of Rotterdam. From here, the 'Boszoom' pipeline links the center of Rotterdam, in this model called 'Rotterdam 1', with the Eastern part of Rotterdam, called 'Rotterdam 2'. From here, a pipeline goes north to the 'B-triangle', which connects the greenhouse areas of the towns of Berkel en Rodenrijs, Bleiswijk, and Bergschenhoek with the heat network of Rotterdam.

Figure 5: Heat network 'WarmtelinQ' (Warmtelinq, 2023).

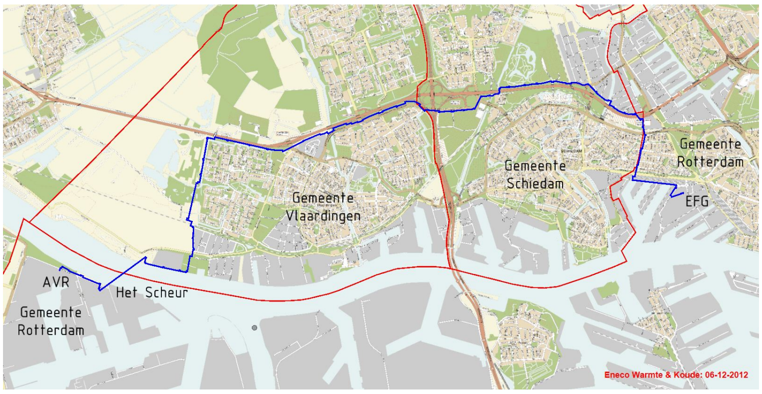


Figure 6: Heat network 'Leiding over Noord' (Warmtenetwerk, 2021).

These two networks are connected in the current model. The program Linny-R is used to model this network, as geographically shown in figure 7 (Segers, Niessink, van den Oever, & Menkveld, 2020). Linny-R is a graphical specification language for mixed integer linear programming (MILP) problems. Input such as waste incineration plants and geothermal power plants are modeled as 'process', in Linny-R shown as boxes. A process represents a transformation of some 'product(s)' into some other 'product(s)'. Demand in cities and towns, price specifications, as well as certain connection points are modeled as 'product', in Linny-R shown as rounded boxes. A product represents something that can be produced or consumed by a process. Products in this model are 'gas', and 'electricity', which have a market price. Processes and products are connected with links, which are inputs and outputs. When these inputs and outputs have a market price, Linny-R will calculate the 'cash flow' generated by the process, as the change between the 'cash-in' and 'cash-out'. The modeling process is shown in figure 8, where the modeler prepares input for the Python shell, the Python shell directs the Linny-R model to run for various defined scenarios, and Python aggregates the output of Linny-R. This will be further elaborated on in the next section.

Figure 7: Heat network South-Holland

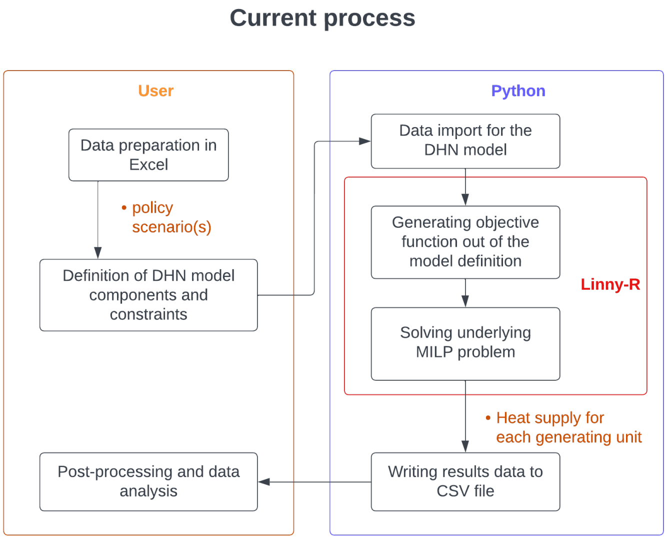


Figure 8: Structure of the modeling process

3.1.3 Input

The inputs of the model consist of supply units, demand substations, buffers, and the electricity, gas, and CO2 prices for each hour. The model aims to optimize the balance of supply and demand and minimize the cost of operation while taking into account possible uncertainties.

Supply The heat sources that are connected to the DHN of South-Holland are listed in table 2. The main sources are the industrial waste heat plant IWH1, the waste incineration plant WI, a collection of gas and CHP assets in Rotterdam and Den Haag. Smaller sources are connected in the area of Den Haag, such as a geothermal source. Certain constraints are in place to determine the order of supply of these plants, due to contracts Eneco has with these heat-supplying parties

[1]. This means that the network is modeled in the sense that it will automatically choose the first unit in the merit order to supply. In the post-processing, this pricing is corrected by multiplying the heat volumes with the actual price of the heat.

Some supply units are modeled in a modular way in Linny-R. This is depicted in the model as 'clusters', which is a tool in Linny-R that groups processes. This is the case for the CHP assets: the DH CHP is a steam and gas turbine, which consists of two separate turbines (figure 9), DH CHP 1 and 2. These are modeled as separate heat-delivering entities, which are also divided into parts: a minimum heat supply (GTmin), a 'minmax' heat supply (GTminmax), a 'steam-to-electricity' unit (GT solo-E), and a 'steam-to-heat' unit (GT1-warmte). 'GT' is the abbreviation for 'gas turbine'. The minimum heat supply is the gas turbine that runs with a constant heat output. The 'minmax' unit can provide additional heat in case the minimum heat supply is not sufficient. The steam produced in this process can be converted to electricity or heat. The electricity can be sold to the market. Another 'parent cluster' is present in Rotterdam, which consists of a gas turbine with a fixed generation, two gas turbines with a lower and upper bound (minmax), and one CHP unit which is built up similarly as explained for the DH CHP. The minimum and maximum production are specified in GJ in Linny-R. The minimum and maximum are the same value if the supply unit has a fixed production. If there is a lower and upper bound of the production, this is specified with these values.

The costs associated with supply units are fuel costs, CO2 costs, variable costs, and start-up costs. Fuel costs can be gas or diesel costs in €/MWh, dependent on the generating supply unit. The diesel price is a set price, while the gas price is dependent on the market, and therefore varies for each time-step. For some supply units, start-up costs and variable costs exist, see table 2. Next to the costs, some supply units such as the RDAM CHP and the DH CHP produce electricity. Similar to the gas price, the electricity price varies depending on the market. Therefore, the optimal division between heat and electricity production can be sought, based on the gas and electricity prices.

Table 2: Supply units of the DHN of South-Holland (confidential)

Production unit	source type	Minimum production (GJ)	Maximum production (GJ)	Start-up cost (€)	Variable cost (€)
Rotterdam					
WI	waste incineration heat				
IWH1	industrial waste heat				
IWH2	industrial waste heat				
RDAM Gas 1	gas				
RDAM Gas 2	gas				
RDAM Gas 3	gas				
RDAM Gas 4	gas				
RDAM Gas 4 additional	gas				
RDAM Gas 5	gas				
RDAM Gas 5 additional	gas				
RDAM Gas 6	gas				
RDAM Diesel	diesel				
RDAM CHP	CHP				
Biomass 1	biomass				
Den Haag					
DH CHP 1	CHP				
DH CHP 2	CHP				
DH Geo	geothermal				
DH Gas 1	gas				
DH Gas 2	gas				
DH Gas 3	gas				

[1] The exact merit order is confidential, and can be requested for research purposes if necessary.

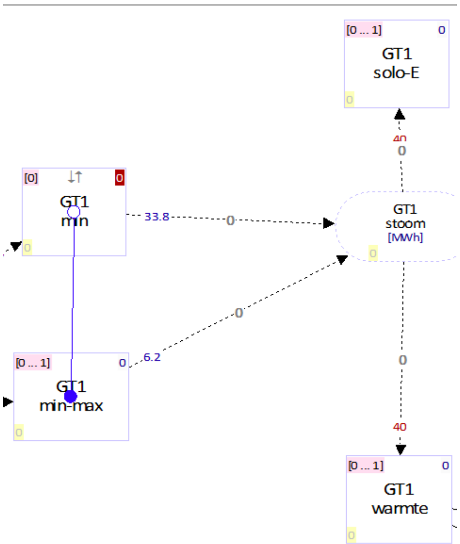


Figure 9: Modular built-up of the CHP in Den Haag

Buffers While the DHN is already a buffer for the heat in the form of a distribution network, additional buffers can be a solution to reduce the short-term uncertainty of heat supply. Buffers, in literature also called 'accumulators', provide the opportunity for heat storage. In the South-Holland DHN, buffers are connected to all customer substations. These buffers vary in size and therefore in storage capacity. However, most buffers in this DHN serve to store heat for approximately 4 hours. In the current Linny-R model, the buffers are modeled as products with bidirectional flows to the consumer station, marked as storage (see figure 10). For example, the buffer of Rotterdam has a flow to and from the consumer substation of Rotterdam. The buffers are modeled without constraints: no costs are involved for running the buffers, and no losses are included. This makes sense for these buffer sizes. However, for buffers with bigger capacities, losses, and operating costs need to be taken into account. The rated capacity of the buffers is how much the buffer can be charged or discharged within one time-step. In the current model, the rated capacity is not taken into account, and therefore equal to the total buffer capacity. However, with long-term buffers, this becomes a relevant constraint.

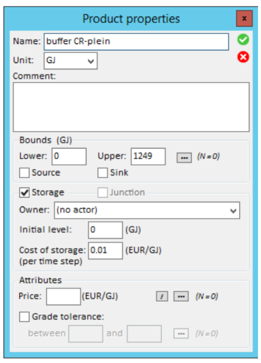


Figure 10: Linny-R window Buffer

Table 3: Buffer capacities DHN South-Holland (confidential)

Buffer	Connected to	Buffer capacity (GJ)	storage cost (€/GJ)
Buffer DH square	DH square		
Buffer Rotterdam 1	Rotterdam 1		
Buffer Rotterdam 2	Rotterdam 2		
Buffer Tuinders	Tuinders		

Demand Sources of heat demand can be divided into three components: heating buildings, providing hot water, and network losses of heat through the pipes. The average demand of the consumer substations is summarized in table 4. These are default values, as in Linny-R, demand values are determined for each time step of the year. As heating buildings is the biggest part of the heating demand, the demand varies depending on the weather conditions. During winter, demand will generally be higher than during summer. Load patterns are usually predicted through regression analysis based on historical values.

Table 4: Average demand of consumer substations of the DHN South-Holland

City	Average demand (GJ)
Den Haag	134.50
Rotterdam 1	380.67
Rotterdam 2	186.57
B-triangle	228.88

The demand for heat is simplified in the Linny-R model to certain districts that operate as single entities in the model. For example, the city of Den Haag is a single demand node, while in reality, there are a few neighborhoods in different locations in the city connected to the DHN. The demand stations can therefore be regarded as customer substations. In Rotterdam, the city is divided into the center of the city (Rotterdam 1) and the eastern part of the city (Rotterdam 2). These are two separate customer substations. The weather year can be changed for the demand, which results in different demand patterns. The demand input can be chosen from the past 5 years (2018-2022), as well as other demand scenarios of Eneco. The total demand over time in 2022 for Den Haag, Rotterdam, and the B-triangle is shown in figure 11.

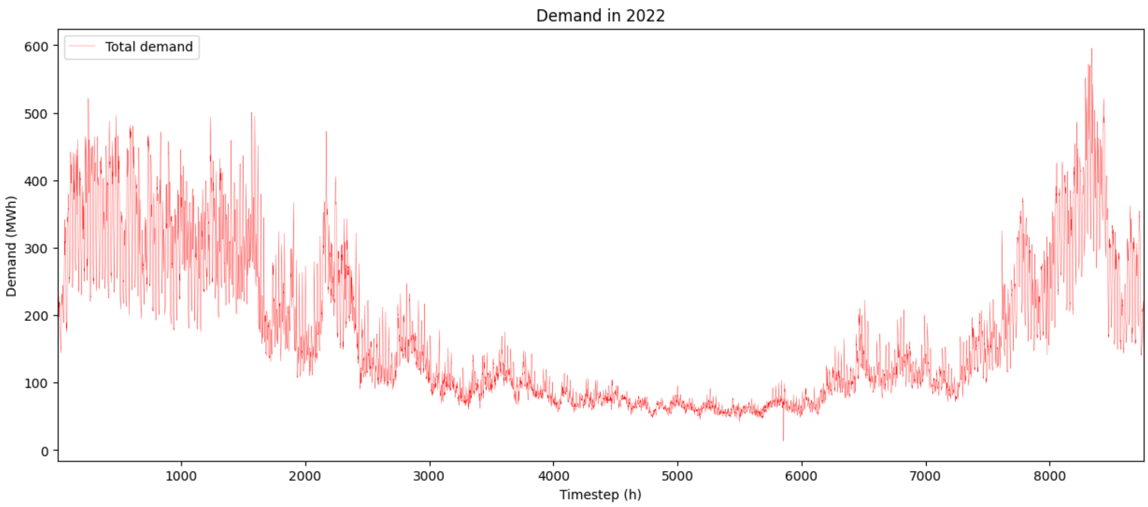


Figure 11: Hourly heat demand of consumers of Eneco in South-Holland in 2022

Electricity, gas, and CO2 prices The prices of gas, electricity, and CO2 are dependent on the hour of the year. The weather year impacts the prices, similarly to the demand pattern. The input of the model is the gas, electricity, and CO2 prices of the past 5 years (2018-2022), as well as other Eneco price scenarios. The price fluctuations on an hourly level for gas, electricity, and CO2 in 2018-2022 are shown in figure 12.

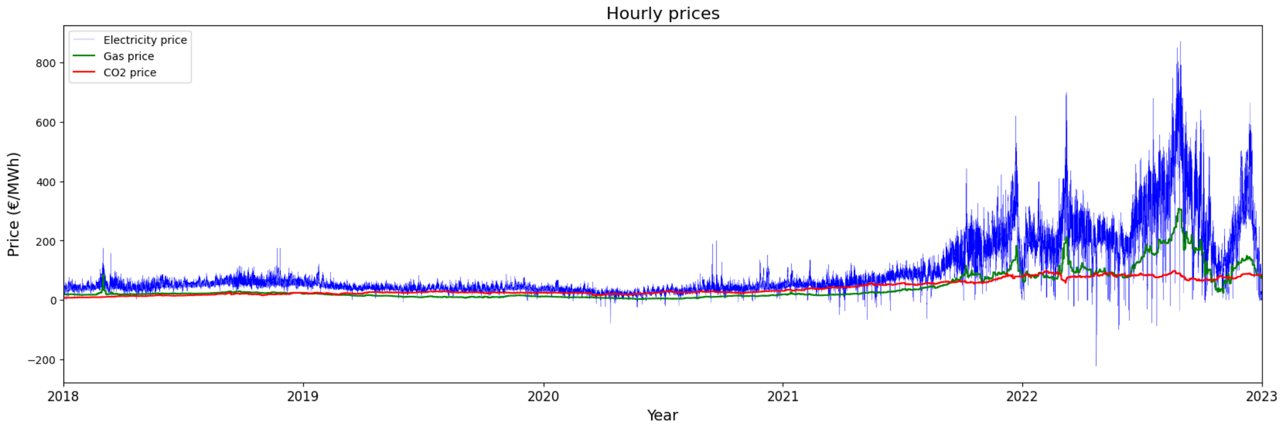


Figure 12: Hourly electricity, gas and CO2 prices of 2018-2022

Policy & subsidies Subsidies, such as the SDE++ are integrated in the Linny-R model. The SDE++ subsidy is short for 'Stimulering Duurzame Energieproductie en Klimaattransitie', meaning it stimulates sustainable energy production and climate transition. This is integrated into the model by for example maximizing the output of a biomass waste incineration plant. Other ways to implement subsidies are included in this model by stimulating the heat flow through certain parts of the network. For example, the usage of the WLQ connection is stimulated by a (non-existing) encouraging demand for heat. Other potential subsidies are not implemented in the network.

Connections The supply, demand, and buffers are connected in a network by virtual heat transportation pipes. In this model, it has not been taken into account that there are standard losses in the transportation pipes. The only losses that are considered are fixed losses in the LoN and the WLQ. These are modeled as volumes of heat loss in GJ. The WLQ and the LoN both have two points of losses connected which are both 14.4 GJ. Another physical constraint of the network is the flow direction of heat. The majority of the network is constrained to the unidirectional flow of heat. The only exception is the Boszoom part, and the buffers (as heat should be able to flow in and out of the buffers). The reason for the physical choice of making the majority of the network unidirectional is because of realistic expectations of how the network will develop in the future. For example, the WLQ connection to the city of Den Haag is developed to provide waste heat from the suppliers in Rotterdam to the city of Den Haag. In the future, it is not expected that any waste heat from Den Haag will flow to Rotterdam. This would also require the doubling of physical pipes underground, which would make the construction of this network more expensive. Lastly, physical constraints in terms of the pipe distance of this network are modeled. An example of this is the heat flow from WI to the B-triangle. The heat from WI can reach the B-triangle, but in practice, the amount of heat is limited due to distance constraints. This is modeled by constraining the hourly flow with a certain percentage/rate. This percentage varies between winter and summer.

Uncertainties Besides the uncertainty in terms of weather forecast, several other uncertainties exist. The price of electricity, fuel, and the price of the right to emit CO2 can vary, which has an impact on the production cost of heat. Furthermore, access to production units is uncertain, as a network relying on a constant supply of a certain unit, can become vulnerable if this specific supply unit is not available due to circumstances. For example, in the case of the DHN of South-Holland, on September 21st, 2023, the biggest supplier of heat to the city of Rotterdam shut down due to a fire in the waste incineration plant. To ensure that customers are satisfied and do not experience disturbances in the situation, other solutions had to be found to fill this gap in supply. Another example is the severe increase in gas prices during the winter of 2022-2023 in the Netherlands, which caused certain production units powered by natural gas to become expensive to run.

3.1.4 Optimization problem

The Linny-R DHN model is modeled as an optimization problem: the aim is to minimize the cost and fulfill the demand while taking into account certain constraints. This is modeled as a Unit Commitment (UC) problem using mixed integer linear programming (MILP). This is a MILP problem, as some decision variables are discrete and some are not. A UC problem is an extension of the Economic Dispatch (ED) problem, where units can be started up and shut down over time. More generally, the UC problem is a multi-period scheduling problem that must include ramping constraints limiting the generating level of any unit between two consecutive time periods. The only start-up costs and variable costs included in this model are those for the RDAM Gas 4 and Gas 2 and the DH CHP, the rest is assumed to be zero (see table 2). Linny-R maximizes the cash flow of the DHN subject to the conditions applied to the supplying units, the consumer substations, products such as fuel, CO2, and electricity, and how these link together. Ultimately it is the owner of the system, for whom Linny-R seeks to maximize cash flow, thereby minimizing the total costs of the network. Therefore, the cash flow U of actor k, in this case, Eneco, is the sum of the asset A profits from all processes owned by k (Noori, Korevaar, Stikkelman, & Ramírez, 2023):

$$U_k = \sum_n CF_n \tag{2}$$

where:

U_k = the cash flow of actor K, and
CF_n = the cash flow of process n owned by k.

The cash flow of process n is expressed by the production of process n multiplied by the costs and revenues of process n:

$$CF_n = PL_n * \sum_n C_r * C_n^{\text{var}} * C_n^{\text{SU}} - PL_n * \sum_m C_m \tag{3}$$

where:

PL_n = the production level of process n,
C_r = the costs of resource r,
C_n^{var} = the variable cost of the plant,
C_n^{SU} = the start-up cost of the plant, and
C_m = the costs of product m.

The main aim of this network is to distribute heat from heat sources to consumers, while minimizing the total costs of the network. In the Linny-R model, the resources used to produce heat are gas, diesel, and CO2, while the products are the heat itself, as well as electricity. Producing heat with gas or diesel as resources results in CO2 emissions. Therefore, CO2 credits need to be purchased to be allowed to produce heat with CO2 emitting resources. While CO2 is a product of the process of producing heat, in this network it is modeled as a resource. The right to a certain amount of CO2 should be purchased to run the supply unit. The owner of this network, Eneco, aims to find the optimal solution to run the heat-supplying units while meeting heat demand. Finally, the total cash flow of the actor is optimized:

$$\text{Minimize} \sum_{t=1}^{t=8760} U_k. \tag{4}$$

While the optimization theory is applied hourly, in practice, the Linny-R model optimizes 24 steps at a time from t=1 to 8760, while looking ahead 12 steps. This means that the model is optimized with a daily granularity. Furthermore, the model looks ahead 12 steps, to ensure that the buffers can be used optimally by looking ahead and optimizing their behavior accordingly. 24 hours is a granularity that ensures that electricity prices can be well predicted while taking into account the start-up costs of supplying plants. Optimization on a yearly basis would assume perfect knowledge of electricity prices, which is not realistic. The solver window in Linny-R therefore is filled in accordingly (see figure 13).

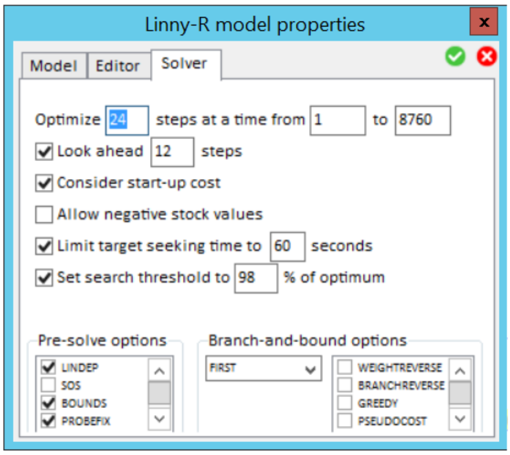


Figure 13: Solver window Linny-R

3.1.5 Output

The output of the current model is the heat in GJ supplied by each source. This differs for each scenario, as electricity prices and fuel prices vary. This output is provided for each hour in a year, which is aggregated to an Excel sheet with a Python script to show accumulated values for each year for each scenario. The outputs are shown in GJ per source to demand area, so total volumes of energy can be compared between years and scenarios. For example, the output specifies how much GJ is provided by the steam and gas turbine (DH CHP) in Den Haag to the city of Den Haag in 2025 in an ambitious scenario of Eneco, which is 554628 GJ. This can be compared to the existing policy scenario in 2025, which amounts to 577219 GJ. This way, a conclusion can be drawn that the DH CHPs deliver more heat to Den Haag if the policy is less strict in terms of climate ambitions. Comparing all different years and sources of heat provides an overview of the most optimal distribution of heat while taking into account constraints of existing contracts that influence the merit order.

3.2 New model

A new DHN is built, with the aim to provide a more user-friendly, modular, fast-performing, and future-proof alternative to the current Linny-R model. The new model aims to allow DHN expansion experimentation, as well as experimentation with price and demand deviations. This way, the new model can provide insights into the future configuration of a DHN, not only for South-Holland, but any other DHN which demands a future outlook. Following from the expert interviews with colleagues and team meetings at Eneco, as well as from the input from the DEMOSES research group, the model requirements and desired functionalities of a DHN are defined. Firstly, the model requirements from the side of Eneco are reported. Secondly, the model requirements for the model to contribute to the DEMOSES research project are outlined. The model input, implementation in Python, model settings, and output are described. Lastly, the Python model is verified and validated.

3.2.1 Conceptualization

To adequately represent the DHN of Eneco, the new model should be a representation of the DHN of South-Holland, taking into account suppliers and demands contracted or operated by Eneco. Inputs of the model are electricity, fuel, and CO2 prices, and the demand of the consumer substations. The expected output of the model is an overview of the distribution of supply provided by the various heat sources, to adequately supply to the consumer substations of Den Haag, Rotterdam, and the B-triangle. Scenarios can be varied by means of simple changes in input values, such as price variations, weather variations, and supply variations. For example, different price scenarios can be run, dependent on possible policy expectations in terms of climate regulations.

By comparing scenarios, it is possible to see what the long-term effects are in terms of electricity prices, fuel prices, and CO2 prices with the current supply portfolio. Based on these outcomes, the appropriate flexibility can be provided to the existing portfolio. By having the option to add and remove supply units and buffer units, the model can be adapted, and the outcomes of these changes can be analyzed. This way, the model can be a helpful tool for deciding which investments to make and which contracts to conclude in the long term. In the shorter term, different weather conditions can be implemented in the model by choosing the base year. For example, if an extremely cold week has taken place in the winter of 2018, this year can be the input of the model. The output of this can help decide on how to deal with similar weather events in the future, through changing buffer capacities and flexible supply units.

The aim of the DEMOSES project is 'to develop decision support models and tools for the redesign of the Dutch energy system by coupling heat, electricity, gas and distribution grids, with a focus on the interdependencies between them and the flexibilities that they provide' (TU Delft, 2021). Therefore, with regard to the DEMOSES project, next to the expandability and modularity of the model, the model should have the possibility to be coupled with dynamic electricity network models. The electricity price input will be variable based on which scenario is chosen. For example, if a scenario is chosen in which a strict climate policy is implemented, electricity prices are more variable, and gas and CO2 prices are increased. In future research, this model can be used to implement electricity prices as modeled by other parties. By coupling these, more precise predictions can be made in terms of network behavior. Lastly, the model should be user-friendly and future-proof, which can be achieved by choosing a common and accessible modeling language. In summary, the model requirements are formulated as:

The model...

- should economically optimize the heat generation for the DHN of South-Holland where Eneco supplies heat while taking into account existing contracts with suppliers and consumers;
- should have the option to compare various scenarios to a base case scenario. The variables that should be possible to vary are electricity price, CO2 price, fuel prices, and demand year (relevant for weather circumstances);
- should be modular and thereby future-proof: possibility to add and remove specific heat supplies, heat buffers, and consumers;
- should be expandable: possibility to expand the current DHN;
- should have the possibility to be coupled with dynamic electricity network models;
- should be user-friendly: the model is implemented in a standard programming language and well documented.

The structure of the modeling process is shown in figure 14. The modeler prepares the data in Excel, depending on what question the modeler has. This can be a question dependent on the average weather year, policy scenarios, and the degree of flexibility. The constraints are defined and imported together with the variables in Python. The objective function is generated and the MILP problem is solved. This results in the heat supply for each generating unit as well as heat storage of each buffer, which is summarized and aggregated in a CSV. Post-processing is done by the modeler, and the data is analyzed, to see what effect a certain change in year, policy scenario, or flexibility has on the DHN.

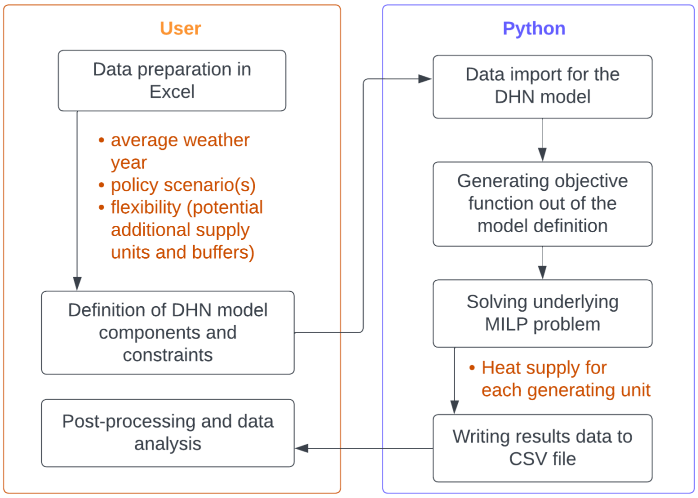


Figure 14: Structure of the new modeling process

3.2.2 Input

In this part, the model inputs are discussed. The differences concerning the old model input are discussed in each section. The model input consists of three Excel files which are imported into Python:

- The network specifying points (nodes) and their connections (edges);
- Hourly demand of the customer substations (nodes);
- Hourly prices of gas, electricity, and CO2.

In the Python script, the weather year can be specified, which results in different input data for demand and prices. For each weather year, a separate sheet is available in the 'demand' and the 'prices' file, which is automatically loaded in Python. This means that the demand and the prices are consistent in terms of year. In terms of the network, nodes and connections can be added by copying the 'base' network and making the desired changes. This way, different networks can be compared for different weather years. Compared to the Linny-R model, the weather and price years and scenarios and the network expansion scenario name only has to be changed once in the Python script.

Supply The production units are shown in table 5. Compared to the previous model, changes are made to increase the user-friendliness and modularity of the model, as well as making it future-proof. The first two changes considering including or excluding existing heat supply units can be carried out in the existing Linny-R model, and can be regarded as 'updates' to the current model. The changes concerning calculation of the heat production and efficiency of the plants are necessary to adequately model the heat production in the Python model. The last change, concerning the input of the model, mainly increases the user-friendliness and modularity of the model: instead of creating multiple model configurations in Linny-R, the model input can be defined by the user in Excel, and the Python model can read the network as defined in Excel. To summarize, the following changes are made to the production units:

- The diesel-powered plant 'RDAM diesel' in Rotterdam is removed, as this plant will not be part of the future configuration anymore. Furthermore, diesel-powered plants are not desired in the future heat-mix. In terms of model input, the diesel prices are therefore not considered as a possible input;
- RDAM Gas 4 additional' & 'RDAM Gas 5 additional' have been removed from the network. Compared to the other gas units in Rotterdam, these gas-powered units run relatively few hours with low production. Furthermore, for the future heat-mix, additional gas units are not desired. Therefore, these are excluded in the new model;

Table 5: Production units of the DHN of South-Holland for new model (confidential)

Production unit	source type	Minimum production (MWh)	Maximum production (MWh)	Gas consumption (MWh)	CO2 consumption (ton)	Electricity production (MWh)	Start-up cost (€)	Variable cost (€)
Rotterdam								
WI	waste							
IWH1	waste							
IWH2	waste							
RDAM Gas 1	gas							
RDAM Gas 2	gas							
RDAM Gas 3	gas							
RDAM Gas 4	gas							
RDAM Gas 5	gas							
RDAM Gas 6	gas							
RDAM CHP	CHP							
Biomass 1	biomass							
Den Haag								
DH CHP 1	CHP							
DH CHP 2	CHP							
DH Geo	geothermal							
DH Gas 1	gas							
DH Gas 2	gas							
DH Gas 3	gas							

Table 6: Buffer capacities DHN South-Holland (confidential)

Buffer	Connected to	Buffer capacity (MWh)	Rated capacity (MWh)
Buffer DH-square	DH-square		
Buffer Rotterdam 1	Rotterdam 1		
C-Buffer	Point C		
Buffer Tuinders	Tuinders		

- For calculation reasons, the unit of production is MWh instead of GJ. For the final output, this can be converted to total GJ per year per producing unit.
- The efficiency of the producing plants is taken into account by including a factor from the input of gas and CO2, compared to the output of heat and electricity. This is further elaborated on in section 3.2.3;
- In the Excel input file, the production unit is specified as a node. Therefore, the demand nodes, buffer nodes, and connecting nodes have a production of 0. This is further explained in the Networkx theory in section 3.2.3.

Buffers and long-term storage As for the producing units, the unit for the buffers is MWh instead of GJ. The values from table 6 are therefore divided by 3.6. For the buffers, operating costs and losses are included as parameters. For the smaller buffers, as they are present in the current model, this is not relevant. It is assumed that there are no storage costs, and the efficiency of charging and discharging is 100%. However, for potential additional buffers in the future with bigger storage capacities, this is relevant. Therefore, the model includes these parameters.

Connections Table A.1 in the appendix, and figure 15 show the connections between the production units, buffers, and demand substations. Heat loss is specified for the connections to 'Point V'. This is a simplified heat loss, as this variable is only applied for the longer connections, where more heat is lost during the transport. Furthermore, a maximum flow is specified for some connections to avoid congestion. The costs of transporting heat over a connection are included as a possible variable. In the base scenario, however, no costs are included for the connections.

The flow rate through the WLQ connection is dependent on the season and the demand: the flow through the pipe is faster or slower and warmer or cooler dependent on how hot the water is delivered and how cool the water flows back when it has been through the demand points. A fixed value/rate per month is implemented in the WLQ pipe to consider this seasonal change in flow, and therefore the heat capacity that can be delivered.

Demand The input of heat demand does not change concerning the Linny-R model. The weather year can be changed for the demand, which results in different demand patterns. The demand input can be chosen from the past 5 years (2018-2022). The demand can be increased or decreased with respect to any of the years 2018 up until 2022.

Electricity, gas and CO2 prices The electricity, gas, and CO2 prices input remains the same compared to the Linny-R model. The weather year impacts the prices, similarly to the demand pattern. The input prices of the model are the gas, electricity, and CO2 prices of the past 5 years (2018-2022). The prices of electricity, gas, and CO2 can be increased or decreased with respect to any of the years 2018 up until 2022.

3.2.3 Model formulation with NetworkX & Pyomo

This section provides a brief explanation of how the implementation has been performed. The model is written in the Pyomo modeling language (Bynum et al., 2021a), and the test scripts are then written in Python, a high-level programming language with a rich set of libraries.

NetworkX NetworkX is a Python package that uses and applies graph theory. Complex networks can be made and their structure, dynamics, and functions can be analyzed (Hagberg, Schult, & Swart, 2008). Networks in NetworkX consist of 'nodes' and 'edges'. A 'node' is a point, and an 'edge' is a connection between two points. In the DHN, the nodes are the points of production, consumption, and storage (buffer), see figure 15. The edges are the connections between these points, which are the physical pipelines that transport the heat between these points. The direction of the pipelines is indicated with directed edges, which provide the direction from one node to another node. Therefore, the DHN is a directed network. NetworkX and Pyomo combined allow us to solve the classical minimum cost flow problem.

Pyomo To mathematically model the DHN of South-Holland, Python Optimization Modeling Objects (Pyomo) software is used as a tool. The modeling objects of Pyomo are embedded within Python, which supports algebraic modeling languages (AML) such as Pyomo (Bynum et al., 2021b; Hart, Watson, & Woodruff, 2011). In Pyomo, a distinction is made between a concrete and an abstract model. An abstract optimization model provides context for a model where the data values will be provided as soon as the solution is obtained. On the other hand, a concrete model requires the data values to be supplied at the time of model definition (Bynum et al., 2021b). In this case, the data values are known at the time of model definition, and therefore, the *ConcreteModel* class is used in Pyomo. In Pyomo, common core components exist (Bynum et al., 2021b):

- *Var*: the *Var* component represents either continuous or discrete optimization variables. The variables in the DHN model are:
  - UC of the supply units;
  - startup state of the supply unit;
  - production level of the supply units;

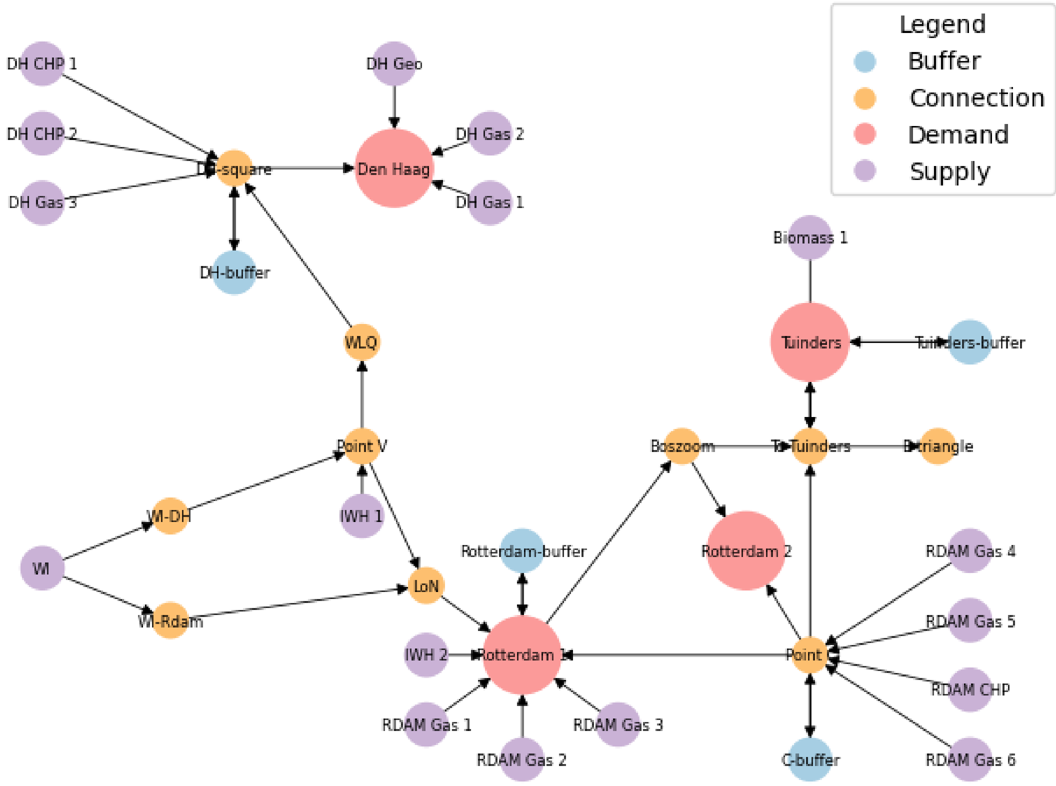


Figure 15: NetworkX representation of the DHN of South-Holland

- heat flow;
- buffer content;
- charge of the buffer;
- discharge of the buffer.

Some variables are binary variables, and other variables have certain bounds, which can be defined within the variable or in an additional constraint.

- *Objective*: the *Objective* component defines the functions to be optimized by the solver. This defines the maximization or minimization of the objective function. In a DHN model, the total costs of the network (nodes and edges) should be minimized.
- *Constraint*: the *Constraint* component is used to have additional restrictions to the optimization variables. Restrictions can be upper and lower bounds, equality, and inequality constraints. In this DHN model, many constraints are present, such as minimum and maximum production levels, seasonal production periods of supply units, maximum flow through the edges, the buffer bounds, buffer maximum, buffer level, and flow conservation through the nodes.
- *Set*: the *Set* component represents a selection of data with numeric or symbolic elements. They are used as a valid index for other components, to loop over in the model. The sets used in the DHN are (1) nodes, (2) edges, (3) and time-steps. This way, the variables, objective expressions, and constraints can be applied for all nodes, edges, or time steps.
- *Param*: the *Param* component is used to represent numeric or symbolic data values for the optimization problem. Examples of parameters in this DHN model are the prices for gas, electricity, and CO2. These have a different value

for each time-step, but also a default value. Furthermore, parameters are defined for values that are determined in the previous run. Instead of simple data values, they are 'mutable', meaning that they can change the value and can have a default value. An example of a mutable parameter in this DHN model is the UC variable of the previous time step. Where this was a variable that was determined in the previous day, when running the model for the next days, the value of the previous time-step is 'remembered'. This way, the model knows if a supply unit was turned on or off in the hour before. Considering the previous time step makes sure that the startup costs of this supply unit are correctly calculated. Another mutable parameter is the buffer content of the buffers. The buffer content of the time step before should be known to decide how much the buffer can charge or discharge in the next time step. Therefore, this is communicated through this mutable parameter. The function of 'remembering' the mutable parameters is further explained in section 3.2.4.

- *Expression*: the *Expression* component is used to make expressions and reuse these expressions in different parts of the model. To adequately structure the model, as well as for the memory efficiency of the model, expressions are useful. In this DHN model, expressions are used to calculate the gas, electricity, and CO2 costs, electricity revenues, startup costs, variable costs, and costs of the edges. This way, all components listed in the objective function are separately defined in expressions. Other expressions are used to define the buffer rate, incoming flow, and outgoing flow. These are in turn used within the constraints.

For this model, *Gurobi* is used as a solver. Pyomo has a specialized interface for this solver, and outperforms other solvers such as GNU Linear Programming Kit (GLPK) in terms of speed. The Gurobi solver uses mathematical optimization to calculate the answer to a problem.

The optimization problem Optimization is the act of obtaining the optimal result under given circumstances by using intuition, experience, experimentation, and formal optimization (mathematical programming). Engineering optimization consists of variables (decisions we can make), an objective function, and constraints that need to be satisfied. The costs of operating the plant (in nodes n) and transporting connection (as edges e) are defined as:

$$C_{n,t}^{\text{nodes}} = C_{n,t}^{\text{gas}} + C_{n,t}^{\text{CO2}} + C_{n,t}^{\text{SU}} + C_{n}^{\text{var}} + C_{n,t}^{\text{elec}} \quad \forall n \in N, \quad \forall t \in T, \tag{5}$$

and

$$C_{e,t}^{\text{edges}} = C_{e,t}^{\text{transport}} * \text{flow}_e \quad \forall e \in E, \quad \forall t \in T \tag{6}$$

where

$C_{n,t}^{\text{nodes}}$ = costs of an operating heat supplying plant in node n at timestep t,
$C_{n,t}^{\text{gas}}$ = gas costs to run a plant in node n at timestep t,
$C_{n,t}^{\text{CO2}}$ = CO2 costs to run a plant in node n at timestep t,
$C_{n,t}^{\text{SU}}$ = start-up cost of the plant in node n at timestep t,
C_{n}^{var} = variable costs to run a plant in node n at timestep t,
$C_{n,t}^{\text{elec}}$ = electricity costs to run a plant in node n at timestep t,
$C_{e,t}^{\text{edges}}$ = costs of transporting connection of edge e at timestep t,
$C_{e,t}^{\text{transport}}$ = cost to transport heat over a connecting line through edge e at timestep t, and
$\text{flow}_{e,t}$ = flow of heat going through edge e at timestep t.

The costs are defined as:

$$C_{n,t}^{\text{gas}} = PL_{n,t} * \text{gas}_{n,t} * {\text{Price}^{\text{gas}}}_t \quad \forall n \in N, \quad \forall t \in T, \tag{7}$$

$$\text{gas}_{n,t} = CL_{n,t}^{\text{gas}} / PL_{n,t} \quad \forall n \in N, \quad \forall t \in T, \tag{8}$$

$$C^{\text{CO2}}_{n,t} = PL_{n,t} * \text{CO2}_n * \text{Price}^{\text{CO2}} \quad \forall n \in N, \quad \forall t \in T, \tag{9}$$

$$\text{CO2}_{n,t} = CL^{\text{CO2}}_{n,t} / PL_{n,t} \quad \forall n \in N, \quad \forall t \in T, \tag{10}$$

$$C^{\text{elec}}_{n,t} = PL_{n,t} * \text{elec}_n * \text{Price}^{\text{elec}}{}_t \quad \forall n \in N, \quad \forall t \in T, \tag{11}$$

$$\text{elec}_{n,t} = PL^{\text{elec}}_{n,t} / PL_{n,t} \quad \forall n \in N, \quad \forall t \in T, \tag{12}$$

$$C^{\text{var}}_{n,t} = u_{n,t} * \text{var}_n \quad \forall n \in N, \quad \forall t \in T, \tag{13}$$

$$C^{\text{SU}}_{n,t} = \delta_{u_{n,t},u_{n,t-1}} * SU_n \quad \forall n \in N, \quad \forall t \in T, \tag{14}$$

$$\delta_{u_{n,t},u_{n,t-1}} = 1, \text{if } u_{n,t} - u_{n,t-1} = 1,\ 0, \text{if } u_{n,t} - u_{n,t-1} \neq 1 \quad \forall n \in N, \quad \forall t \in T, \tag{15}$$

where:

$PL_{n,t}$ = the production level in node n at timestep t,
$\text{gas}_{n,t}$ = amount of gas needed to produce the heat of node n at timestep t,
$\text{Price}^{\text{gas}}{}_t$ = gas price at timestep t,
$CL^{\text{gas}}_{n,t}$ = gas consumption needed to produce the heat of production unit n at timestep t,
$\text{CO2}_{n,t}$ = amount of CO2 credits needed to produce the heat of node n at timestep t,
$CL^{\text{CO2}}_{n,t}$ = CO2 consumption needed to produce the heat of production unit n at timestep t,
$C^{\text{elec}}_{n,t}$ = amount of electricity produced in the production of heat of node n at timestep t,
$PL^{\text{elec}}_{n,t}$ = electricity produced or consumed when generating the heat from production unit n at timestep t,
$u_{n,t}$ = a binary value determining status of production unit n at timestep t,
var_n = variable costs of production unit n,
$\delta_{u_{n,t},u_{n,t-1}}$ = Krockener delta function (δ) to represent the change from $u_{n,t}$ to $u_{n,t-1}$, and
SU_n = startup costs of production unit n.

The gas price, electricity price, and CO2 price vary hourly. As electricity can be both consumed as well as produced by some heat supply units, the electricity 'costs' can be both negative as well as positive. Startup costs and variable costs are only applicable to RDAM Gas 4, Gas 2, RDAM CHP, and DH CHP 1 and 2. The heat demand is determined based on deterministic prediction, while the heat load is dependent on constant ramping up and down constraints. The thermal loads are continuous decision variables and binary variables are included as plants by means of describing the on/off status of a heat-generating unit. Accumulators are included to provide the possibility of storage. For each step in time, in this model the granularity is hourly, and the cost is minimized through Multi Period UC. Therefore, the objective function and the corresponding constraints are defined as:

$$\underset{C_{\text{total}}}{\text{minimize}} \quad = \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{e=1}^{E} C\text{nodes}_{n,t} + C\text{edges}_{e,t} \tag{16a}$$

subject to

$$u_{n,t} \in 0,1 \quad \forall n \in N \quad \forall t \in T, \tag{16b}$$

$$u_{n,t}PL_n^{\min} \leq PL_{n,t} \leq u_{n,t}PL_n^{\max} \quad \forall n \in N \quad \forall t \in T, \tag{16c}$$

$$\text{inflow}_{n,t} = \sum \text{flow}_{(i,n),t} - E_{i,n}^{\text{loss}} \quad \forall n \in N \quad \text{if} \quad (i,n) \in E \quad \forall t \in T, \tag{16d}$$

$$\text{outflow}_{n,t} = \sum \text{flow}_{(n,i),t} \quad \forall n \in N \quad \text{if} \quad (n,i) \in E \quad \forall t \in T, \tag{16e}$$

$$\text{flow}_{e,t} \leq EF_e^{\max} \quad \forall e \in E \quad \forall t \in T, \tag{16f}$$

$$\text{outflow}_{n,t} - \text{inflow}_{n,t} = PL_{n,t} - CL_{n,t} - r_{n,t} \quad \forall n \in N \quad \forall t \in T, \tag{16g}$$

$$r_{n,t} = B_{n,t}^{\text{charge}} - B_{n,t}^{\text{discharge}} \quad \forall n \in N \quad \forall t \in T, \tag{16h}$$

$$BL_{n,t} = BL_{n,t-1} + \Delta T * (B_{n,t}^{\text{charge}} * \eta_n^{\text{charge}} - B_{n,t}^{\text{discharge}} * \eta_n^{\text{discharge}}) \quad \forall n \in N \quad \forall t \in T, \tag{16i}$$

$$-r_n^{\text{rated}} \leq r_{n,t} \leq r_n^{\text{rated}} \quad \forall n \in N \quad \forall t \in T, \tag{16j}$$

$$0 \leq BL_{n,t} \leq BL_n^{\max} \quad \forall n \in N \quad \forall t \in T \tag{16k}$$

where:

$PL_n^{\min}$ = minimum amount that can be produced by a power plant if it is turned on,
$PL_n^{\max}$ = maximum amount that can be produced by a power plant if it is turned on,
$\text{inflow}_{n,t}$ = inflow in node n at timestep t,
$\text{flow}_{(i,n),t}$ = flow through edge (i,n) to node n at timestep t,
$E_{i,n}^{\text{loss}}$ = heat loss through the edge (i,n) to node n,
$\text{outflow}_{n,t}$ = outflow from node n at timestep t,
$EF_e^{\max}$ = maximum flow through edge e,
$CL_{n,t}$ = consumption level of node n at timestep t,
$r_{n,t}$ = power from the buffer that is exchanged in node n at timestep t,
$B_{n,t}^{\text{charge}}$ = buffer consumption in node n at timestep t,
$B_{n,t}^{\text{discharge}}$ = buffer production in node n at timestep t,
$BL_{n,t}$ = buffer content level in node n at timestep t,
η_n^{charge} = efficiency of charging the buffer in node n,
$\eta_n^{\text{discharge}}$ = efficiency of discharging the buffer in node n,
r_n^{rated} = maximum power supplied by the buffer in node n per timestep, and
$BL_n^{\max}$ = maximum buffer content level in node n.

Equation 16g determines the balance for each node, where inflow should be equal to outflow, considering production ($PL_{n,t}$), consumption ($CL_{n,t}$), and buffer rate ($r_{n,t}$) of the node in that specific time-step. For the inflow and outflow of node n, the losses over the edges are taken into account (16d, 16e). The flow through each edge should not exceed the maximum capacity of the edge (16f). The buffer rate is determined by the charge and discharge of a buffer in node n (16h. This also constrains buffers from charging and discharging at the same time. $r_{n,t}$ is negative when the buffer is filled and heat is stored in node n at time-step t. $r_{n,t}$ is positive when the buffer is emptied and the heat is consumed in node n at time-step t. Furthermore, the buffer level ($BL_{n,t}$) is dependent on the buffer level of the previous time step, as well as on the efficiency of charging and discharging for each time step. As this constraint will be met for each time step, ΔT will always be 1. The maximum buffer content level is determined in equation 16k.

Apart from the above constraints, constraints regarding seasonality are included. Firstly, the WI delivers heat to the cities of Rotterdam and Den Haag. However, for Den Haag, the price for heat from WI depends on the season. In the winter months and in the summer months, the price differs from a base price of approximately 0.8 €/MWh. In the summer, this is subtracted from the base price, and in the winter this is added to the base price. However, to adequately model this and not affect the WI supply to the city of Rotterdam, this price is added to the edge connecting the WI with the city of Den Haag. Secondly, the biomass plant Biomass 1 has a period during summer when maintenance is planned. Therefore, an off-period is implemented where Biomass 1 does not supply any heat.

Lastly, in the previous Linny-R model, a constraint exists that determines the total heat production per year for the supply unit IWH1. This means that the production of each time step in a year is summed and that this is equal to or lower than the contracted amount of heat. This constraint can only be met in the current model configuration with seasonal flow limits, as the rolling time horizon prevents the model from calculating the sum over all solved runs. The supply unit IWH1 is now defined as having different flow limits over the connection from IWH1 to Rotterdam. This approach is based on the seasonal storage management modeling method as applied by (Castelli, Moretti, Manzolini, & Martelli, 2020). Castelli et al. (2020) base the maximum allowed value on past years, to define the typical behavior of the supply unit in the network, during different seasons. With this method, the maximum flow (max. 39.18 MWh) is allowed during the winter, when the heat demand is the highest. A lower flow limit is defined for the spring and autumn periods (max. 15 MWh), and an even lower limit for the summer period (max. 7 MWh). Building a shell around the rolling time horizon to fulfill this constraint for one single supply unit is out of the scope of this research. The rolling time horizon will be further elaborated on in section 3.2.4.

3.2.4 Model settings

Temporal resolution The temporal resolution defines the size of each time step in the model. The smaller the time steps, the higher the accuracy of the results of the model. On the other hand, this requires computational power, where many smaller time steps increase the computational burden. In this DHN model, time-steps of one hour are the smallest possible time-steps that can be taken. The reason for this is that the time series for the electricity and gas prices are in hourly resolution, as well as the demand patterns of the consumer substations. This is due to the structure of electricity trading, where day-ahead prices are determined at noon for the next day. Day-ahead prices are determined for each hour. An even smaller temporal resolution could be included by taking into account intra-day electricity trading dynamics. The intra-day market determines the electricity prices over a 15-minute period. However, these electricity prices are only known on the same day. Therefore, this change in electricity prices as a result of the intra-day market is not taken into account in the model. Expanding the temporal resolution would reduce the computational burden, however, it is not desired for this model. The hourly resolution is required for the price and demand accuracy, as well as for an adequate and realistic function of storage in the network. Therefore, each time-step is one hour.

Look-ahead period The look-ahead period is the period following the optimization period, for which certain data is already known. The solver will consider the consequences of certain decisions within the optimization period, to be prepared for the next optimization period. At noon, the day-ahead market is cleared, meaning that the electricity prices of the next day are determined. Therefore, in a DHN considering day-ahead electricity prices, a look-ahead period of 12 hours should be considered, as electricity prices further ahead are unknown. This is especially relevant for the functioning of the storage with the DHN network, as these can anticipate the electricity prices, and act as a potential balancing service for the electricity grid (Javanshir, Syri, Tervo, & Rosin, 2023b). Without a look-ahead period, the storage would be empty at the end of each optimization period. This would result in empty storage levels at the beginning of the next optimization period. An increase in the look-ahead period would increase the computational burden, as the decision variables for a larger number of time-steps need to be considered. The look-ahead period of this DHN model is 12 hours, so 12 time steps.

Optimization period The optimization period determines the specific time frame or duration over which the optimization is carried out. The longer the optimization period, the higher the computational burden as the decision variables need to be determined for a longer time frame. For this model, the rolling time horizon requires the model to optimize in blocks.

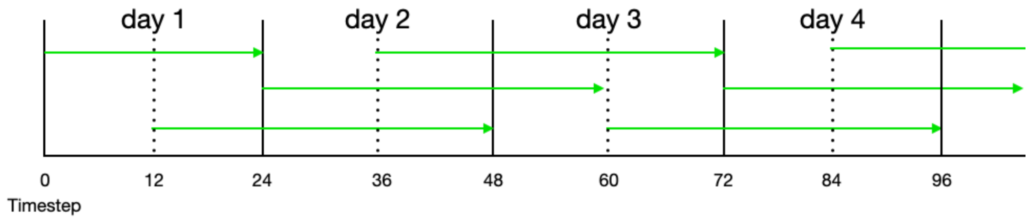


Figure 16: Rolling time horizon

In the model, the number of days can be specified, which is 365 days for running an entire year. As the look-ahead period needs to be taken into account, the model begins to optimize the model at time-step 12 (hour 12). From this moment, the electricity prices are known for the next day. Therefore, the model optimizes for the next 36 hours, so from time-step 12 to time-step 48. The optimization period of the model is therefore 36 hours. The model starts the next run for the next day, for the time-steps 36 to time-step 72, see equation 17. For the first 24 time-steps, the model is optimized instead with a time-steps range of 1 to 24. For each optimization period, the buffer content and the unit commitment state of the supply units of the first time step should be remembered from the previous optimization period. Therefore, it is crucial to have overlap in the optimization periods for the model to remember the exact value of these variables, instead of an average of the previous 12 time-steps. The rolling time horizon is visualized in figure 16.

$$\text{timesteps} = [t^{\text{lookahead}} + 24 * (\text{day} - 1)\,,\; t^{\text{lookahead}} + t^{\text{opt}} + 24 * (\text{day} - 1)] \quad \forall \text{day} \in \text{days} \tag{17}$$

$$\text{days} = [1, 365] \tag{18}$$

where:

$t^{\text{lookahead}}$ = the look-ahead period of 12 time-steps, and
t^{opt} = the optimization period of 36 time-steps.

Run-time The model is running for a year, meaning 8760 time steps. The model is optimizing for each day while looking ahead to 12 hours. The year for which the model runs can be chosen, which is dependent on the electricity, gas, and CO2 prices and heat demand. The possible years to run this model with the current input are 2018-2022. For this research, the years 2018, 2021, and 2022 are used as price and demand inputs to generate meaningful results. Solving the model with the *Gurobi* solver, the run-time is 20 minutes if the network is optimized for one year. This is the case when the Mixed-Integer Programming gap 'MIPgap' is set to 0.02. The 'MIPgap' is the parameter that controls the minimal quality of the returned solution, as it determines the upper bound on the MIPgap of the final solution (Miltenberger, 2023). The used computer runs on an Intel(R) Core(TM) i5-5350U CPU 1.80GHz.

3.2.5 Output

The first objective of the model is to optimize the DHN, by minimizing the total cost of the network. Therefore, the main output is the total costs of the network for each optimization period. This is solved by determining the value of each variable. Therefore, the output of the model is the calculation of all the variables for each node or edge, and for each time step, as listed in section 3.2.3. The final objective as well as each variable can be plotted for each desired period. The variable 'production level of the supply units' is multiplied by the gas consumption, electricity consumption/production, and CO2 production of the supply units, to calculate the gas, electricity, and CO2 costs for each supply unit. The variable 'startup state of the supply unit' is multiplied by the startup costs of each supply unit, to calculate the startup costs of each supply unit. Pyomo also allows the extraction of values of the defined expressions in the model. Examples of expressions in this DHN model include the calculated costs of gas, electricity, CO2, startup, and variable costs for each supply unit, for each time-step. The variable 'heat flow' can be visualized with a flow diagram if the heat flow for a specific time-step should be visualized. The variable 'buffer content' is dependent on the charge and discharge variables of the buffers. The buffer content can be visualized to explain relative highs and lows compared to the demand. The difference between the years 2018 and 2022 can be visualized if the model is run for these different years. Furthermore, the difference between different network configurations can be visualized by adding and removing certain nodes and edges to the network.

3.2.6 Model verification

Model verification is the assessment of whether the model accurately represents the conceptual model description and the model specifications. During the modeling process, various test runs have been conducted to assess whether the constraints, expressions, and variables act as expected and as intended. This has been done by doing reviews of the model and inspection of the model in an iterative manner. Finally, the model should meet the requirements as specified in section 3.2.1.

Test runs have been conducted by removing certain parts of the objective function. The objective function consists of gas, electricity, CO2, variable, and startup costs. Each of these parts have been removed, to analyze the effect on the network behavior. This is plotted for one year (8760 time-steps) to observe overall trends, and for 2 weeks (336 time-steps) to have a detailed view, see appendix B. The yearly production per unit for each case is shown in table B.1. The difference between the base case and the case with the removal of the following aspects is analyzed:

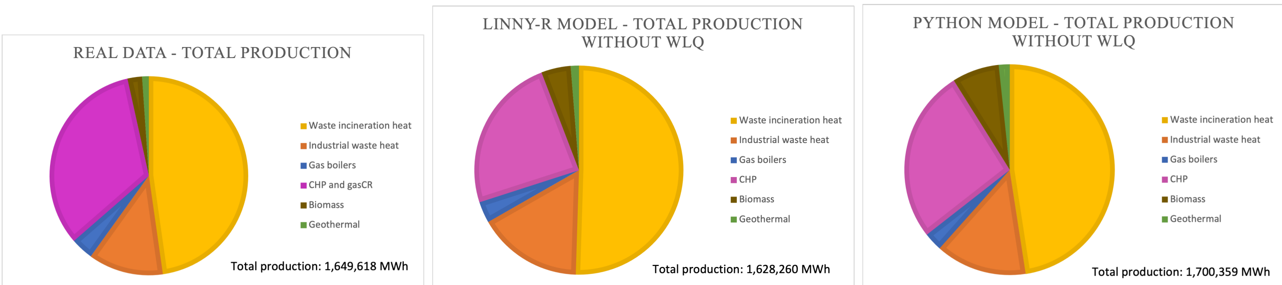
- remove electricity costs;
- remove gas costs;
- remove CO2 costs;
- remove startup costs;
- remove variable costs;
- remove edge barriers;
- remove buffers from network.

Firstly, removing electricity prices from the objective results in different units produced compared to the base case, as shown in figure B.1b, compared to figure B.1a. Instead of the CHPs, gas boilers are produced in this case. This is expected behavior, as these units provide revenue to the network by producing electricity as well as heat. Therefore, if electricity prices are removed, these revenues are not taken into account, and gas boilers can provide heat more efficiently. When gas costs are removed instead, as seen in figure B.1c, The CHPs are the main producing units. In this case, the units that do not have costs in this network (geothermal and industrial waste heat) are even turned off most of the time. This is expected behavior as the CHPs do not have to pay for gas, and therefore produce as much electricity as possible when electricity prices are high. When CO2 is removed, as visible in figure B.1d, the model shows similar behavior as the base case. This is expected behavior, as the gas boilers, which have the highest CO2 costs, are not running during many time steps in the base case as well as in the case without CO2 costs. When startup costs are removed (figure B.1e), the model shows that the CHPs are turned on and off more often. These are, next to the RDAM Gas 4 and RDAM Gas 5 the only units with startup costs, so this is expected. Removing variable costs does not show a significant difference compared to the base case, as the revenues of the units with variable costs are significantly higher than the variable costs that these units have (CHP units). Removing edge barriers does not show a significant difference either, as the only edge with costs in the base case is the connection from the waste incineration to the city of Den Haag. The heat supply from waste incineration to Den Haag is almost always 0, so this does not contribute to high costs in the base case. Lastly, removing the buffers from the network shows an exact match of the production with the demand pattern, as shown in figure B.1h. This is expected from the model, as the network should exactly produce the necessary heat for each hour, without the possibility to charge or discharge any buffer.

3.2.7 Model validation

Model validation is the assessment of the extent to which the model represents the real-world system. In this case, a DHN model should accurately represent the district heating network of South-Holland. The model is validated by comparing the model results of 2022 to the actual production levels in 2022 and the results of the Linny-R model for 2022.

Comparison with the real world The actual district heating network in 2022 consists of two separate networks, as they are not yet connected by the WLQ. Therefore, for a true comparison, the real world is compared to the base case of the model, where the WLQ connection is removed. Furthermore, the industrial waste heat from the IWH2 production unit is disconnected from the base case, as this unit was not yet delivering heat to the network in 2022. The total production and the difference percentage of the total production in 2022 per unit are shown in table C.1. The production of DH CHP and DH Gas 3 are summed in the output of the actual data, and therefore this is also done for the model output. Furthermore, the actual production data of the biomass plant and the geothermal unit is uncertain, and the gas unit RDAM Gas 2 unit has missing data. Therefore, comparing in a detailed manner is not realistic, however, the main trends are similar in the real world compared to the model. Compared to the total, the difference in the total production per unit in 2022 does not show extreme values. This is also visible when looking at figure 17a. The waste incineration heat source is the largest contributor, and the CHPs and industrial waste heat follow in both the real world as well as in the model.



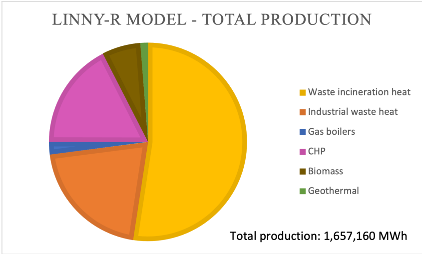
(a) Real world (b) Linny-R model (c) Python model

Figure 17: Comparison of the total production in 2022 without the WLQ connection.

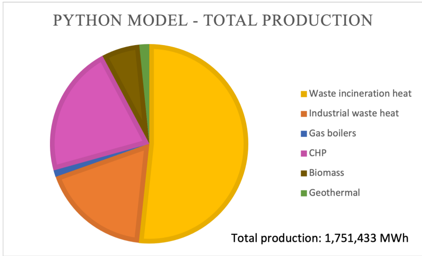
Comparison with the Linny-R model For comparing the model to the previous model, the input of the Linny-R model and the Python model are as similar as possible. The models are compared for two cases: (1) with the WLQ connection and (2) without the WLQ connection. This way, it is possible to assess the effect of the WLQ and how this connection affects the production level of the supply units in both models.

First, the Linny-R model and the Python model are compared with the WLQ connection. The production of each supply unit and the difference compared to the total production are shown in table C.2. This is visualized in figure 18a and 18b. The main difference between the two models is the production of the CHPs. The CHP produces 5.3% more than in the Linny-R model. Other gas-powered heat sources which provide heat to Rotterdam in turn produce less in the Python model, such as the gas boilers. Furthermore, the industrial waste heat could deliver more heat, however, the seasonal flow constraint which should imitate the yearly heat production limit, the industrial waste heat delivers less than in the Linny-R model.

When comparing the Linny-R model to the Python model, the difference between the production levels compared to the total production is not greater than 2.2% for any producing unit (see table C.2). Furthermore, as shown in figure 17b and 17c, the heat production from waste incineration is around 50% in both models, followed by the CHPs and industrial waste heat as biggest producers. Therefore, the output of the Python model compared to the Linny-R model is valid.



(a) Linny-R model



(b) Python model

Figure 18: Comparison of the total production in 2022 with the WLQ connection.

4 Results

In this section, model experimentation design and results are discussed. The input data, scenarios, and experiments are explained, and the results of the experiments are provided. The experiments are based on the current developments of the district heating network expansion in South-Holland, national demand, and price projections. The results will be discussed in light of the flexibility and sustainability of the DHN.

4.1 Experiment design

For this research, experimentation is carried out by varying the input of the DHN model, creating different scenarios, and experimenting with these scenarios. Firstly, for this experimentation, the variable model inputs are discussed. Secondly, scenarios are constructed by combining the different model inputs. Lastly, the experiments done with these scenarios will be elaborated.

4.1.1 Input data

The input data which can be varied to carry out the experiments is described in this section. The input data discussed is the electricity, gas, and CO2 prices, the demand, and the network expansion in terms of additional heat sources and heat storage.

Electricity, gas and CO2 prices The model input for electricity, gas, and CO2 prices can be varied between 2018 to 2022. The demand year can be varied according to these same years. The hourly prices are shown in figure 19 and the mean electricity, gas, and CO2 prices for each year are shown in table 7. It can be observed that the price of gas, electricity, and CO2 have changed drastically in the last five years in the Netherlands. Historical price observations show stable prices for electricity, gas, and CO2 in 2018. From 2018 to 2022, the lowest mean electricity and gas prices have been observed in 2020. After 2021, the gas and electricity prices have been going up, where the gas and electricity prices were three times higher than the year before. This is due to the worldwide energy crisis, resulting from the reduced energy demand during the COVID-19 pandemic, followed by a demand increase after this period, as well as the Russian-Ukrainian war. Furthermore, the CO2 price doubled in 2021 with respect to 2020, as a result of climate policy. In 2022, gas and electricity prices more than doubled again with regard to the previous year, and the CO2 price increased. Lastly, the KEV projects the electricity and gas prices in 2030, where the gas price is higher compared to 2021, but the electricity price is lower compared to 2021. The CO2 price projection for 2030 is a doubling of the price compared to 2021. In conclusion, electricity prices have experienced a sharp increase and have become more dynamic in the last five years, especially in 2021-2023.

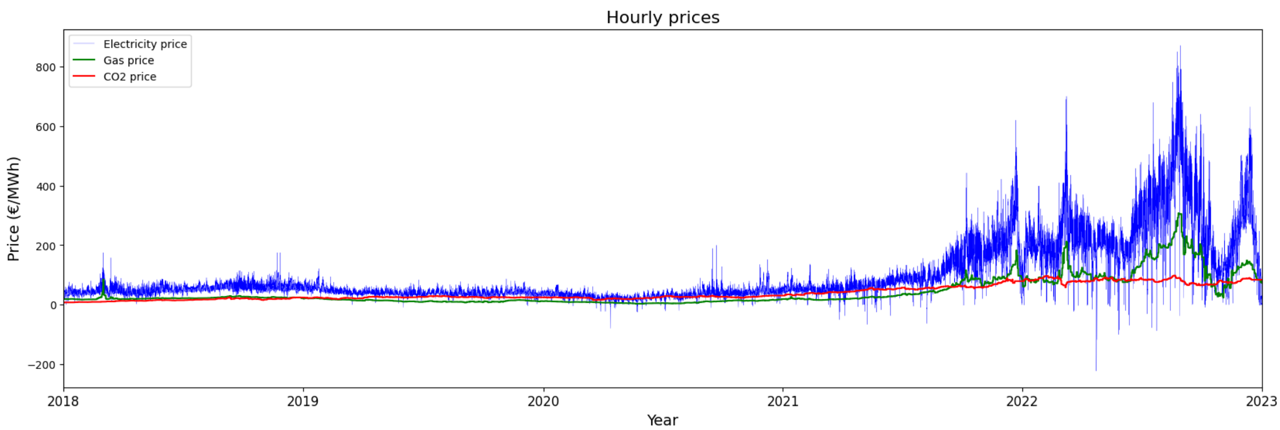


Figure 19: Electricity, gas, and CO2 prices of 2018-2022.

Table 7: Mean electricity, gas and CO2 prices from 2018 to 2022 and 2030 (PBL, 2023).

Year	Mean electricity price (€/MWh)	Mean gas price (€/MWh)	Mean CO2 price (€/ton)
2018	53	23	16
2019	41	14	25
2020	32	9	25
2021	103	46	53
2022	242	121	81
2030*	73	54.9	110

Considering the seasonal variation of electricity and gas prices, it can be said that 2018 is the most (recent) standard year for wind and solar. Because of increasing renewable integration in the energy mix in the Netherlands from 2018 to 2022, from 2020 onward, negative electricity prices are observed on an hourly level. While the gas price from 2018-2020 shows a strong seasonal pattern, with gas prices around 10 €/MWh during summer and 20 €/MWh during winter, the electricity price fluctuates more. From 2021 onward, these peaks and declines in electricity prices become more common and more extreme. At the end of 2021, the electricity price peaks up to 600 €/MWh. The gas price shows the same pattern, however, with less fluctuations on an hourly basis. Whereas in the previous years, the CO2 price increased by around 5 €/ton, in 2021 the CO2 increased from 30 €/ton to 80 €/ton. In 2022, electricity prices fluctuate severely. Apart from the extreme fluctuations, the electricity price rises during the year to more than 800 €/MWh and stays high in the last weeks of 2022 up until 600 €/MWh. The gas price peaks at the beginning of winter at 300 €/MWh. The CO2 price fluctuates between 60 and 100 €/ton. The prices of 2030 are projections by the Dutch Environmental Assessment Agency in the climate and energy exploration report of 2022 (KEV) (PBL, 2023). Comparing these prices to the price scenarios used by Eneco, the electricity, gas, and CO2 prices for 2030 are similar to one of the Eneco price scenarios [2].

Demand The demand for heat in each of the consumer substations for each year from 2018-2022 is provided by Eneco. The developments in heat demand are based on the policy analysis, in which developments and plans concerning the DHN of South-Holland are indicated. The extent of demand increase is projected in various reports, such as the II3050 as well as the outlook of the Dutch Environmental Assessment Agency, the KEV. Based on these projections, the demand increase is determined.

Network expansion The DHN model of South-Holland is expanded with additional heat sources and heat storage. Different network expansion possibilities are explored, based on district heating policy and regulations on different governance levels, as well as projections for heat transition in the Netherlands such as the II3050. The different networks are compared, concerning the behavior of the heat sources and heat storage units, with regard to the electricity, gas, and CO2 prices and demand increase.

Additional heat sources All new technologies have their own merits and drawbacks which directly impact their suitability for implementation in a DHN. The II3050 report expects a shift from the heat supply of CHPs and waste incineration plants to P2H solutions such as e-boilers and heat pumps, as well as geothermal heat (TenneT, 2021b). On the neighborhood level, the study of Oorschot (2020) proposed a differentiation of heat sources to be developed over a longer period. Table 8 shows the capital expenditure (CAPEX) and the operating expenditure (OPEX) of these potential additional heat sources. While the CAPEX of heat sources is not taken into account in this model, the difference between the CAPEX of a gas boiler and the other heat sources is significant. This poses a severe barrier to investing in heat sources such as geothermal, heat pumps, and e-boilers.

The costs are an estimated average in 2030 with an electricity price of 89 €/MWh (24.7 €/GJ), average biomass costs of 6 €/GJ, and average gas costs of 11.7 €/GJ (PBL, 2022; PBL, TNO, CBS & RIVM, 2023). Therefore, the OPEX of these heat sources is subject to variable prices of electricity, gas, and CO2. For example, the variable costs of an e-boiler

[2] The exact scenario is confidential and can be requested if necessary

depend on the electricity price. Where an e-boiler and heat pump can be flexibly used according to the electricity price in a specific hour, the variable costs of a biomass power plant are always dependent on the biomass price. An e-boiler is more dependent on the electricity price than a heat pump, due to the difference in efficiency: an e-boiler has an efficiency of 99%, while a heat pump can reach an efficiency of 400%. From the perspective of energy companies, in terms of CAPEX, risk distribution is managed by contract agreements or bank financing.

Table 8: CAPEX & OPEX of additional heat sources (Jongsma et al., 2023)

Heat source	CAPEX (€/kW)	OPEX (€/GJ)
Gas boiler	10.76	20.59
Biomass	92.37	6.67
Ground-source heat pump (aqua thermal)	168.31	7.31
E-boiler	110.73	25.39
Geothermal	166.68	1.24

E-boilers have a quick response time: they can be turned on or off on short notice. Therefore, e-boilers are suitable to participate not only in the day-ahead market, but also in the intraday, the Frequency Containment Reserve (FCR), the automatic Frequency Restoration Reserve (aFRR), and the congestion market. On the other hand, heat pumps take half an hour to an hour to start. Without technical adjustments, heat pumps are only reliable to play a role in the intraday, congestion, and imbalance market (Jongsma et al., 2023). A barrier to implementing e-boilers is the network tariff of connecting an e-boiler to the grid. This increases the CAPEX of an e-boiler. E-boilers are a good option in a network with many expensive sources. However, e-boilers become a less favorable option in DHN with sources with minimal CO2 emissions and low costs (Jongsma et al., 2023; Netbeheer Nederland, 2022).

Additional heat storage The II3050 and KEV projections do not mention heat storage. However, considering the potential interaction of P2H sources with heat storage, it is considered in this research. Table 9 shows the fixed costs (CAPEX) and the variable costs (OPEX) of potential additional heat storage in the network. Tank Thermal Energy Storage (TTES) functions as a short-term buffer for up to 12 hours, while Pit Thermal Energy Storage (PTES) can store heat for up to 30 days (Jongsma et al., 2023). ATES can be used as short- and long-term storage. Long-term ATES is not considered in this research, as long-term storage up to 1 year is not implemented in this DHN model. Low-temperature ATES has already been implemented on a large scale in the Netherlands (CE Delft, 2019), in combination with local heat pumps. PTES has only been implemented in Denmark, while TTES with large tanks has been implemented in combination with e-boilers and CHP in the industry and greenhouse industry in the Netherlands. Short-term storage of heat in TTES systems has an efficiency of 99% and the storage costs are negligible (Jongsma et al., 2023). TTES with smaller tanks has been largely implemented for separate households (RVO, 2023b). For this model, the storage behavior is optimized on a 36-hour level, and therefore, TTES is considered. Combining sustainable heat sources with storage can potentially generate additional revenue for the network, by storing the heat that is produced during hours with low electricity and gas prices. This heat can be used to supply households during peak heat demand when electricity and gas prices also spike.

Table 9: CAPEX & OPEX of additional heat storage (CE Delft, 2019; Jongsma et al., 2023)

Heat storage	CAPEX (€/kW)	OPEX (€/GJ)
ATES (low/med/high temperature)	26.08	1.11
TTES	2.56	0.46
PTES	29.56	0.56

4.1.2 Scenarios

In this section, the price, demand, and network scenarios are discussed. The scenarios are constructed with the input of the previous section, based on policy developments and projections.

Electricity, gas, and CO2 prices Model experimentation in terms of prices is done by varying the electricity, gas, and CO2 prices, and analyzing the effect in different periods during the year. The model is run with the actual prices of electricity, gas, and CO2 for 2021 and 2022. Next, these prices are multiplied by 1.25 and 1.50, and the total difference in the supply mix is examined. As the electricity prices can be negative during certain hours, this means that the electricity price does not necessarily increase, but it will fluctuate strongly. Therefore, the prices increase by 25% or 50% if the prices are positive, and the prices decrease by 25% or 50% if the prices are negative. Lastly, the price projections for 2030 of the KEV are used as input, of which the yearly means are indicated in table 7.

Demand Further experimentation with the model is done by varying the heat demand of the customer substations. Considering the policy analysis, the DHN in South-Holland are expected to expand. Expanding the heat network means that the heat demand will increase, as more households will be connected to the DHN. The II3050 report projects the total heat demand in 2050 to stay equal to the demand in 2019, this is, however, the sum of heat demand from industry, the greenhouse industry, as well as the built environment (TenneT, 2021b). According to the II3050 projections, the heat demand shifts from the industry to the built environment. In terms of the heat demand of the built environment, the II3050 expects a doubling of the heat demand in the built environment in 2030, if the climate agreement goals are met. In the KEV, an increase from 6% to 8% of heat delivery by means of district heating is projected, which is interpreted as a 33% increase for district heating in 2030 with respect to 2021 (PBL, 2023). Considering the existing developments and plans in the province of South-Holland regarding DHN expansion, this demand increase is an ambitious goal. Therefore, lower demand increase percentages of 10% and 15% are considered. Taking these policy developments and projections into account, experiments will be done with a demand increase of 0%, 10%, 15%, and 33%. The 33% demand increase is indicated as the KEV 2030 demand scenario.

Network expansion For the expansion of the network, three different cases are analyzed (see table 12). Case 1 includes only additional heat sources that are under development or planned according to the municipality's visions. Secondly, case 2 includes only additional heat storage. As the plans of the municipality do not include concrete projects on heat storage, a standard TTES buffer tank is added to three locations in the network, since the investment and operational costs are relatively low, and this allows for high-temperature heat storage. Lastly, case 3 includes both heat sources as well as heat storage.

Table 10 shows the additional sources. No startup or variable costs are included. Furthermore, gas consumption and CO2 consumption are not relevant for the additional sources. Instead of electricity production, the additional sources use electricity. Therefore, the electricity consumption is dependent on the COP, which is the heat produced in MWh divided by the electricity consumed in MWh to produce this heat. For example, a heat pump with a COP of 3 (300% efficiency), consumes 10 MW of electricity to produce 30 MW of heat. Table 11 shows the additional storage. It is assumed that storage costs are not present and that the efficiency of charge and discharge is 100%. Figure 20 shows the network with the additional sources and storage.

Table 10: Additional production units of the DHN of South-Holland for case 1 and 3.

Production unit	source type	Minimum production (MW)	Maximum production (MW)	COP
Rotterdam				
Geothermal RDAM	geothermal	4	4	8
Heat pump RDAM	HP	10	30	3
Den Haag				
Geothermal DH1	geothermal	4	4	8
Geothermal DH2	geothermal	4	4	8
Geothermal DH3	geothermal	4	4	8
Heat pump DH	HP	10	30	3
E-boiler DH	e-boiler	10	20	1
B-triangle				
Geothermal B-triangle	geothermal	4	4	8

Table 11: Additional storage capacities DHN South-Holland for case 2 and 3.

Storage	Connected to	Buffer capacity (MWh)	Rated capacity (MWh)
Storage DH	Den Haag	500	50
Storage RDAM	Rotterdam	500	50
Storage B-triangle	B-triangle	500	50

Table 12: Network expansion cases

Case	Network expansion
Base	Base case
1	additional sources
2	additional storage
3	additional storage and sources

4.1.3 Experiments

The experiment scenarios are summarized in terms of price and demand scenarios in table 13. Firstly, experiments are done by changing the weather year. This means that the demand and price input of that specific year are taken. For example, if the weather year is 2018, the electricity, gas, and CO2 prices of 2018 are considered, as well as the heat demand of 2018. Next, a comparison between the years 2018 and 2022 will be provided in terms of heat production and buffer behavior. With this comparison, the difference between the two years in terms of weather and market conditions can be shown. As 2022 was an extreme year in terms of electricity and gas prices, comparing this to 2018 can provide insight into more typical seasonal variations of heat production in 2018. A comparison between the warmest and coldest week in 2022 is provided to show seasonal differences on the hourly level.

Secondly, the model results are elaborated for the price, demand, and network scenarios as discussed in section 4.1.2. The year 2022 is discussed because this is the most recent year with complete data input, as well as an interesting year in terms of price and demand dynamics. The effect of a price increase of 25% and 50% will be examined in scenarios PI1 and PI2, respectively. Furthermore, the effect of a demand increase of 10% and 15% will be examined in scenarios DI1 and DI2. Next, the 2030 projections of the KEV, which are projections with respect to the prices of 2021, are discussed to show how the DHN responds to the price and demand projections of 2030. The base case with the prices and demand of 2021 can this way be compared to the scenario P2030, with the projected prices of the KEV. Lastly, scenario PD2030

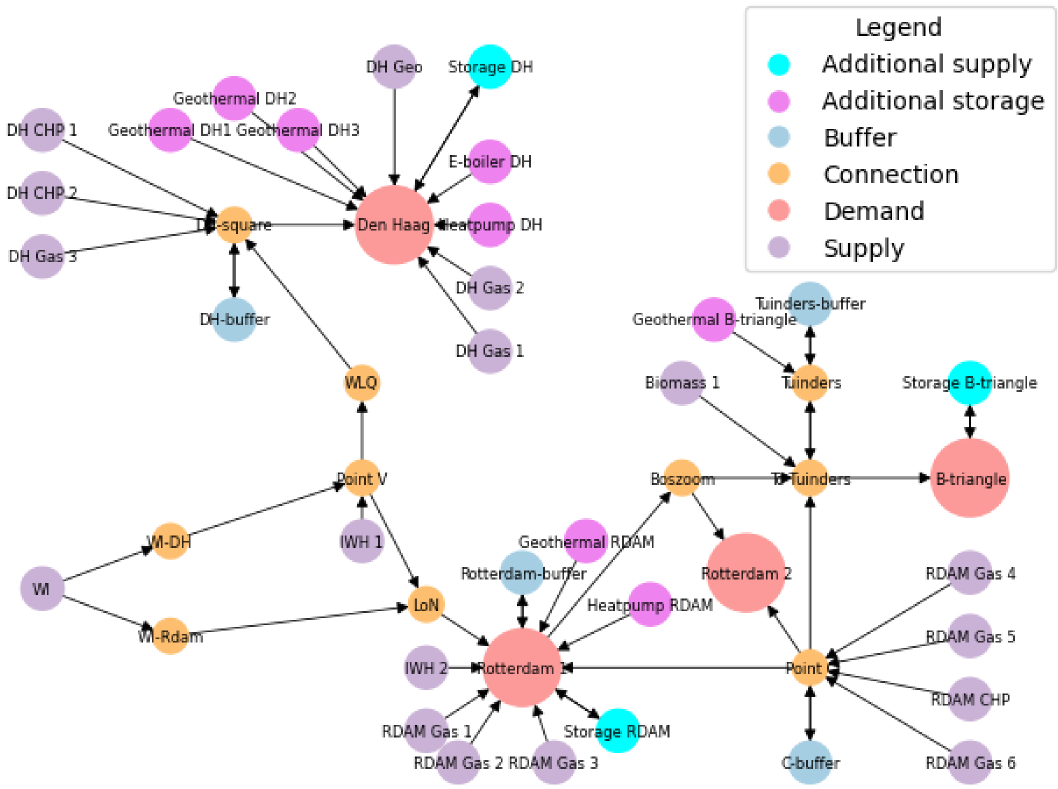


Figure 20: NetworkX representation of the DHN of South-Holland with additional sources and storage

shows results with both the KEV price and demand projections of 2030.

Table 13: Experiment scenarios

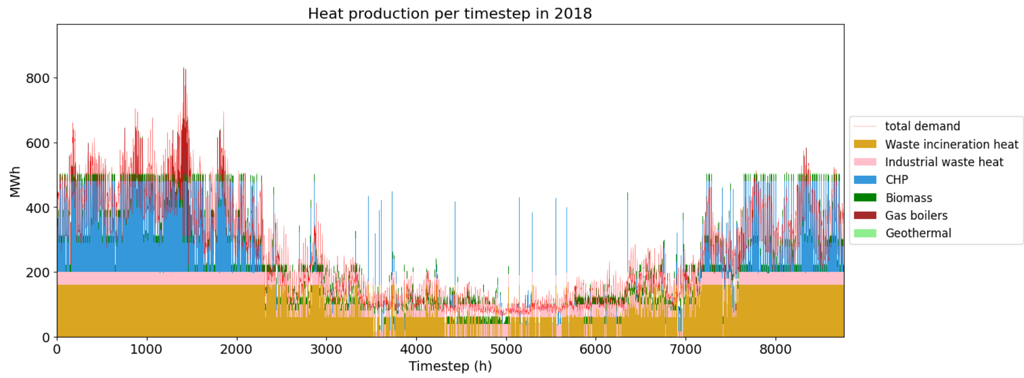
Scenario	Price	Demand
	2018	
Base	Base case	Base case
	2022	
Base	Base case	Base case
PI1	25% increase	Base case
PI2	50% increase	Base case
DI1	Base case	10% increase
DI2	Base case	15% increase
	2030	
Base	Base case	Base case
P2030	KEV 2030	Base case
PD2030	KEV 2030	KEV 2030

4.2 Experiment results

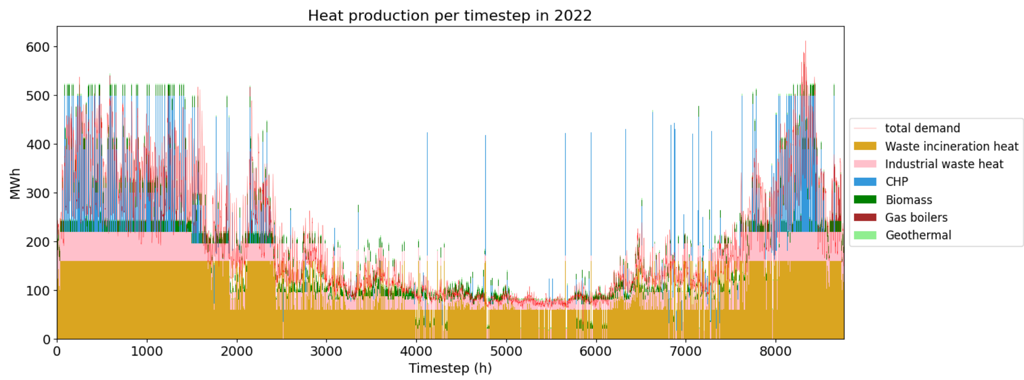
The difference between the results of the different weather years is discussed. Next, the results of the scenarios are summarized in table 14 for 2022, excluding the KEV 2030 projection scenario for price and demand. As the KEV projections are based on 2021 as the base year, the results of the 2030 projection are compared to the base case results of 2021. Next, the experiment scenarios are discussed. For each scenario, the heat production, costs, and CO2 emissions are discussed to draw conclusions in terms of the flexibility and sustainability of the network.

4.2.1 Base case

Heat production in 2018 and 2022 The difference between the weather years 2018 and 2022 is observed in terms of heat production and production costs. Figure 21 shows the total production per supply unit for each time-step in 2018 and 2022. For both years, a seasonal variation is visible. As visible in figure 22 for 2018 and 2022, the waste incineration unit is the main producing unit which produces at maximum capacity during the winter months and produces at its minimum capacity during the summer months. Sporadically, the unit is turned off, during hours with high electricity prices. During these hours, the CHPs are turned on, produce and sell electricity and the buffers store the heat for the following hours. During these hours, it is more profitable to turn on gas-powered CHPs, instead of the waste incineration unit. Similar behavior is seen for the residual heat. The residual heat units produce at peak load during winter months, at half load during spring and autumn months, and produce close to zero during summer months. Furthermore, the CHPs are producing to meet peak demand, especially during hours when electricity prices are high. This way, the generated electricity can be sold to the market. The behavior of the CHPs differs between 2018 and 2022, due to more extreme electricity prices in 2022 compared to 2018. Plateaus are visible in figure 22 due to the maximum capacity of the heat production units, and the possibility to store the heat temporarily. It is visible that with more extreme gas and electricity prices and higher CO2 prices, the CHPs produce more heat during fewer hours in 2022, compared to 2018. As visible in figure 21, the CHPs are also turned on during some hours, when the electricity price is high. Lastly, the gas boilers are mainly used to deliver peak load in 2018, whereas, in 2022, the gas boilers are only used when the total load is between 200 and 400 MW, see figure 22. However, the peak load in 2018 reached higher values than in 2022. To fulfill demand in 2018, the only option is to turn on gas boilers when the peak load is higher than 520 MW.

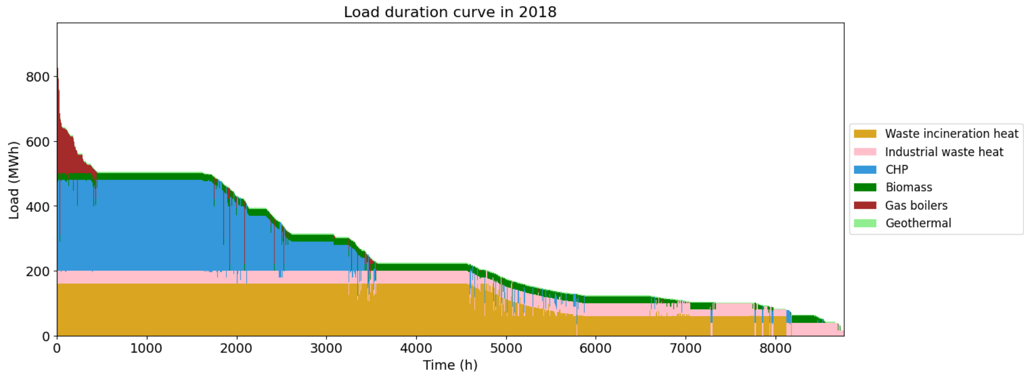


(a) 2018

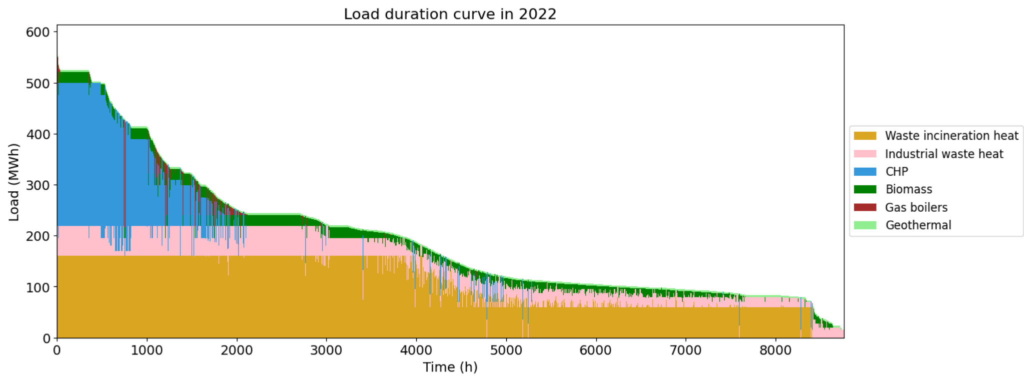


(b) 2022

Figure 21: Production per unit and total demand for each hour in 2022



(a) 2018

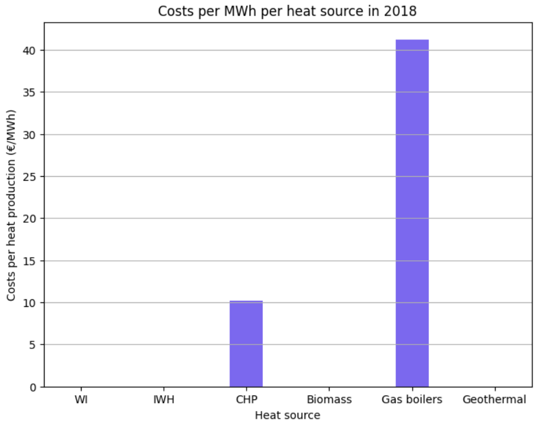


(b) 2022

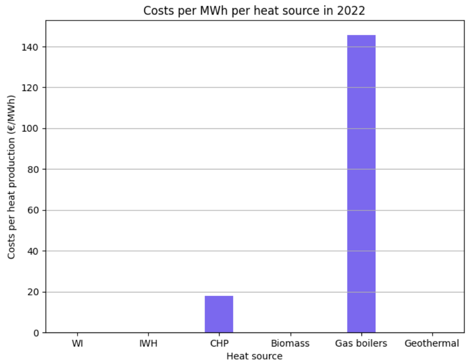
Figure 22: Load duration curve of 2018 and 2022 per heat production source

The effect of different electricity, gas, and CO2 prices is visible in the production in the first two weeks of 2022 in figure B.1a, and the first two weeks in 2018 in figure B.2. In 2018, the RDAM CHP is almost always running, while in 2022, the RDAM CHP is only turned on during the hours with peak electricity prices. This is due to the lower electricity and gas prices, and the startup costs of the RDAM CHP. Relatively, the startup costs for RDAM CHP are high compared to the gas and electricity costs in 2018. Therefore, the RDAM CHP only shut down a few times in 2018, instead of almost every day in 2022. Furthermore, at the end of the first week and beginning of the second week in 2018, the demand was relatively high. The lowest temperature of January 2018 was on the 8th of January, with -3.1°C. This results in the production of heat from gas-fired power plants to meet peak demand.

Apart from the production in 2018 and 2022, the costs of heat production per unit can be compared. The costs per MWh per unit are shown in figure 23. The main difference between these two years is the scale: the scale of 2018 goes from 0 to 100 €/MWh, while the scale of 2022 goes from 0 to 300 €/MWh. This is explained by the difference in the electricity and gas prices between 2018 and 2022. Furthermore, the gas-fired power plant 'RDAM gas 2' is not producing in 2022, and therefore excluded from the 2022 figure. It is also visible that the RDAM Gas 4 and 2 are more expensive to run in 2022 than in 2018 due to the higher gas costs. However, the RDAM CHP unit does not show this increase in 2022 compared to 2018, as this unit also produces electricity for the network. All the gas units show higher costs per unit of heat due to higher gas prices.



(a) 2018



(b) 2022

Figure 23: Comparison of the costs of heat for each production unit in 2018 and 2022.

Buffer behavior in 2022 The produced heat is temporarily stored in the buffers, as shown in figure 24. Figure 24 shows the buffer utilization of each buffer, for each hour in 2022. The buffers are more frequently charged and discharged during the colder months. The buffers are still used during the summer months, but a more extreme pattern is visible during the summer: if the buffers are used, they are used to their maximum capacity. This is the result of cost minimization of the network: if heat supply by the CHPs provides more revenues in terms of electricity production, the base load from WI and IWH are turned off. The excess heat produced by the CHPs is temporarily stored and used in the following hours.

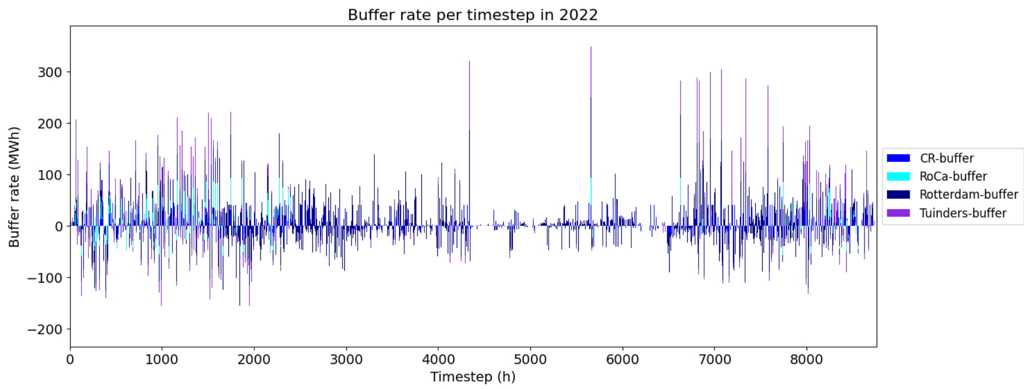
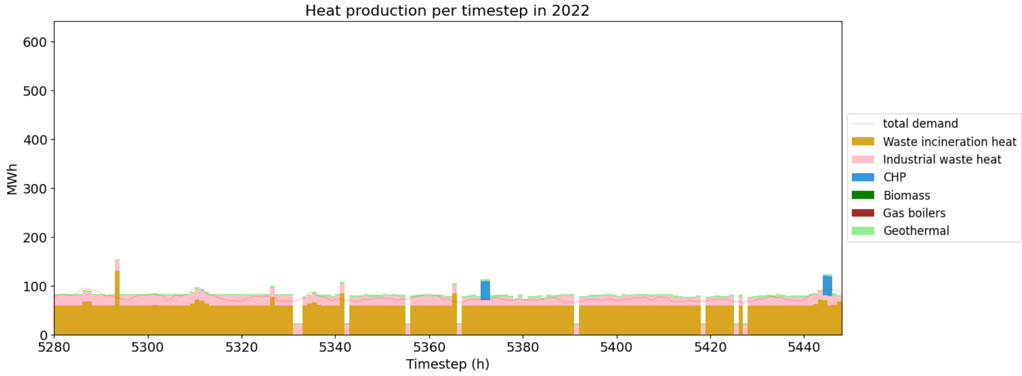
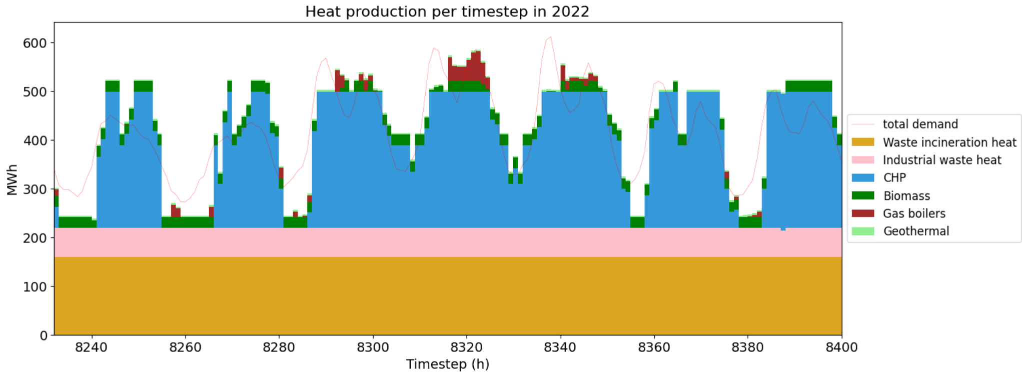


Figure 24: Base case output: buffer utilization for each hour in 2022.

Warmest and coldest week in 2022 When comparing the warmest and coldest week of 2022 in figure 25, it can be seen that the waste incineration heat is producing at its minimum capacity during the warmest week of 9-16 of August, and during some hours it is turned off. Furthermore, industrial waste heat and geothermal heat are delivered. Instead, during 10-18 of December, the coldest week of 2022, the waste incineration plant is producing at peak load, as well as for the industrial waste heat. Peak load is met primarily by CHPs, with gas boilers meeting the highest demand during short periods. Comparing the buffer behavior for these weeks in figure 26, it can be seen that the buffers are charged and discharged to a higher extent during the coldest week. The buffers dampen the peak load, and therefore also show a daily pattern. This is less clear during the warmest week. The buffers are only minimally used during this week.

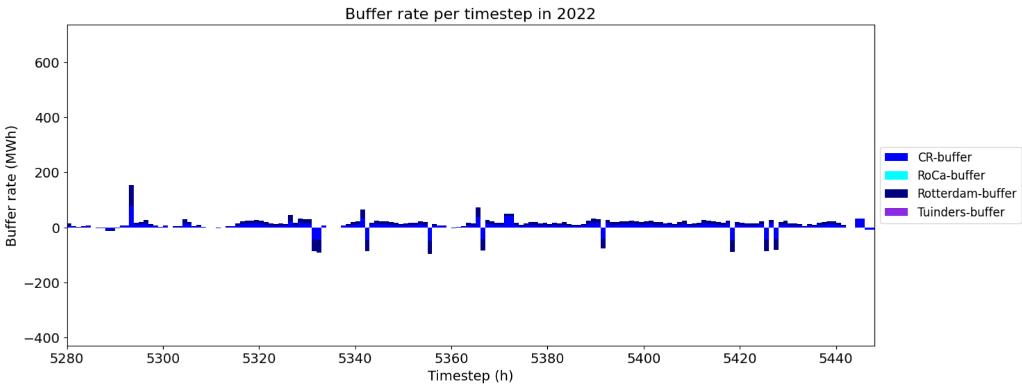


(a) Warmest week: 9-16 August 2022

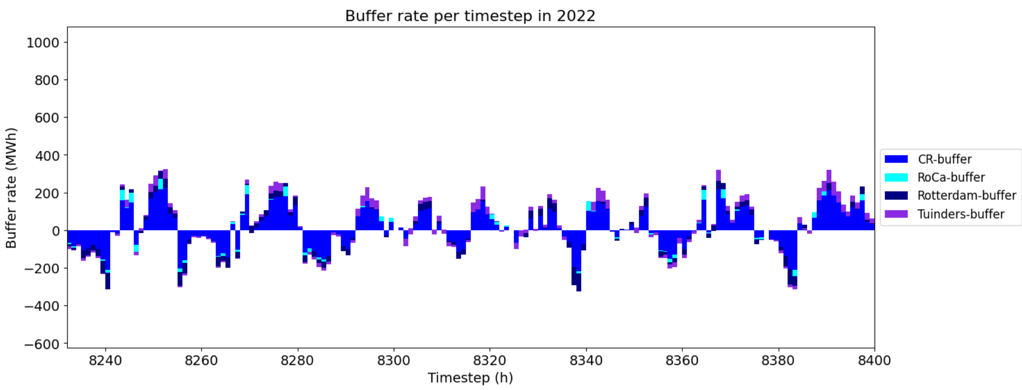


(b) Coldest week: 10-18 December 2022

Figure 25: Comparison of the total heat production per location for the warmest and coldest week in 2022 (KNMI, 2023).



(a) Warmest week: 9-16 August 2022

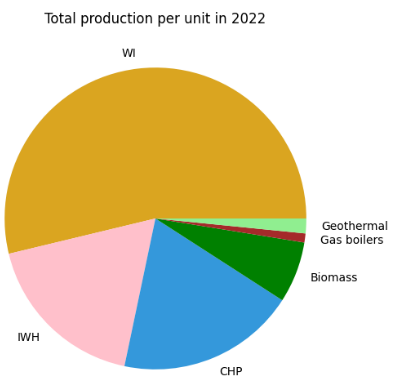


(b) Coldest week: 10-18 December 2022

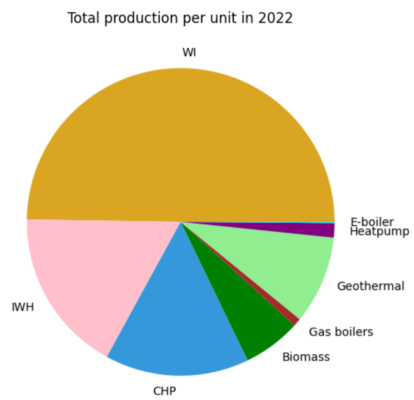
Figure 26: Comparison of the buffer utilization per location for the warmest and coldest week in 2022.

Heat production of network expansion cases Table 14 shows the results of the heat production for each network case, as well as for the different price and demand scenarios in 2022. The absolute production and the percentage change compared to the base case are provided for cases 1, 2, and 3. The first 3 columns show the absolute values in MWh, and the second 3 columns show the percentage change of the production compared to the base case. Percentage change cannot be provided for the heat pump and e-boiler as heat production sources, as these sources are not present in the current network.

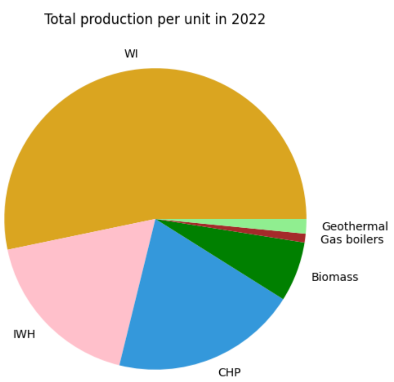
Figure 27 shows the total heat production per heat production source for each network expansion case in 2022. The largest production of heat comes from WI, followed by IWH and the CHPs. The heat produced by WI, IWH, biomass, and geothermal sources provide the base load, as this heat is contracted and therefore has minimal costs in this network. The CHPs, heat pumps, and e-boilers, on the other hand, produce during peak load hours, or hours with high electricity prices. Cases 1 and 3 result in a smaller part of the heat production coming from WI compared the base case and case 2, as this is replaced by the heat from geothermal sources. Especially the three geothermal sources added to the customer substation of Den Haag play a role here, as these sources are less expensive than the heat from the WI through the WLQ connection. While the contribution of geothermal heat is substantial, the contribution of heat pumps and e-boilers is only minimal compared to the total heat production. This makes sense, as only one e-boiler and two heat pumps are added to these networks, while substantially more geothermal units are added, which provide a base heat load. As the base case and case 2, as well as case 1 and case 3 show similar results, the additional storage does not affect the division of heat production per heat production source.



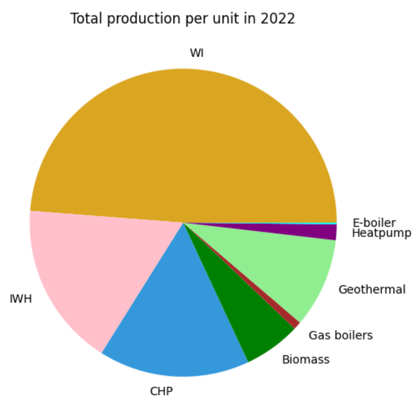
(a) Base case



(b) Case 1



(c) Case 2



(d) Case 3

Figure 27: Total heat production per heat production source for each case in 2022.

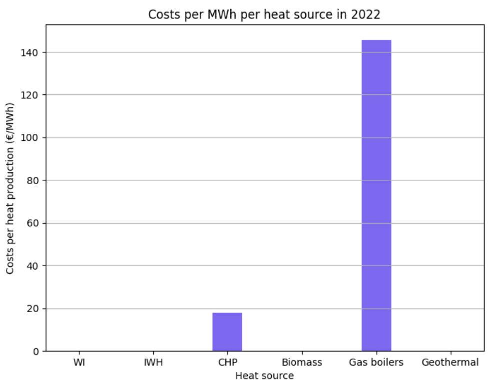
Adding additional sources (case 1) to the network mostly decreases the heat production from CHPs and gas boilers. The heat supply from the added geothermal sources 'replaces' the base load previously provided by the WI and IWH. Furthermore, the geothermal source provides enough heat to also store this, and this results in the CHPs and gas boilers

Table 14: Results of production per heat production type for different cases compared to the base case in 2022

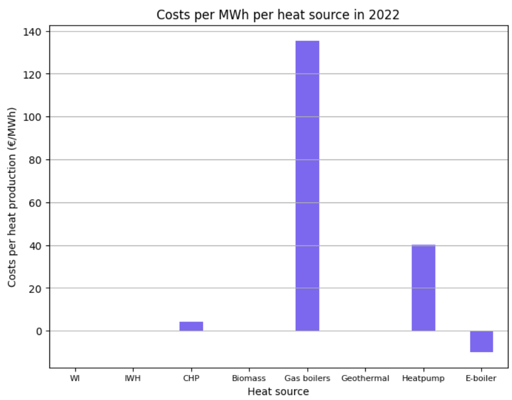
Heat production source	Base case (MWh)	Case 1 (MWh)	Case 2 (MWh)	Case 3 (MWh)	Case 1 (%)	Case 2 (%)	Case 3 (%)
Base case							
WI	934,783	863,840	931,285	850,867	-7.6%	-0.4%	-9.0%
IWH	311,922	300,375	312,777	301,776	-3.7%	0.3%	-3.3%
CHPs	333,619	262,826	347,876	277,119	-21.2%	4.3%	-16.9%
biomass	114,058	105,394	112,368	104,016	-7.6%	-1.5%	-8.8%
gas boilers	16,810	14,776	16,499	14,689	-12.1%	-1.9%	-12.6%
geothermal	27,550	160,992	27,383	164,149	484.4%	-0.6%	495.8%
heat pump	-	26,423	-	29,047			
e-boiler	-	2,006	-	2,847			
PI1: 25% increase in prices compared to 2022 prices							
WI	901,981	860,526	929,984	848,972	-4.6%	3.1%	-5.9%
IWH	314,350	300,485	312,699	301,586	-4.4%	-0.5%	-4.1%
CHPs	382,398	271,182	353,513	283,466	-29.1%	-7.6%	-25.9%
biomass	107,214	103,756	110,548	102,931	-3.2%	3.1%	-4.0%
gas boilers	18,200	13,745	15,935	13,968	-24.5%	-12.4%	-23.3%
geothermal	27,427	160,530	27,287	163,476	485.3%	-0.5%	496.0%
heat pump	-	25,579	-	28,337			
e-boiler	-	2,015	-	2,760			
PI2: 50% increase in prices compared to 2022 prices							
WI	901,784	858,931	927,565	847,088	-5%	3%	-6%
IWH	314,561	300,492	312,900	301,491	-4%	-1%	-4%
CHPs	386,528	277,140	357,114	290,493	-28%	-8%	-25%
biomass	106,586	102,971	109,650	102,284	-3%	3%	-4%
gas boilers	17,897	12,211	16,440	12,239	-32%	-8%	-32%
geothermal	27,327	160,085	27,253	162,638	486%	0%	495%
heat pump	-	25,184	-	27,366			
e-boiler	-	2,015	-	2,760			
DI1: 10% increase in heat demand compared to 2022 demand							
WI	983,845	915,701	980,664	906,441	-7%	0%	-8%
IWH	315,582	302,991	315,264	304,379	-4%	0%	-4%
CHPs	415,561	330,467	427,760	342,525	-20%	3%	-18%
biomass	121,743	113,921	121,038	113,056	-6%	-1%	-7%
gas boilers	25,242	15,765	25,912	15,724	-38%	3%	-38%
geothermal	27,723	166,531	27,667	168,655	501%	0%	508%
heat pump	-	41,589	-	43,398			
e-boiler	-	2,444	-	3,380			
DI2: 15% increase in heat demand compared to 2022 demand							
WI	1,009,255	939,179	1,003,493	928,354	-7%	-1%	-8%
IWH	316,220	305,244	316,601	306,590	-3%	0%	-3%
CHPs	455,308	363,091	468,265	374,883	-20%	3%	-18%
biomass	125,588	117,694	125,344	116,777	-6%	0%	-7%
gas boilers	33,862	18,909	34,362	18,830	-44%	1%	-44%
geothermal	27,767	168,847	27,837	171,415	508%	0%	517%
heat pump	-	50,388	-	53,211			
e-boiler	-	2,867	-	3,773			

decreasing their production. In case 2, with additional storage, it is observed that the heat production from CHPs increases. Here, the additional storage provides the possibility to produce heat during hours with high electricity prices and store the heat to use during hours with lower electricity prices. In case 3, compared to case 1, the CHP production increases, due to the availability to store the heat during the hours with higher electricity prices. Furthermore, the heat production from the gas boilers has decreased further with respect to case 1, due to the increased flexibility of the network. With additional storage, the heat demand peak is lowered, resulting in a decrease in heat from gas boilers.

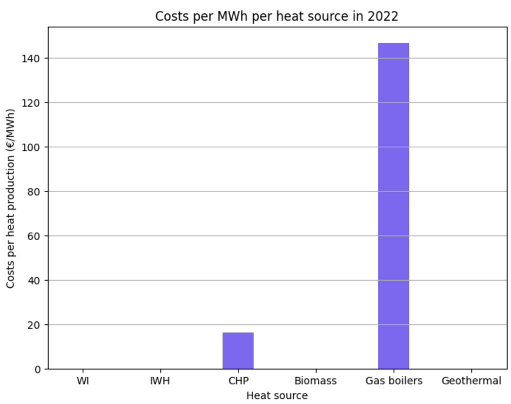
Costs Figure 28 shows the marginal costs of heat production for each heat production source. WI, IWH, biomass and geothermal do not have costs. The model takes into account existing contract structures, in terms of predetermined prices and heat volumes on an hourly or yearly basis. In the base case and case 2, the gas boilers have the highest costs. As the gas boilers have to buy gas to produce heat and do not produce electricity, they are generally more expensive to run than CHPs. In cases 1 and 3, this is followed by the heat pumps, instead of the CHPs. The CHP prices are lower which is the result of the additional sources. The added geothermal sources, heat pumps, and e-boiler provide flexibility by responding to the hourly electricity prices. The heat production from these sources results in relatively inexpensive heat from the new sources. This way, the heat supply from the CHPs decreases, and the CHPs only run during hours when it is most profitable to do so (see figure 28b). E-boilers provide revenues to the network. The revenues are the result of the e-boilers running during hours with negative electricity prices.



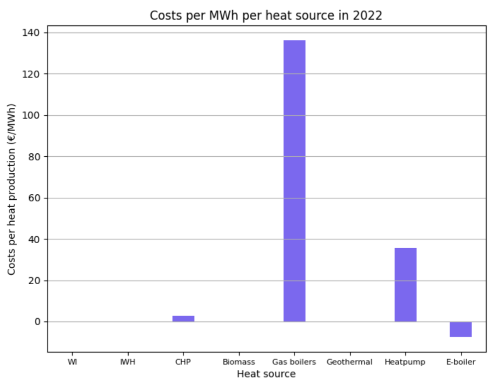
(a) Base case



(b) Case 1



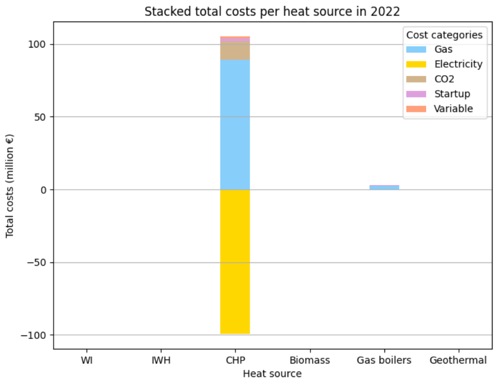
(c) Case 2



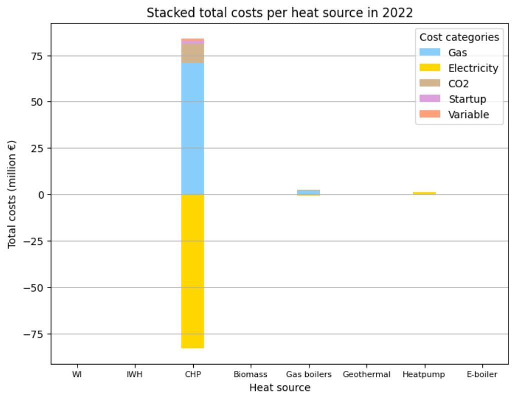
(d) Case 3

Figure 28: Costs of heat production per unit of heat for each case in 2022.

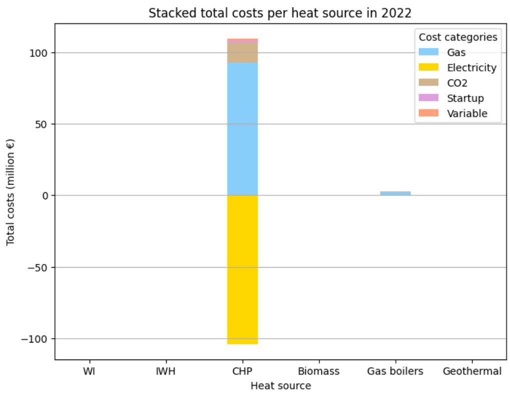
A further breakdown of the costs is shown in figure 29. This shows the total costs and revenues of heat production per cost category for each case in 2022. The costs are positive, and the revenues are 'negative costs'. For the base case and case 2, the electricity revenues are almost equal to the costs of the CHPs, which consist of primarily gas costs. For cases 1 and 3, the costs as well as the revenues of the CHPs are 25% lower. In these cases, the CHPs only run during the hours when the gas price is low, and the electricity price is high. Furthermore, the electricity costs of the heat pumps are visible, however, this is relatively small compared to the costs and revenues of the CHPs. This is due to the limited production capacity of heat pumps in this network. Furthermore, they can run during hours when the electricity price is very low or even negative. The same counts for e-boilers, however, the revenues made by the e-boilers are relatively small, so it cannot be observed in this figure.



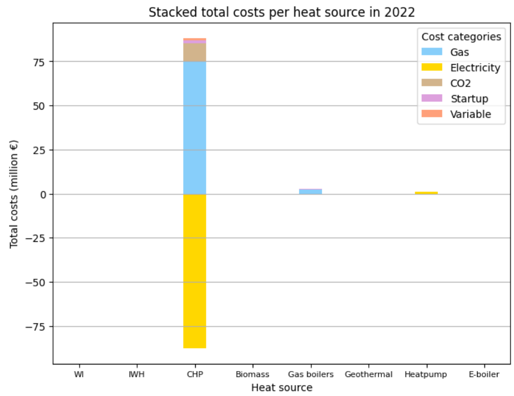
(a) Base case



(b) Case 1



(c) Case 2



(d) Case 3

Figure 29: Total costs and revenues of heat production per cost category for each case in 2022.

Lastly, figure 30a shows that the total costs of the network are the highest with the current network configuration. If additional sources are included (cases 1 and 3), the costs of the network decrease drastically. Geothermal sources in Den Haag provide cheaper heat at base load, and heat pumps and e-boilers are dependent on electricity prices. With additional sources and storage (case 3), the costs decrease further, as the heat from the heat pumps and e-boilers can be stored, and advantage can be taken from extremely high or low electricity prices.

CO2 emissions Figure 32a shows a comparison of the CO2 emissions per scenario in 2022 and for the 2030 projection. While the prices decrease with additional storage (case 2), the total CO2 emissions of the network increase. The storage provides flexibility to the network, however, it does not discriminate between storing heat from conventional supply units or more sustainable supply units. With only additional storage (case 1), the CO2 emissions are reduced compared to the base case, as the additional sources are geothermal, heat pumps, and e-boilers.

4.2.2 PI1 & PI2

Heat production For the 25% increase in the electricity, gas, and CO2 prices (PI1), the biggest decrease in heat supply is the WI. The biggest increase compared to base prices in heat production is observed for the CHPs. With more extreme electricity, gas, and CO2 prices, the units that produce electricity are producing more compared to the base scenario.

These are the units that can respond to peak demand while making a profit from the extreme electricity prices. The increasing electricity prices result in such high revenues during certain hours, that the gas and CO2 costs are only a small cost compared to this. For the PI2 scenario, when the prices are increased by 50%, the same conclusions can be drawn. In this case, the CHPs produce even more, and other units that do not have any costs or revenues produce slightly less. With the increased prices, the revenues from the CHPs are higher, which explains this increase.

Concerning the network expansion cases, the heat production from the gas boilers reduces twice as much for cases 1 and 3. For scenario PI1, the increase in gas and CO2 prices makes the gas boilers more expensive to run. The same effect is visible for the CHPs. If the prices of electricity, gas, and CO2 are increased by 50% (PI2), the same trend is observed for gas boilers. The heat production from the gas boilers in cases 1 and 3 has reduced even more compared to the 25% price increase. On the other hand, the CHP production does not decrease further. In scenario PI2, the extreme electricity prices result in the CHPs being less expensive or even profitable with respect to the gas boilers.

Costs Besides the costs of each unit (CHP, gas boilers, heat pumps) and each category (gas, electricity, CO2, startup, variable), the total costs of each case can be compared. Figure 30a and 31a show the total costs and the costs per heat unit for the base case and cases 1, 2, and 3. These comparisons are provided for 2022 and 2030, based on the 2021 prices and demand. For 2022, the demand increases of 10% and 15% compared to 2022 are shown, as well as the price increases of 25% and 50% compared to 2022.

For 2022, this shows that any addition to the network in terms of (sustainable) sources or storage will bring down the total costs of the network. However, a strong decrease in costs is seen in case 1, with additional sources, and case 3 with additional sources and storage. case 2 shows a decrease in costs; however, this is only minimal compared to the other two cases. For scenarios PI1 and PI2, the total costs of the network increase. However, with additional sources, the cost increase is minimal. The additional sources do not rely on gas and CO2 prices, which brings down the costs. Still, the costs do increase, as heat pumps and e-boilers are dependent on the electricity prices, however, with additional sources (case 2), storing this heat during hours with lower electricity prices provides flexibility to the network, and therefore lower costs.

CO2 emissions A similar increase in CO2 emissions is observed for scenarios PI1 and PI2 (see figure 32a). The 25% price increase leads to increased CO2 emissions in the current network, as the increased gas and CO2 prices result in higher heat production costs by the gas boilers and CHPs. However, if additional sources are added (case 1), the CO2 emissions only slightly increase compared to the base scenario. The added sources are not dependent on gas or CO2 prices, and can therefore produce heat at lower costs. Furthermore, with the price increase, the CO2 emissions are lowered if additional sources are added to the network. In this case, the flexibility that the additional storage provides increases the sustainability of the network. In this case, the prices have increased in such a way that sustainable heat production is stimulated in terms of operation. Especially in terms of heat production by the CHPs, the storage provides flexibility by being able to produce heat during the hours with lower electricity prices. In scenario PI2, the CO2 emissions increase only slightly with respect to scenario PI1. It seems that the price increase of gas, CO2, and electricity in this case results in the same behavior of the CHPs.

4.2.3 DI1 & DI2

Heat production If the demand is increased by 10%, the heat production from waste incineration, CHPs, and gas boilers increases significantly. The heat production by the biomass and IWH supply units also increases, however, the production of these units is close to reaching its limits in this network. An overall increase in heat supply is necessary to meet the increasing demand and happens to a more extreme extent with a demand increase of 15% (DI2).

In terms of the network expansion cases, with additional sources (case 1), the heat is sourced to a larger extent from the geothermal sources and heat pumps. The heat pumps can provide heat at relatively low costs, and have the room to increase their heat output in this network. The heat pumps and e-boilers can take advantage of producing heat during hours with low electricity prices. With this, the heat production from the CHPs and gas boilers decreases to a large extent. In case 2, the heat produced by CHPs increases compared to the base scenario. While the geothermal sources could provide more heat in this case, the CHPs are used instead. This is the case as the CHPs are profitable during the hours with high electricity prices, whereas, geothermal sources do not provide revenues. This effect is visible for scenarios DI1 and DI2.

Costs Figure 30a shows that the demand increase results in increasing total costs of the network. More heat should be generated from the same sources. The units that can ramp up their production are the CHPs and gas boilers. Especially the gas boilers are expensive to run, which explains the increasing costs of the network. With additional sources (case 1), these costs are decreased because of the availability of geothermal heat, heat from heat pumps, and e-boilers. With additional storage (case 2), the costs decrease slightly, due to the added flexibility. As the biggest increasing heat source is the CHPs, these can be used during hours with higher electricity prices to generate higher profits. For case 3, the effects of cases 1 and 2 are combined.

CO2 emissions In terms of CO2 emissions, increasing demand results in increased CO2 emissions, as visible in figure 32a. While the costs of the network decrease with additional sources (cases 2 and 3), the CO2 emissions increase. The increased heat production from the CHPs and gas boilers as explained in the previous section, causes this increase of CO2 emissions.

4.2.4 P2030

Heat production Table 15 summarizes the heat production of the base scenario, the price projection for 2030, and the price and demand projection for 2030. Compared to the base scenario, the P2030 scenario results in a sharp decrease in heat production from the CHPs. This is produced instead by the gas boilers. This is explained by the relatively low electricity prices compared to 2022. In this case, the costs of producing heat with gas boilers instead of CHPs are lower, due to the reduced electricity revenues that could be generated with the CHPs at these lower electricity prices.

Case 1, with additional sources, confirms this, as the heat produced by the gas boilers is reduced, and replaced by the heat from geothermal sources, heat pumps, and the e-boiler. If only storage is added (case 2), the heat production from the gas boilers and CHPs increases slightly, while the production from WI decreases. The heat storage in this case does not perform optimally due to the short optimization period, as costs and CO2 emissions are higher than without storage. The storage responds to the prices with a 36-hour foresight, therefore, on a yearly basis, these decisions can sometimes turn out to be sub-optimal. Case 3 shows again a combined effect of cases 1 and 2.

Costs Taking the price projections for 2030 as input for the model, the total costs of the network increase severely, compared to the base scenario. This is visible in figure 30b. The increase in total costs is the result of a doubling of the CO2 price, a small increase of the gas price, and a decrease of the electricity price with respect to the prices of 2021 (see table 7). When running gas turbines and CHPs, the gas used to produce heat, as well as the CO2 credits that need to be purchased are more expensive, while the electricity generated by the CHPs delivers a reduced revenue, compared to 2021. Therefore, the network will try to optimize the network, taking into account the high costs of gas and CO2.

In cases 1 and 3, with additional sources, the total costs do not increase as significantly, as the added sources are not dependent on gas or CO2 prices. However, with additional storage (case 2), the total costs increase slightly. This is the effect of the network optimizing with storage on a 36-hour level, which, with the increase in the use of CHPs and gas boilers, turns out to be more expensive on a yearly basis.

CO2 emissions It is visible in figure 32b that the CO2 emissions decrease significantly compared to the base scenario. With the price projections of 2030, besides a sharp increase in total network costs, an increase in gas and CO2 prices also results in a decrease in CO2 emissions. Furthermore, with additional sources (cases 1 and 3), the CO2 emissions decrease further, resulting from the geothermal sources, heat pumps, and the e-boiler which do not emit CO2 or use gas. The slight increase in CO2 emissions with additional sources (case 2) has the same reason as with the total costs: the storage leads to short-term optimization, but is more expensive over the course of a year.

Table 15: Results of production per heat production type for different cases in 2030

Heat production source	Base case (MWh)	Case 1 (MWh)	Case 2 (MWh)	Case 3 (MWh)	Case 1 (%)	Case 2 (%)	Case 3 (%)
Base case							
WI	1,059,382	991,225	1,056,348	982,025	-6%	0%	-7%
IWH	320,383	309,990	319,867	308,831	-3%	0%	-4%
CHPs	516,603	410,344	524,173	417,311	-21%	1%	-19%
biomass	141,883	136,377	142,312	135,857	-4%	0%	-4%
gas boilers	50,632	33,098	51,512	33,567	-35%	2%	-34%
geothermal	28,040	177,958	28,583	185,331	535%	2%	561%
heat pump		53,296		56,015			
e-boiler		2,052		2,824			
P2030: price projections for 2030							
WI	1,079,257	1,005,632	1,076,411	1,002,073	-7%	0%	-7%
IWH	325,307	319,105	326,398	316,310	-2%	0%	-3%
CHPs	74,216	41,487	74,704	40,434	-44%	1%	-46%
biomass	147,529	143,147	148,832	142,791	-3%	1%	-3%
gas boilers	437,983	206,853	448,532	209,115	-53%	2%	-52%
geothermal	28,620	184,458	29,187	192,253	545%	2%	572%
heat pump		170,685		171,664			
e-boiler		25,342		27,442			
PD2030: prices and demand projections for 2030							
WI	1,204,275	1,144,350	1,203,352	1,140,184	-5%	0%	-5%
IWH	329,165	325,166	329,487	324,430	-1%	0%	-1%
CHPs	107,885	77,110	108,283	75,987	-29%	0%	-30%
biomass	164,422	160,503	164,625	160,206	-2%	0%	-3%
gas boilers	910,813	535,852	935,475	543,808	-41%	3%	-40%
geothermal	28,680	192,042	29,200	197,355	570%	2%	588%
heat pump		252,971		254,454			
e-boiler		52,797		54,684			

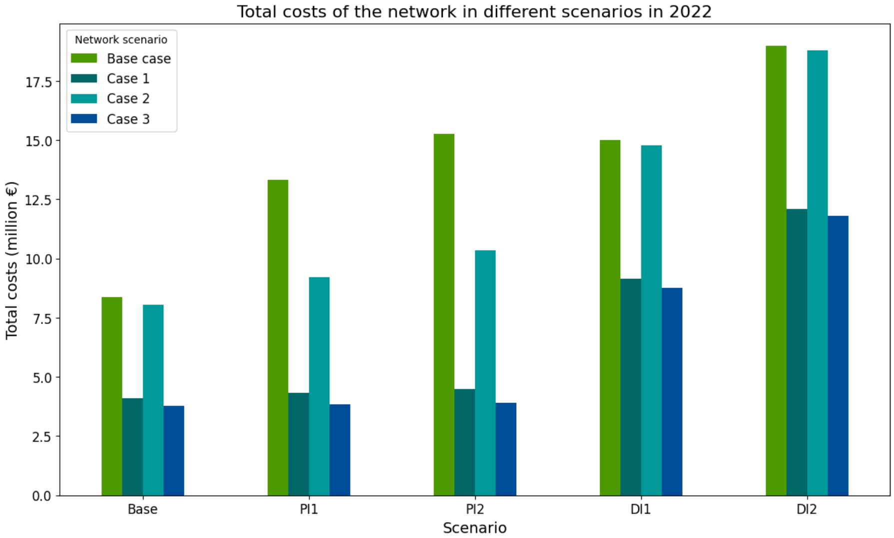
4.2.5 PD2030

Heat production The total production, as summarized in table 15 with the price and demand projections of 2030 shows a sharp increase in the gas boilers' heat production. Furthermore, the WI increases significantly compared to base demand. This increase in production is necessary to meet the 33% demand increase as projected in 2030. The heat production from the CHPs decreases significantly. With the price projection of 2030, it is more profitable to run gas boilers for heat production than CHPs.

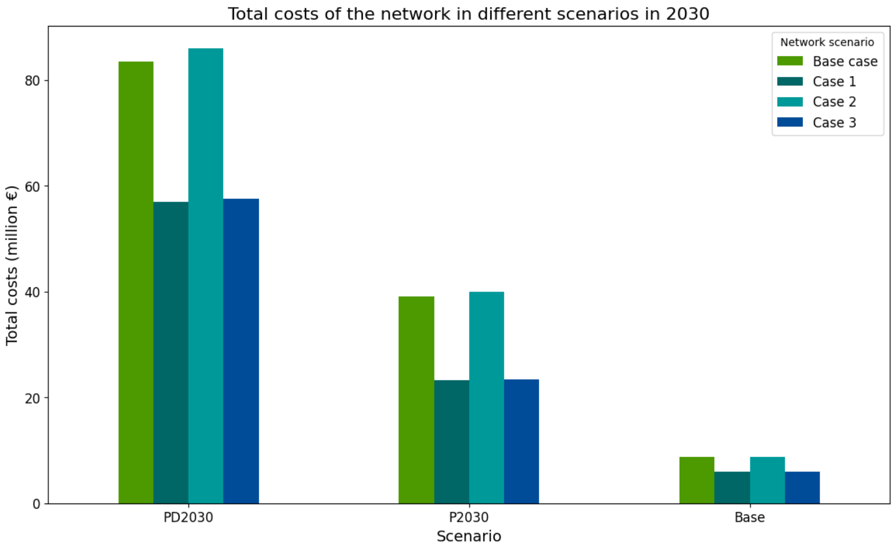
With additional sources (case 1), the heat production from geothermal sources increases. Furthermore, compared to the base scenario, the heat production from heat pumps and e-boilers increases severely, which is necessary to meet demand, as well as the most profitable and flexible way of producing heat in this case. With additional storage (case 2), the gas boilers produce slightly more due to imperfect optimization on the yearly level. Lastly, case 3 shows the same results as case 1, as the additional storage has a relatively low impact on the entire network.

Costs Considering the total costs of the network (see figure 30b), the total costs increase severely compared to the base scenario. Considering the demand projections for 2030, the increase of 33% of demand results in a severe increase in the total costs. This is expected, as the increased demand should be met with the existing network, without any additional sources or storage. The result is that heat sources need to provide peak load more often, which is mainly delivered by gas boilers and CHPs. The gas and CO2 credits necessary for this production drive up the expenses of the network. If the demand and price projections of 2030 are combined, the gas and CO2 prices have increased significantly, which results in the high total costs of the network.

CO2 emissions On the other hand, the CO2 emissions with this demand increase only slightly compared to the base scenario. For the 2030 projection, figure 32b shows that the prices and demand of the KEV show the highest CO2 emissions. However, considering the increased demand and prices compared to the base scenario, this increase in CO2 emissions is only minor. Furthermore, if additional sources are added to the network (case 1), the CO2 emissions are significantly lower than the base case. Additional storage (case 2) only increases the CO2 emissions of the scenarios slightly, due to the same reason as for scenario P2030. In case 3, with additional sources and storage, this is also observed.

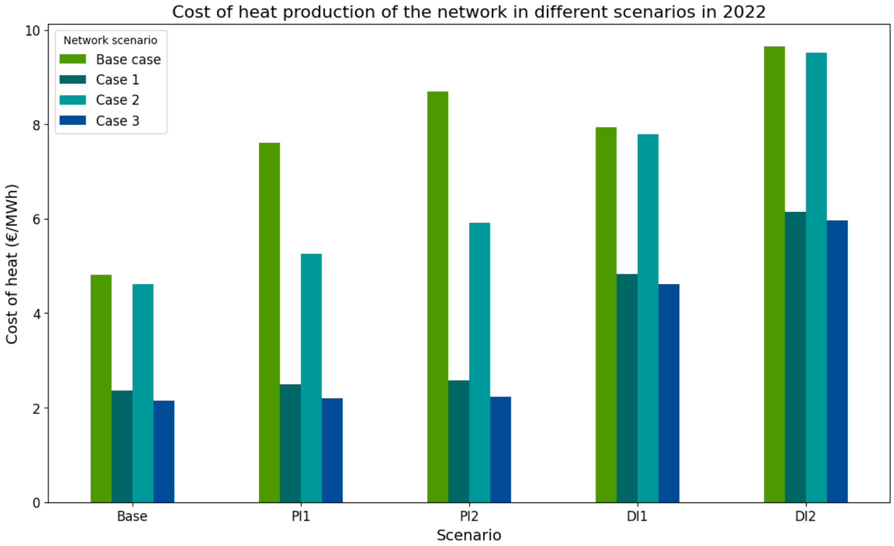


(a) 2022

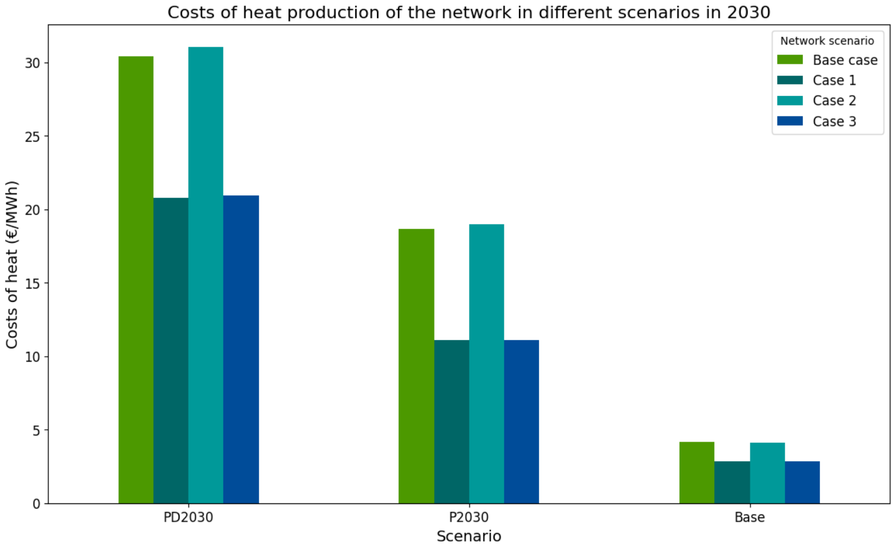


(b) 2030 projections

Figure 30: Total costs per scenario

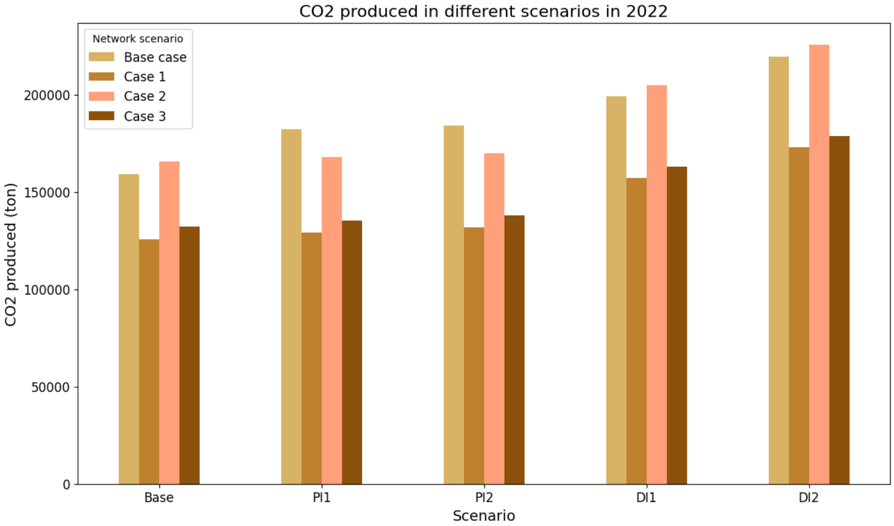


(a) 2022

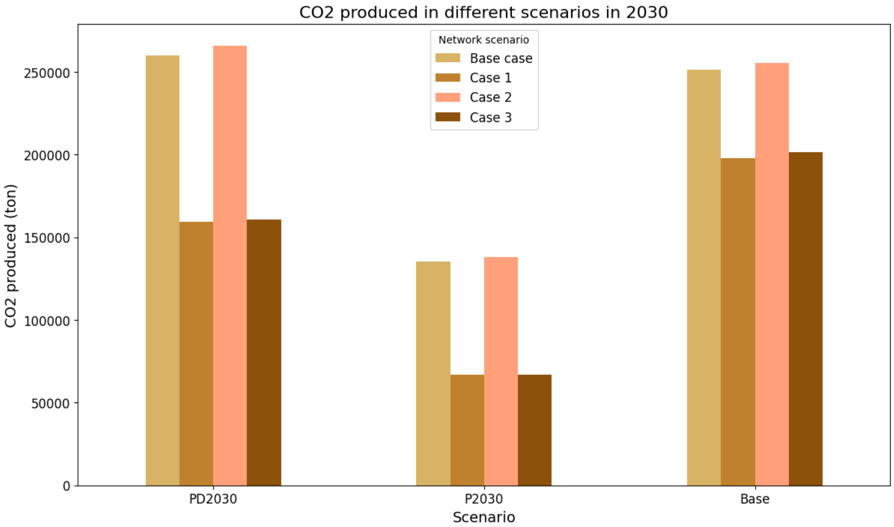


(b) 2030 projections

Figure 31: Total costs per heat unit per scenario.



(a) 2022



(b) 2030 projections

Figure 32: Total CO2 emissions per scenario

5 Discussion

In this chapter, the results of this study are discussed, and answers are provided to the sub-questions. Next, the methodology is evaluated, and the limitations of the methods are discussed.

5.1 Interpretation of experiment results

The experiment results provide insights into the impact of price (scenario PI1 and PI2) and demand (DI1 and DI2) increase on the DHN with different network configurations. Furthermore, the experiments show how the DHN behaves in terms of total yearly costs, costs per heat unit, and CO2 produced. Scenarios P2030 and PD2030 show how the network responds to the projection price and demand in 2030.

5.1.1 Case 1: additional sources

For each scenario, expanding the network with additional sources that do not emit CO2 and are run on electricity or geothermal (case 1), increases the flexibility and sustainability of the DHN. The maximum reduction of CO2 emissions and the maximum cost reduction are achieved if additional heat sources are present (case 1). The extra sources are utilized to a larger extent if the gas and CO2 prices increase. The conventional heat sources running on gas and paying for CO2 credits are in this case more expensive than added geothermal heat sources, heat pumps, and the e-boiler.

5.1.2 Case 2: additional storage

Additional heat storage (case 2) leads to increased CO2 emissions. This is the result of the extra flexibility that heat storage provides, where the heat source can be from both fossil fuel-powered heat sources, as well as renewable-powered heat sources. Due to the economic optimization of the model, the heat produced by the CHPs and the gas boilers will be produced and possibly stored during hours with high electricity prices. As these assets are powered by natural gas, this does increase CO2 emissions. However, as long as the costs for emitting CO2 and the gas costs are lower than the electricity revenues, the storage capacity will be used to this end. Therefore, expanding the network with additional storage (case 2) increases the short-term flexibility of the network, however, the sustainability of the network does not necessarily increase.

5.1.3 Case 3: additional sources and storage

Expanding the DHN with additional source and storage (case 3) results in increased flexibility of the network, as the effect of additional sources and storage is combined. In case 3, the effects of cases 1 and 2 are combined: the emissions as well as the total costs of the network are reduced. While the emissions of case 3 are higher in each scenario compared to case 1, the total costs of the network are the lowest for each scenario. In a network with more renewable heat sources, the combination of additional sources and storage therefore is expected to be the most profitable, sustainable, and flexible network expansion, provided that the electricity used for the additional sources is renewable.

5.1.4 2030 projection

Lastly, for the 2030 projection, the P2030 and PD2030 scenarios show sharp cost increases and only slight CO2 emissions increases. With additional sources, these price and CO2 increases are not as extreme, however, still higher than the base cases. Extra storage shows a similar effect as for the 2022 cases. Considering the increased demand, the projected scenarios for 2030 perform relatively well in terms of CO2 emissions. In conclusion, with the projected price and demand as projection in the KEV, increased costs of the network should be anticipated, and the development of additional sources should be considered to reduce costs and CO2 emissions.

5.1.5 Investment strategy for the DHN of South-Holland

Investing in additional heat sources for the South-Holland DHN, such as geothermal sources, heat pumps, and e-boilers, results in a decrease in total network costs, as well as a decrease in CO2 emissions. While these sources have high initial investment costs, the operational costs, especially considering geothermal heat, are relatively low. Even without price or demand increase of the DHN, investing in geothermal sources results in significantly lower network costs and emissions. Heat pumps and e-boilers provide a significant share of heat production in the DHN if the prices and demand develop as projected for 2030.

Investing in additional heat storage can provide the necessary potential flexibility and sustainability to the network, with relatively low investment and operational costs. In combination with additional sources such as geothermal heat, heat pumps, and e-boilers, the storage provides flexibility as well as sustainability. If additional storage is added in a network with many conventional heat sources, such as gas boilers and CHPs, the storage can instead result in decreased sustainability of the network.

5.2 Sub-questions

5.2.1 SQ1: regulatory and policy frameworks

What regulatory and policy frameworks are necessary to support the implementation of heat storage and additional heat sources within the South-Holland DHN, and how can they work as an incentive for sustainable and future-proof practices?

As presented in Chapter 2, regulatory and policy frameworks are present to stimulate investments in additional heat sources and heat storage for the DHN of South-Holland. Financial instruments, guiding instruments, and regional cooperation are necessary to plan and execute the DHN expansion in South-Holland. This study has presented the network behavior with the plans for network expansion in terms of additional heat sources and storage. Expanding the network with additional heat sources, as well as the combination of heat sources and heat storage reduces the long-term costs of the network, and reduces the CO2 emissions of the households connected to this network significantly. With the electricity, gas, and CO2 price projections for 2030, additional subsidies should be made available to invest in additional heat sources and storage, to limit the costs of the DHN in South-Holland.

Furthermore, network expansion in terms of connecting additional households to the DHN should go hand-in-hand with connecting additional sources, to meet the growing heat demand. With the current targets to connect the number of households to the DHN before 2050 in Den Haag, Rotterdam, and the B-triangle, this increasing demand should be met with additional heat sources and storage. Subsidies such as the 'SDE++' and 'GE' reduce the capital expenditure of these assets, and can therefore stimulate investment in the short-term. Furthermore, with increasing gas and CO2 prices, the network costs significantly increase with the current set of assets in the DHN of South-Holland. Therefore, for energy companies, municipalities, housing associations, and DHN customers, the sooner investments in heat sources and storage can be made, facilitated by financial support, the lower the costs and emissions of the network, and the sooner a flexible and sustainable network is realized.

5.2.2 SQ2: model requirements

What are the requirements for a DHN model to facilitate informed investment decisions, considering factors such as growth, decarbonization, and changing heat demand patterns?

A DHN model should economically optimize the heat generation for the DHN. Besides, a DHN model should take into account existing contracts with heat suppliers and consumers. Secondly, a DHN model should be able to easily compare different cases. This includes different possible network expansions, electricity, gas, and CO2 price variations, as well as demand variations. Furthermore, the input year for price and demand should be variable to compare different historical weather patterns. Thirdly, a DHN model should be future-proof, which is realized by means of a modular setup, having the possibility to add and remove specific heat production sources, heat storage, and heat demand consumption substations.

Lastly, the model should be written in a standard modeling language that is well-documented. This ensures that a DHN model is user-friendly, and it is possible to expand the model or couple the model for various research objectives.

5.2.3 SQ3: district heat network expansion

What effect does expanding the district heat network with additional heat sources and heat storage have on the flexibility and sustainability of the DHN, particularly in adapting to fluctuating heat demand and supply conditions?

For this research, the DHN of South-Holland is expanded with different heat sources and heat storage in various locations in the network, based on local policies for the near future of the DHN. Besides the geothermal sources added, the heat pumps and e-boilers are dependent on electricity to produce heat. Electrification of heat production is one of the possible ways to make the network more sustainable, but only in case this electricity is from renewable sources. Electricity supply from renewable sources such as wind and solar, varies from hour to hour. This is reflected in the hourly electricity prices. Therefore, the flexibility of the DHN can be measured by the costs of heat production. To what extent and within which time frame the network can act upon electricity and gas prices has an impact on the flexibility of the network.

With increasing electricity, gas, and CO2 prices, additional sources (case 1), additional storage (case 2), and combining the two (case 3) significantly reduce the total yearly costs of the network. With increasing heat demand, the total costs of the network are reduced with additional sources (case 1). However, additional storage (case 2 and 3) only slightly decreases the total costs. Taking into account the price and demand projections of 2030, the total costs of the DHN increase significantly. This cost increase can be reduced by adding additional sources (case 1). However, additional storage does not reduce the total costs, as the relatively low gas and electricity price result in a large part of the heat production from gas boilers, facilitated by additional storage. The 36-hour optimization in this case requires conventional assets to run, while this would not be the optimal solution looking at the yearly costs.

Next to the flexibility of the network, the sustainability of the network is measured by the total yearly CO2 emitted. Although the addition of heat sources to the network (case 1) leads to a reduction of CO2 emitted, the addition of storage (case 2) leads to an increase in CO2 emitted. While the network becomes more flexible due to available heat storage, this flexibility is used for all assets, including the assets that run on gas and produce electricity. This way, the flexibility of the network in the form of heat storage does not always lead to increased sustainability of the network. Considering the price projections for 2030, the CO2 emissions of the network are significantly reduced. Similarly, the additional heat sources mainly contribute to a further decrease in CO2 emissions. With the projected heat demand increase for 2030, the CO2 emissions increase, which shows the need for additional heat sources.

5.3 Main research question

The main research question of this study was: *how can the integration of heat storage and additional heat sources enhance the flexibility and long-term sustainability of the South-Holland DHN?*

Modeling additional heat sources and heat storage provides relevant insight into the flexibility and sustainability of the DHN of South-Holland. Expanding the network with additional heat sources can improve the sustainability of the network in case the emissions of these additional sources are minimal. Geothermal sources, heat pumps, and e-boilers, as proposed in regional and local policies, improve the sustainability of the network. In terms of flexibility of the network, geothermal sources in many cases provide a base load, while heat pumps and e-boilers can benefit from flexible power prices. Expanding the network with additional heat storage primarily improves the flexibility of the DHN. Moreover, additional storage can result in higher CO2 emissions of the network, therefore decreasing the sustainability of the network. The more sustainable heat sources are connected to the network, the more additional heat storage can contribute to the sustainability of the DHN. Therefore, additional storage mainly makes sense in combination with additional heat sources.

5.4 Evaluation of methodology and limitations

In this section, the methodology is evaluated and possible limitations are discussed in terms of model setup, model experimentation, and policy issues.

5.4.1 Model setup

Firstly, the Python DHN model works with a rolling time horizon, where the optimization period is 36 hours. For this reason, constraints that are relevant over longer periods cannot be met. This would be relevant in the case that, for example, a certain amount of heat is contracted on a yearly basis with a heat production company by an energy provider. Producing units are only modeled according to their production limits. Therefore, to imitate a yearly maximum production of heat for certain units, different production limits are set depending on the season or expected production during a certain period. This way, fixed maintenance periods can also be scheduled in the model, by specifying during which time-steps the maximum production of a unit is zero. With different seasonal limits, the heat production is imitated realistically. However, a potential additional function of the model could be added to take yearly constraints into account. One should be aware that a time horizon of 36 hours with an additional yearly constraint is computationally more challenging. Therefore, the model would take more time to optimize with a yearly constraint.

Secondly, CO2 emissions, gas costs, electricity costs, and electricity revenues are considered solely from supply and storage units owned by Eneco. These are the units for which full information regarding efficiency is available. Emissions from supply or storage units contracted by Eneco are not taken into account. The heat-producing party pays for their fuel costs and CO2 credits. Therefore, full disclosure of the total CO2 emissions of the DHN cannot be provided. It is only possible to know the approximate CO2 emissions of the supply units owned by Eneco. Furthermore, no CO2 emissions are accounted for the electricity used to run heat pumps and e-boilers. Indirectly, the network would emit CO2 if the electricity is generated with fossil fuels. However, the current electricity mix in the Netherlands is not 100% renewable. This could be taken into account, if there is interest in approximating all the direct as well as indirect emissions.

Thirdly, seasonal variation in the performance of supply units, especially relevant for heat pumps, is not considered. Aqua thermal and direct air heat pumps perform with a higher COP during summer months compared to winter months, as opposed to geothermal heat pumps. While a higher amount of heat is required during winter, the efficiency of heat pumps is lower during those months. This could be taken into account if the model will be further developed. Furthermore, the startup time of heat pumps is not taken into account. As heat pumps take half an hour to start, the response time of heat pumps is slower than e-boilers. This is not taken into account in the model.

Lastly, for the validation of the model, a comparison with the actual heat production is carried out. However, the actual values are incomplete and uncertain. The comparison is carried out by comparing the units for which the data was complete. Therefore, it is recommended to better record actual heat production per hour for each unit within the DHN of Eneco. This does not only help future validation of DHN model, but it provides a relevant insight into the behavior of production units.

5.4.2 Scenarios

For this research, several network expansion cases are set up based on existing plans and developments on the municipal scale. Furthermore, these cases are run with increased demand and increased gas, electricity, and CO2 prices. Firstly, it should be noted that 2022 was an extreme year in terms of electricity and gas prices, compared to previous years. Due to the energy crisis, the year does not have a regular seasonal pattern. This can give extreme outcomes, especially on an hourly level. Therefore, the results for the year 2018 are also included to validate the model. Looking at the electricity and gas prices of 2023, the prices have stabilized compared to 2022. However, the prices have not decreased to the level of 2020 or even 2021, which were also extreme due to the COVID-19 pandemic. This should also be taken into account for the prices and demand for 2030 as considered by the KEV are projections, which are based on the prices of 2021.

Secondly, the increase in prices of electricity, gas, and CO2 of 25% and 50% for running experiments with the model is not based on actual forecasts. These are merely used to experiment with the different cases and analyze how extreme prices have an impact on the network behavior. The same counts for the increase in heat demand of 10% and 15%. These are based on national and regional policy on district heating developments in the coming years. These percentages are used to experiment with the model and analyze network expansion. Network expansion without increasing heat demand and only increased sources and storage would not be realistic.

Thirdly, as stressed earlier, the network expansion cases are based on local policy documents on the heat transition. Additional heat sources and storage units are in many cases plans which are not yet in development. Therefore, it is hard to predict if these plans will be carried out. With current regulatory and policy proposals, the investment climate for DHN is, and become increasingly uncertain. For this reason, the network expansion cases are merely taken as a model input to explore the behavior of the production units concerning the flexibility and sustainability of the network.

5.4.3 Technical issues

Besides the uncertainty of current plans and development for expanding the DHN of South-Holland, technical issues in implementing certain heat solutions play a role. Firstly, long-term storage is not included in this model, due to modeling complications, as well as technical challenges. Long-term storage brings uncertainty due to high costs, and technical issues which are dependent on the location, as well as permits (Jongsma et al., 2023). For example, hot water storage is complicated to implement due to limited available space, especially in the urban region of South-Holland.

Secondly, certain techniques which could have high potential are not included in this research. Techniques include aqua thermal heat sources, hot- and cold-water storage, and other lower-temperature heat solutions (Jongsma et al., 2023). Besides the high investment costs of these techniques, the type of DHN plays a role. Currently, 3rd generation district heating is the most common in the Netherlands. This entails that the network is suitable for hot water until 100°C, as opposed to 4th and 5th generation district heating, which allows a maximum of 65°C and a temperature between 8°C and 25°C, respectively (Lavrijssen & Vitéz, 2021). 3rd Generation district heating allows conventional heat sources (oil, biomass, waste incineration, solar thermal, geothermal, excess heat from industry), whereas 4th generation district heating has a larger potential for renewable sources. 5th generation district heating allows hot- and cold-water storage, and all renewable heat sources are possible to connect to these networks. However, 4th and 5th generation district heating requires well-insulated, energy-efficient buildings, which demand heating and cooling needs (Lavrijssen & Vitéz, 2021). Therefore, to allow a wider range of renewable heat sources to connect to the network, the temperature of the network should be changed, or the heat should be upgraded to higher temperatures. Lastly, better insulation of homes could be considered to reduce peak heat demand and allow for lower temperature district heating to achieve efficient results (CE Delft, 2022).

5.5 Observations

In the research process, several observations are made relevant to governing a DHN in the Netherlands, outside of the scope of the model. In terms of regulatory issues, six relevant aspects are identified: (1) ownership structure and operation of DHN, (2) the price of heat for consumers, (3) metering, (4) consumer DHN connection and usage, (5) third-party access, and (6) support measures for DHN and national carbon taxes. Insights in these topics can provide clarity for all stakeholders involved in the development of DHN in the Netherlands. Certain aspects are further elaborated in this section.

5.5.1 Ownership issues

As proposed in the Dutch Collective Heat System Act, the ownership of a DHN should be at least 50% in public hands. From the perspective of energy companies, this proposal brings uncertainties. Investing in network expansion is therefore not attractive. For this reason, national subsidies aim to accelerate investments by energy companies and other stakeholders in the DHN. Whether this sufficiently minimizes investment risks for energy companies and municipalities is uncertain. Collaboration between municipalities, energy companies, and housing associations, as well as a national subsidy scheme, are crucial to guarantee a just heat transition.

5.5.2 Efficiency of DHN

While it is not considered in this research, the efficiency of the network from the side of the customers would reduce the heat demand in a DHN. An example of this is the isolation of buildings and households. While the focus of this study is on high-temperature district heating, in the case of well-isolated buildings, low- or medium-temperature district heating networks (4th or 5th generation) have potential. This would provide the possibility to connect heat sources to the network that facilitates heating at lower temperatures, as well as cooling. Isolation of homes is required in this case to minimize losses in the network.

5.5.3 Municipal expertise and third-party access

With the proposal of the Dutch Collective Heat System Act, the responsibility for the heat transition is in the hands of municipalities. On the one hand, this allows exploring locally optimal solutions that provide more sustainability and flexibility to the DHN. The possibilities for network expansion are highly dependent on local circumstances in terms of available sources. To illustrate, in the city of Den Haag, the potential for geothermal energy is higher than in the city of Rotterdam, while Rotterdam has more waste heat from the port and other industries available. Therefore, plans to expand the DHN for each projected neighborhood should be explored, developed, and realized with clear coordination. This in turn also requires increased cooperation between municipalities, energy companies, and housing associations, especially in a transition phase of increased public ownership of DHN. Therefore, specific knowledge of energy infrastructure and the costs of the district heating network is necessary to make informed decisions.

5.5.4 Financial support measures

Progress of the heat transition should be guaranteed, to realize the EU and National climate goals. Municipalities have determined targets for connecting neighborhoods to district heating before 2025, 2030, and 2040. However, with the current regulations, municipalities cannot decide which home to connect to the network, without agreement by the home-owners. Therefore, expanding the DHN depends on the willingness of the customers, where the main public value is the affordability of heating. This brings municipalities in a difficult position between the customer and other stakeholders of the DHN such as energy companies and housing associations. While the sustainability of the network is appreciated, for customers the affordability of heating is the main concern. Furthermore, the question is whether investments in additional heat sources and storage are attractive for energy companies when ownership of these assets in the following years cannot be guaranteed. In the absence of public authority to ensure an increasing heat demand by customers, additional financial support should be implemented to guarantee progress in the heat transition and to reduce short-term uncertainty in business cases.

6 Conclusion and recommendations

In this section, the conclusions of this research are provided. Secondly, recommendations in terms of policy, strategy, modeling, and recommendations for further research are provided.

6.1 Conclusions

This master thesis aims to study to what extent the integration of heat storage and additional heat sources can enhance the flexibility and long-term sustainability of the South-Holland district heating network (DHN). This is done by developing and analyzing a modular, future-proof optimization model for the Eneco DHN of South-Holland. Model experiments are done by changing the electricity, gas, and CO2 prices, as well as the demand, taking into account price and demand projections for 2030. Furthermore, the network is expanded with additional heat sources and heat storage.

Additional heat sources lead to increased flexibility and sustainability of the network, while additional heat storage primarily increases the flexibility. Looking ahead to 2030, to realize the heat transition in South-Holland, many additional sources, potentially in combination with heat storage, should be added in the following years to realize a flexible, sustainable, and affordable district heating network. Considering the projected electricity, gas, and CO2 prices for 2030, financial support should be provided to invest in heat sources, and storage in combination with heat sources, to limit the costs and CO2 emissions of the DHN in South Holland, and meet the heat demand.

A modular, future-proof optimization model for DHN can be used to study the behavior of a network with different types of assets, based on the electricity, gas, and CO2 prices and the heat demand. Experimenting with price and demand increases, as well as different network expansion cases has provided insights into the heat production, flexibility, and sustainability of a DHN. Research outcomes can be considered in policy-making and planning for the heat transition.

6.2 Recommendations and further research

6.2.1 Policy

The Collective Heat System Act states the goal to connect 500,000 Dutch homes to the DHN in 2030, and 2,6 million homes in 2050. To realize this, further research is required on the current proposal of the Collective Heat System Act, what the effects are on investments in the network, as well as how this can impact the sustainability and flexibility of DHN in the Netherlands.

6.2.2 Strategy

From the strategic point of view, besides the sustainability and flexibility of the network, the costs of the network are decreased, which will result in low and stable heat prices for customers. Therefore, developing both heat sources as well heat storage is recommended. Where low-carbon heat sources provide the necessary sustainability of the network as well as decreased costs, additional heat storage facilitates increased network flexibility.

6.2.3 Model

Regarding modeling DHN, further research can be done on combining constraints of different time frames. In this research, constraints only apply to an hourly time frame, whereas seasonal and yearly constraints are becoming increasingly relevant to model long-term storage. It is recommended to take into account different optimization periods, to see how the model behaves over a longer period. Firstly, the look-ahead period can be changed to take into account the weather predictions of several days or even weeks ahead. Secondly, to consider the long-term constraints of the network in terms of contracting assets or long-term storage, the optimization period can be changed and the impact of this can be analyzed with respect to the 36-hour optimization period. This is relevant if long-term heat storage can be added to the network.

Furthermore, future experimentation can be done with the model in the context of low- and medium-temperature DHN. The effect of a demand decrease could be analyzed if the isolation of buildings and households is considered, as well as the addition of multiple smaller heating and cooling sources. Therefore, this would allow different heat sources and storage techniques to be added to the network.

Moreover, for future research on DHN modeling, the model output can be compared to real data and validated more precisely, provided that the real data is accurate and complete. Lastly, this model can potentially be coupled with other energy system models in the DEMOSES research project, which can serve as decision-support and a tool to make the Dutch energy system future-proof. This can be done by coupling heat, electricity, and gas distribution grids, and studying how their interaction can provide increased flexibility and sustainability.

7 Reflection

When I came back from my exchange at the University of Bologna, I did not feel like I was ready to start my master's thesis. Instead, I felt the need to deepen my academic knowledge of future energy systems, especially considering intelligent electrical power grids and modeling and co-simulation of energy systems. Following several courses from the Master Sustainable Energy Technology helped me gain this additional knowledge while deepening my interest in this field. Together with the interdisciplinary knowledge provided by the courses of the master program Complex Systems Engineering and the track-specific energy courses, the master thesis with the DEMOSES research project felt like the ideal opportunity to combine these fields of knowledge. This also provided the opportunity to simultaneously do the graduation internship at the project partner Eneco.

Starting this master thesis project, modeling the district heating network of South-Holland seemed like an exciting and challenging part of the project. As a result of my broad interest in societal as well as technical aspects of energy systems, I tend to approach projects with many questions and the willingness to answer them all. During this first part of the project, I learned to scope the project by identifying the research methods, and the time frame in which I could execute this. After working out the model requirements with Eneco and identifying relevant output within a realistic scope, the actual modeling was a true challenge: I had little experience with modeling in Python. My supervisors Sugandha and Chris proved to be extremely helpful during this process. Their focus on defining the model requirements and mathematical equations helped me break the modeling process into smaller pieces, and realize a working model. Sometimes, planning certain tasks of the modeling was hard, as it can be difficult to estimate the expected time it takes to add a constraint, solve a bug, or organize the input and output of the model. Overcoming these barriers and providing reasonable model output gave me enormous fulfillment.

Scoping my thesis topic has been a challenge from the start. With a model, it is possible to add and explore many variables. Identifying what was relevant to my research questions was hard at times. The earlier I defined my scope in terms of input and output, the easier the process would have been. My supervisors at the TU Delft and Eneco have been helpful in this process with their feedback during the update meetings. In this process, I learned to ask myself what output I needed to answer my research question and divide between modeling outcomes and other observations, out of the modeling scope. What I would do differently if I were to carry out a similar project is define my research questions and methods more specifically, to guide myself during the research process.

Lastly, I would like to say that doing your own research, means you have control and responsibility for your project. On the one hand, this can sometimes feel like a weight on your shoulders. On the other hand, it gives you the freedom to do what you want on your own time. This master thesis project has positively challenged me and it has given me confidence about my research and modeling skills in interdisciplinary fields of knowledge.

References

Alavijeh, N. M., Steen, D., Norwood, Z., Tuan, L. A., & Agathokleous, C. (2020). Cost-effectiveness of carbon emission abatement strategies for a local multi-energy system - a case study of chalmers university of technology campus [Article]. *Energies*, *13*(7). Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85082739178&doi=10.3390%2fen13071626&partnerID=40&md5=cbc1697f6da848381bd50b8e1af4bb0a (Cited by: 10; All Open Access, Gold Open Access, Green Open Access) doi: 10.3390/en13071626

Aunedi, M., Pantaleo, A. M., Kuriyan, K., Strbac, G., & Shah, N. (2020). Modelling of national and local interactions between heat and electricity networks in low-carbon energy systems. *Applied Energy*, *276*, 115522.

Ayele, G. T., Mabrouk, M. T., Haurant, P., Laumert, B., & Lacarrière, B. (2019). Optimal placement and sizing of heat pumps and heat only boilers in a coupled electricity and heating networks. *Energy*, *182*, 122–134.

Billerbeck, A., Breitschopf, B., Preuß, S., Winkler, J., Ragwitz, M., & Keles, D. (2024). Perception of district heating in europe: A deep dive into influencing factors and the role of regulation [Article]. *Energy Policy*, *184*. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85174638540&doi=10.1016%2fj.enpol.2023.113860&partnerID=40&md5=073980c71c3de1d7d36ddb6af33effb5 (Cited by: 0; All Open Access, Hybrid Gold Open Access) doi: 10.1016/j.enpol.2023.113860

Billerbeck, A., Breitschopf, B., Winkler, J., Bürger, V., Köhler, B., Bacquet, A., ... Ragwitz, M. (2023). Policy frameworks for district heating: A comprehensive overview and analysis of regulations and support measures across europe. *Energy Policy*, *173*, 113377. Retrieved from https://www.sciencedirect.com/science/article/pii/S0301421522005961 doi: https://doi.org/10.1016/j.enpol.2022.113377

Boldrini, A., Jiménez Navarro, J., Crijns-Graus, W., & van den Broek, M. (2022). The role of district heating systems to provide balancing services in the european union. *Renewable and Sustainable Energy Reviews*, *154*, 111853. Retrieved from https://www.sciencedirect.com/science/article/pii/S1364032121011205 doi: https://doi.org/10.1016/j.rser.2021.111853

Bynum, M. L., Hackebeil, G. A., Hart, W. E., Laird, C. D., Nicholson, B. L., Siirola, J. D., ... others (2021a). *Pyomo-optimization modeling in python* (Vol. 67). Springer.

Bynum, M. L., Hackebeil, G. A., Hart, W. E., Laird, C. D., Nicholson, B. L., Siirola, J. D., ... Woodruff, D. L. (2021b). *Pyomo–optimization modeling in python* (Third ed., Vol. 67). Springer Science & Business Media.

Capone, M., Guelpa, E., & Verda, V. (2021). Multi-objective optimization of district energy systems with demand response. *Energy*, *227*, 120472.

Castelli, A. F., Moretti, L., Manzolini, G., & Martelli, E. (2020). A robust rolling-horizon algorithm for the optimal operation of multi-energy systems with yearly constraints and seasonal storage. In S. Pierucci, F. Manenti, G. L. Bozzano, & D. Manca (Eds.), *30th european symposium on computer aided process engineering* (Vol. 48, p. 1513-1518). Elsevier. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128233771502536 doi: https://doi.org/10.1016/B978-0-12-823377-1.50253-6

CE Delft. (2019). Hybride warmtenetten: kansen voor den haag. *CE Delft*.

CE Delft. (2022). The natural gas phase-out in the netherlands. *CE Delft*.

Chang, M., Lund, H., Thellufsen, J. Z., & Østergaard, P. A. (2023). Perspectives on purpose-driven coupling of energy system models. *Energy*, *265*, 126335.

Eneco. (2022). Eneco: kabinet vertraagt warmtetransitie. *Eneco*.

Eneco. (2022). Overzicht warmtenetten 2022. *Eneco*.

Eneco. (2023). Opweg naar klimaatneutral in 2035. *One Planet Plan*.

Epstein, J. M. (2008). Why Model? *Journal of Artificial Societies and Social Simulation*, *11*(4), 1-12. Retrieved from https://ideas.repec.org/a/jas/jasssj/2008-57-1.html

European Parliament. (2021). Directive (eu) 2018/2002 of the european parliament and of the council of 11 december 2018 amending directive 2012/27/eu on energy efficiency (text with eea relevance.). *Official Journal of the European Union*.

European Union. (2023). Directive (eu) 2023/2413 of the european parliament and of the council. *Official Journal of the European Union*.

Gemeente Den Haag. (2021). Transitievisie warmte den haag. *Gemeente Den Haag*.

Gemeente Den Haag. (2023). Warmteplannen bij de energiecentrale. *Gemeente Den Haag*.

Gemeente Lansingerland. (2019). Transitievisie warmte lansingerland gebouwde omgeving. *Gemeente Lansingerland*.

Gemeente Rotterdam. (2021a). Rotterdam aardgasvrij: de rotterdamse transitievisie warmte. *Gemeente Rotterdam*.

Gemeente Rotterdam. (2021b). Wat-kaart 2021. *Gemeente Rotterdam*.

Haagse Aardwarmte. (2023). Leyweg: het project. *Haagse Aardwarmte*.

Hagberg, A. A., Schult, D. A., & Swart, P. J. (2008). Exploring network structure, dynamics, and function using networkx. In G. Varoquaux, T. Vaught, & J. Millman (Eds.), *Proceedings of the 7th python in science conference* (p. 11 - 15). Pasadena, CA USA.

Hart, W. E., Watson, J.-P., & Woodruff, D. L. (2011). Pyomo: modeling and solving mathematical programs in python. *Mathematical Programming Computation*, *3*(3), 219–260.

Henrich, B. A., Hoppe, T., Diran, D., & Lukszo, Z. (2021). The use of energy models in local heating transition decision making: insights from ten municipalities in the netherlands. *Energies*, *14*(2), 423.

Herreras Martinez, S., Harmsen, R., Menkveld, M., Kramer, G. J., Faaij, A., et al. (2023). Why go public? public configurations and the supportive and divergent views towards public district heating in the netherlands. *Frontiers in Sustainable Cities*, *5*.

IPCC. (2022). *Climate change 2022: Mitigation of climate change. contribution of working group iii to the sixth assessment report of the intergovernmental panel on climate change* (P. Shukla et al., Eds.) [Book]. Cambridge, UK and New York, NY, USA: Cambridge University Press. Retrieved from `https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf` doi: 10.1017/9781009157926

IRENA. (2018). Power system flexibility for the energy transition, part 1: Overview for policy makers. *International Renewable Energy Agency, Abu Dhabi*.

Javanshir, N., Syri, S., Tervo, S., & Rosin, A. (2023a). Operation of district heat network in electricity and balancing markets with the power-to-heat sector coupling. *Energy*, *266*, 126423. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0360544222033096` doi: https://doi.org/10.1016/j.energy.2022.126423

Javanshir, N., Syri, S., Tervo, S., & Rosin, A. (2023b). Operation of district heat network in electricity and balancing markets with the power-to-heat sector coupling. *Energy*, *266*, 126423. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0360544222033096` doi: https://doi.org/10.1016/j.energy.2022.126423

Jongsma, C., Dehens, J., Nauta, M., & Scholten, T. (2023). Power-to-heat en warmteopslag in warmtenetten. *CE Delft*.

KNMI. (2023). Jaar 2022. *Ministerie van Infrastructuur en Waterstaat*. Retrieved from `www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/2022/jaar#:~:text=2022%20was%20met%20een%20gemiddelde,19%20juli%20in%20Beek%20gemeten.`

Kühnbach, M., Guthoff, F., Bekk, A., & Eltrop, L. (2020). Development of scenarios for a multi-model system analysis based on the example of a cellular energy system. *Energies*, *13*(4), 773.

Lavrijssen, S., & Vitéz, B. (2021). Good governance and the regulation of the district heating market. In *Shaping an inclusive energy transition* (pp. 185–227). Springer International Publishing Cham.

Lente Akkoord. (2019). Warmtenetten in beng. *Lente Akkoord*.

Liu, H., Liu, X., Cai, C., & Jin, Q. (2023). A new power flow model for combined heat and electricity analysis in an integrated energy system. *Applied Thermal Engineering*, *219*, 119597.

Miltenberger, M. (2023). What is the mipgap? *Gurobi optimization*.

Ministerie van economische zaken. (2023a). Voortgang voorstel wet collectieve warmte. *Rijksoverheid*.

Ministerie van economische zaken. (2023b). Wetsvoorstel collectieve warmte voor betaalbare en duurzame warmtelevering aan burgers en bedrijven. *Rijksoverheid*.

Ministerie van Verkeer en Waterstaat. (2008). De waterwet in het kort. *Rijksoverheid*.

Ministerie voor economische zaken en klimaat. (2023). Nationaal plan energiesysteem. *Rijksoverheid*.

Moallemi, E. A., & Malekpour, S. (2018). A participatory exploratory modelling approach for long-term planning in energy transitions. *Energy Research & Social Science*, *35*, 205-216. (Energy and the Future) doi: https://doi.org/10.1016/j.erss.2017.10.022

Mugnini, A., Comodi, G., Salvi, D., & Arteconi, A. (2021). Energy flexible chp-dhn systems: Unlocking the flexibility in a real plant. *Energy Conversion and Management: X*, *12*, 100110. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2590174521000350` doi: https://doi.org/10.1016/j.ecmx.2021.100110

Nami, H., Anvari-Moghaddam, A., & Arabkoohsar, A. (2020). Application of cchps in a centralized domestic heating, cooling and power network—thermodynamic and economic implications [Article]. *Sustainable Cities and Society*, *60*. Retrieved from `https://www.scopus.com/inward/record.uri?eid=2-s2.0-85084845766&doi=10.1016%2fj.scs.2020.102151&partnerID=40&md5=f4857c576d0398e8bbf11586e635ff5b` (Cited by: 32; All Open Access, Green Open Access) doi: 10.1016/j.scs.2020.102151

NEA. (2023). Co2 heffing algemeen. *Nederlandse Emissie Autoriteit*.

Netbeheer Nederland. (2022). Netimpact van warmtealternatieven. *Netbeheer Nederland*.

Nikas, A., Gambhir, A., Trutnevyte, E., Koasidis, K., Lund, H., Thellufsen, J., ... Doukas, H. (2021). Perspective of comprehensive and comprehensible multi-model energy and climate science in europe. *Energy*, *215*, 119153. Retrieved from `https://www.sciencedirect.com/science/article/pii/S036054422032260X` doi: https://doi.org/10.1016/j.energy.2020.119153

Noori, S., Korevaar, G., Stikkelman, R., & Ramírez, A. (2023). Exploring the emergence of waste recovery and exchange in industrial clusters. *Journal of Industrial Ecology*, *27*(3), 937-950. doi: https://doi.org/10.1111/jiec.13381

NPLM. (2023). Lokale warmtetransitie in beeld 2023: Kwalitatief beeld van de lokale warmtetransitie, op basis van gesprekken met ruim 300 gemeenten. *NPLW*.

NRC. (2023). Eerst utrecht, nu den haag: wéér is de aanleg van een warmtenet stopgezet. *NRC*.

Oorschot, L. (2020). Dutch hybrid neighbourhoods of 1860–1910 in heat transition: The case study of zeeheldenkwartier in the hague. *Energies*, *13*(20), 5255.

Paardekooper, S., Lund, H., Thellufsen, J. Z., Bertelsen, N., & Mathiesen, B. V. (2022). Heat roadmap europe: strategic heating transition typology as a basis for policy recommendations. *Energy Efficiency*, *15*(5), 32.

PBL. (2022). Eindadvies basisbedragen sde++ 2022. *Den Haag: Planbureau voor de Leefomgeving*.

PBL. (2023). Reflectie op voorstellen voor de inzet van middelen uit het klimaatfonds. *PBL*.

PBL, TNO, CBS & RIVM. (2022). Klimaat- en energieverkenning (kev) 2022. ramingen van broeikasgase- missies, energiebesparing en hernieuwbare energie op hoofdlijnen. *Den Haag: Planbureau voor de Leefomgeving*.

PBL, TNO, CBS & RIVM. (2023). Klimaat- en energieverkenning (kev) 2023. ramingen van broeikasgase- missies, energiebesparing en hernieuwbare energie op hoofdlijnen. *Den Haag: Planbureau voor de Leefomgeving*.

PwC. (2022). Eindrapport: Effecten van publiek eigendomsverplichting op de realisatiekracht voor collectieve warmtesystemen. *PwC*.

Regio Rotterdam Den Haag. (2021). Res 1.0 - regionale energiestrategie rotterdam den haag. *Regionale Energiestrategie Rotterdam Den Haag*.

Regio Rotterdam Den Haag. (2023). Voortgangsrapportage. *Regionale Energiestrategie Rotterdam Den Haag*.

Regio Rotterdam Den Haag, & CE Delft. (2023). Transitievisies warmte in de regio rotterdam den haag: Analyse van de 23 tvw's in de res regio. *Regionale Energiestrategie Rotterdam Den Haag*.

Rijksoverheid. (2019). Klimaatakkoord. *Rijksoverheid, Den Haag*, rijksoverheid.nl.

Rijksoverheid. (2023). Deelnemende gemeenten aardgasvrije wijken. *Rijksoverheid*.

RVO. (2022). Duurzaamheidsrapportage 2022. *RVO*. Retrieved from `www.rvo.nl/sites/default/files/202310/Duurzaamheidsrapportage%202022-V2.pdf`

RVO. (2023a). Energie-efficiëntie glastuinbouw (eg). *Rijksoverheid*.

RVO. (2023b). Routekaart energieopslag. *Ministerie van Economische Zaken en Klimaat*.

RVO. (2023c). Stimulering duurzame energieproductie en klimaattransitie (sde++). *Klimaat en Energie*.

Schmidt, R.-R., & Leitner, B. (2021). A collection of swot factors (strength, weaknesses, opportunities and threats) for hybrid energy networks. *Energy Reports*, *7*, 55-61. Retrieved from `https://www.sciencedirect.com/science/article/pii/S2352484721008465` (The 17th International Symposium on District Heating and Cooling) doi: https://doi.org/10.1016/j.egyr.2021.09.040

Segers, R., Niessink, R., van den Oever, R., & Menkveld, M. (2020). Warmtemonitor 2019. *TNO and PBL*.

TenneT. (2021a). Balanceringsverantwoordelijkheid. *TenneT*. Retrieved from `https://www.tennet.eu/nl/de-elektriciteitsmarkt/nederlandse-klanten/balanceringsverantwoordelijkheid`

TenneT. (2021b). Het energiesysteem van de toekomst - integrale infrastructuurverkenning 2030 - 2050. *Netbeheer Nederland*.

TU Delft. (2021). Demoses. *TU Delft*. Retrieved from `https://www.tudelft.nl/ewi/over-de-faculteit/afdelingen/electrical-sustainable-energy/intelligent-electrical-power-grids-iepg-group/projects/current-projects/demoses`

Van Dam, K. H., Nikolic, I., & Lukszo, Z. (2012). *Agent-based modelling of socio-technical systems* (Vol. 9). Springer Science & Business Media.

Warmtelinq. (2023). Traject vlaardingen - den haag. *Project Atlas*.

Warmtenetwerk. (2021). Warmtesysteem noord rotterdam. *Warmtenetwerk voor de energietransitie*.

Yu, S., Mandel, T., Thomas, S., & Brugger, H. (2022). Applying the energy efficiency first principle based on a decision-tree framework. *Energy Efficiency*, *15*(6), 42.

Appendices

A Model configuration

A.1 shows the connections of the DHN of South-Holland of the python model. A.2 show the connection for the additional sources and additional storage to the network for the test cases. It is assumed that no losses occur and no costs are present.

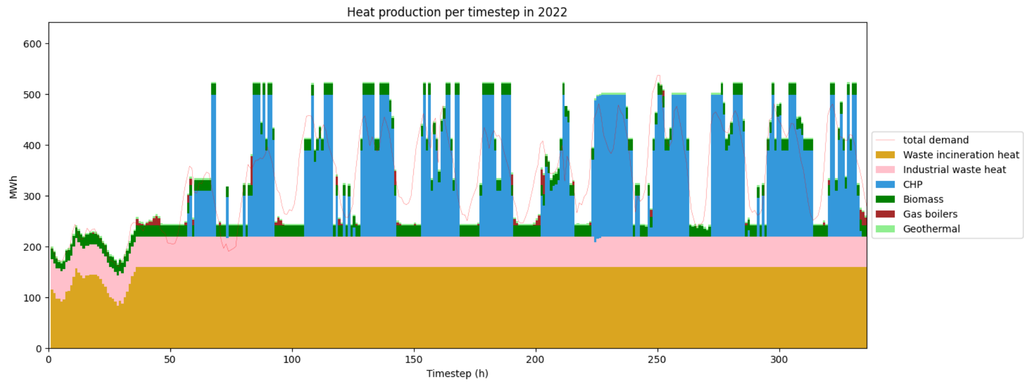
Table A.1: Connections for the network for new model (confidential)

From	To	heat loss (MWh)	Maximum flow (MWh)	Cost (€/MWh)

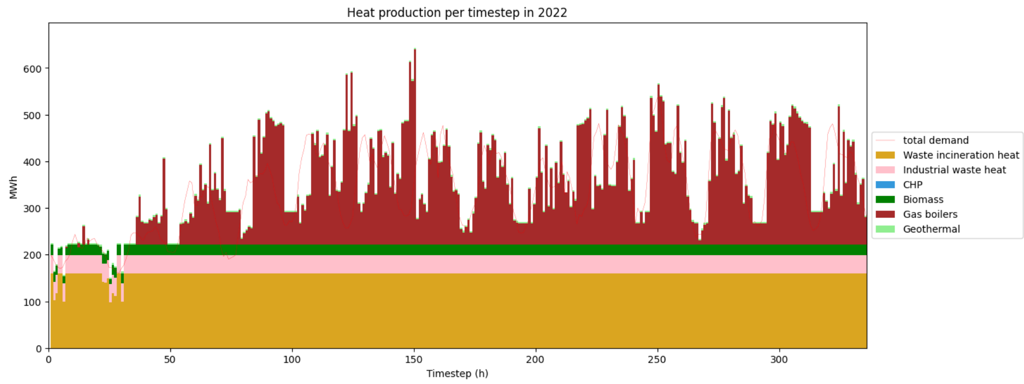
Table A.2: Connections for the network for additional sources and storage.

From	To	heat loss (MWh)	Maximum flow (MWh)	Cost (€/MWh)
Additional sources				
Heatpump DH	Den Haag			
E-boiler	Den Haag			
Geothermal DH1	Den Haag			
Geothermal DH2	Den Haag			
Geothermal DH3	Den Haag			
Heatpump RDAM	Rotterdam 1			
Geothermal RDAM	Rotterdam 1			
Geothermal B-triangle	B-triangle			
Additional storage				
Storage DH	Den Haag			
Den Haag	Storage DH			
Storage RDAM	Rotterdam 1			
Rotterdam 1	Storage RDAM			
Storage B-triangle	B-triangle			
B-triangle	Storage B-triangle			

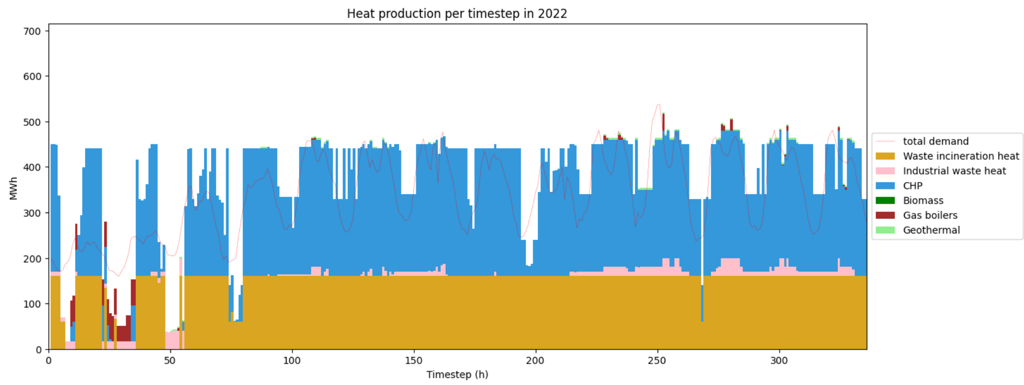
B Model verification



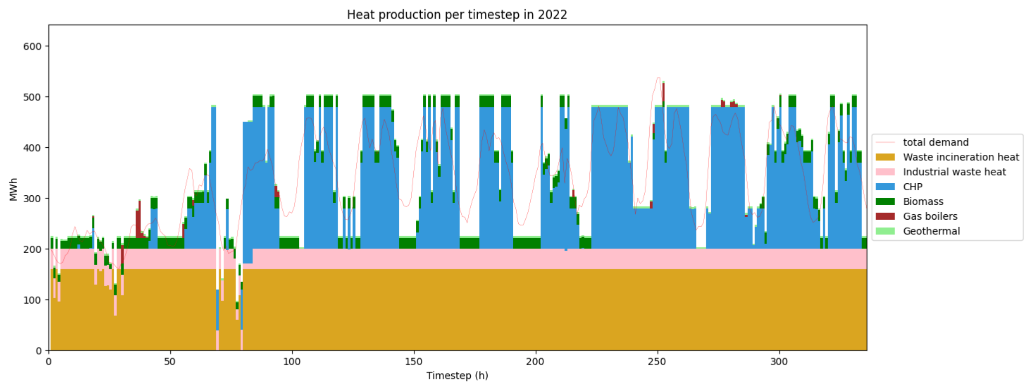
(a) Base Case



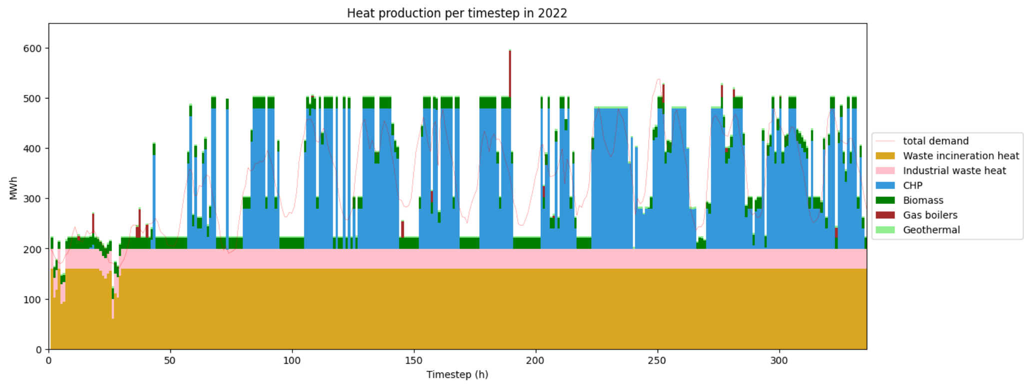
(b) No electricity costs



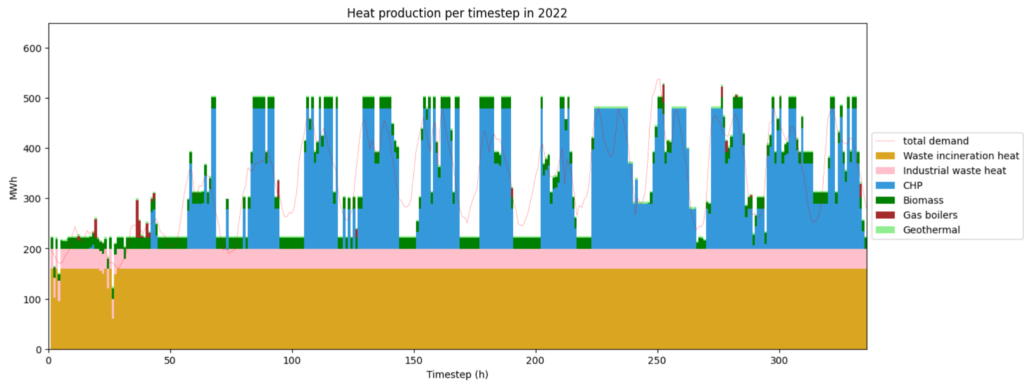
(c) No gas costs



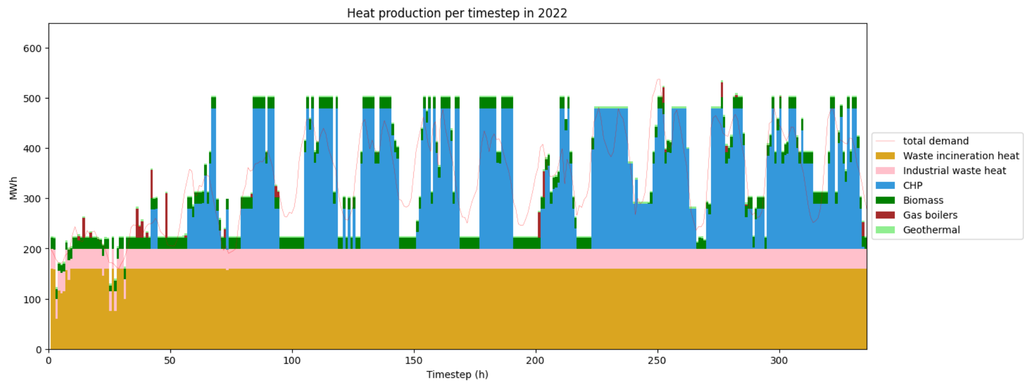
(d) No CO2 costs



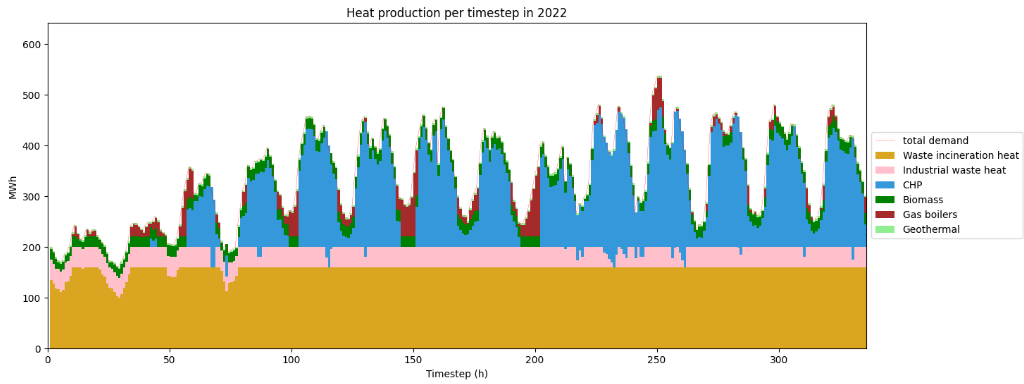
(e) No startup costs



(f) No variable costs



(g) No edge costs



(h) No buffers

Figure B.1: Model verification: total production per time step from January 1st to January 14th, 2022.

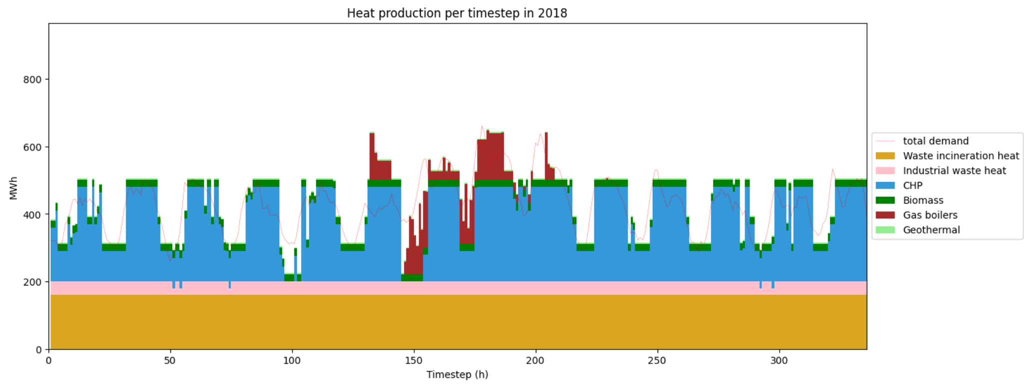


Figure B.2: Model verification: total production per time step from January 1st to January 14th, 2018.

Table B.1: Model verification: total production (MWh) per supply unit for different verification scenarios in 2022.

Production unit	Base case	No CO2 costs	No edge costs	No electricity price	No gas costs	No startup costs	No variable costs	No buffers
Waste incineration heat	905,835	876,692	999,689	925,503	689,165	894,161	901,043	933,611
Industrial waste heat	315,941	293,688	208,577	324,897	95,155	312,683	313,589	275,261
Gas boilers	18,933	11,317	18,559	342,701	161,618	17,489	17,229	40,955
CHP	376,733	511,235	375,767	-	1,070,673	405,255	385,482	291,017
Biomass	108,244	90,798	112,874	117,959	1,564	103,084	108,147	97,799
Geothermal	27,590	22,880	16,803	29,190	1,673	27,287	27,073	26,910
Total	1,753,277	1,806,609	1,732,269	1,740,250	2,019,849	1,759,959	1,752,563	1,665,553

C Model validation

Table C.1: Model validation: Total production per supply unit for Python model without WLQ connection and the actual production in 2022.

Production unit	Actual production (MWh)	Python model production (MWh)	Difference percentage of total (%)	Comment
Waste incineration heat	787,512	966,379	10.8%	
Industrial waste heat	201,265	69,230	-8.0%	Uncertainty about data
Gas boilers	60,769	5,313	-3.4%	Data of some gas boilers is missing
CHP and DH Gas 1	543,362	509,540	-2.1%	
Biomass	38,864	94,077	3.3%	Uncertainty about data
Geothermal	17,846	27,914	0.6%	Uncertainty about data
total	1,649,618	1,672,453	1.4%	

Table C.2: Model validation: Total production per supply unit for Python and Linny-R models without the WLQ connection between Den Haag and Rotterdam in 2022.

Production unit	Linny-R model production (MWh)	Python model production (MWh)	Difference percentage of total (%)	Linny-R model production without WLQ (MWh)	Python model production without WLQ (MWh)	Difference percentage of total without WLQ (%)
Waste incineration heat	868,634	905,359	2.2%	822,201	808,695	-0.8%
Industrial waste heat	340,503	314,205	-1.6%	264,695	238,613	-1.6%
Gas boilers	34,161	18,851	-0.9%	53,609	48,538	-0.3%
CHP	289,374	376,521	5.3%	393,245	453,012	3.7%
Biomass	103,848	108,851	0.3%	73,869	123,587	3.1%
Geothermal	20,640	27,647	0.4%	20,640	27,914	0.4%
Total	1,657,160	1,751,433	5.7%	1,628,260	1,700,359	4.4%

D Model results

Table D.1: Comparison of total costs (EUR) in 2022.

Demand/price scenario	Base case	Case 1	Case 2	Case 3
Base	16,715,656	8,231,776	16,116,115	7,522,866
25% price increase	26,653,509	8,683,458	18,422,770	7,702,706
50% price increase	30,512,490	8,981,040	20,697,483	7,811,148
10% demand increase	30,013,193	18,266,976	29,568,779	17,522,947
15% demand increase	37,971,468	24,184,706	37,609,943	23,575,728

Table D.2: Comparison of CO2 emissions (ton) in 2022

Demand/price scenario	Base case	Case 1	Case 2	Case 3
Base	159042	125643	165642	132315
25% price increase	182053	129276	1681189	135091
50% price increase	183902	131672	169916	137944
10% demand increase	199022	157227	204888	162868
15% demand increase	219422	173111	225589	178619