Decarbonizing the Dutch Energy System: The Impact of Renewable District Heating on the Electricity and Heating Sector

A.S. De Bruin

DECARBONIZING THE DUTCH ENERGY SYSTEM: THE IMPACT OF RENEWABLE DISTRICT HEATING ON THE ELECTRICITY AND HEATING SECTOR

A thesis submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of

Master of Science Complex System Engineering and Management

by

Simone de Bruin, 4491165

To be defended in public on March 29th 2022

Simone de Bruin: *Decarbonizing the Dutch Energy System: The Impact of Renewable District Heating on the Electricity and Heating Sector* (2022)

The work in this thesis was made at the:

Faculty of Technology, Policy & Management
Delft University of Technology

TU Delft Supervisors:	Dr. A. F. Correljé, Section Economics of Technology and Innovation
	Dr. S. Pfenninger, Section Energy and Industry
	Dr. L. M. Kamp, Section Energy and Industry
External Supervisor:	Dr. Ir. J. G. Rödel, Vattenfall

EXECUTIVE SUMMARY

Introduction
Urgent and significant changes in all parts of the current Dutch energy system are required to achieve the national climate goals. This thesis explores the impact from traditional to renewable district heating (DH) on the Dutch electricity and heating sector, at both a national and regional level. The results provide relevant lessons for policy-makers and project developers regarding the realization of DH projects and the electricity and heat transition overall. The main research question is answered: *What is the impact of the transition from traditional to renewable district heating on the Dutch electricity and heating sector?*

Research Approach
Both qualitative and quantitative methods are applied within this exploratory research. On the national level, future trends within the electricity and heating sector are analyzed using scenario analysis and energy flow analysis (EFA). On the regional level, regional energy plans are analyzed in order to determine how the trends are substantiated within the region North-Holland South. This case study includes a stakeholder analysis, interviews with involved actors and an EFA.

Main Findings
There is uncertainty regarding the realization of the national heat and DH transition. The national transition to renewable DH does not always seem to make sense alongside the strong expectations of a fully renewable electricity supply. Nonetheless, within the region North-Holland South, renewable DH is expected to be one the main heating alternatives. The transition to renewable DH is expected to have the following impact:

- Electricity sector: I) the use of renewable high-temperature DH sources limits electricity demand, II) the use of renewable low-temperature sources in combination with a collective heat pump or E-boiler increases electricity demand, but can provide flexibility to the electricity grid through thermal storage.
- Heating sector: I) individual natural gas-fired boilers are substituted, II) current DH sources are substituted by uncertain renewable DH sources.

The desirability of the shift to renewable DH depends on the regional context. Important factors are energy source availability and the decision-making by municipalities. In the region North-Holland South, uncertainty regarding the source availability of the planned renewable heating alternatives results in risks. The implementation of renewable DH can contribute to spreading these risks, and can provide some relief for the electricity sector, as a significant electrification is expected. However, spreading the risks does naturally not remove these risks. Municipalities in the region North-Holland South lack experience regarding the local heat transition. This can lead to ineffective decision-making, resulting in misaligned local initiatives, policy delays and malfunctioning infrastructural and heat source lock-ins.

Recommendations
To steer the heat transition, concrete choices regarding renewable heating sources and synergies between electricity and heat must be made and effective legal and regulatory frameworks are urgently required. Therefore, municipalities are strongly advised to collect new knowledge, expertise and competences and assertively collaborate with provinces, energy producers and grid operators. It is particularly important to be aware of the risks and stimulate the development of renewable heat

sources and thermal storage. Implementing these recommendations within the region North-Holland South and possibly within other energy regions contributes to the realization of the national heat transition and therefore a future low carbon Dutch energy system.

ACKNOWLEDGEMENTS

This thesis marks the end of my Master's degree Complex System Engineering and Management at Delft University of Technology. Moreover, it represents the end of my time as a student in Delft. In this section, I would like to express my gratitude to everyone who has supported me throughout my thesis process!

First of all, I would like to thank my TU Delft supervisors, Stefan Pfenninger, Linda Kamp and Aad Correljé. Stefan and Linda, you both have been very involved and provided very helpful feedback throughout the entire thesis process. Your feedback was very hands-on and on point and you were always available to support me. Aad, as my third supervisor, you really helped me to upgrade my thesis, both on an academic and societal level. Thank you!

Secondly, I would like to show my gratitude to my Vattenfall supervisor Hans Rödel. I always looked forward to our weekly meetings as they were not only educational but also fun! Your extensive knowledge, enthusiasm and critical attitude regarding the Dutch energy transition were driving factors for me. I also want to thank the rest of the Vattenfall Asset Management team and all interviewees for their contributions to the thesis. Your insights made the case study very captivating.

Finally, I would like to thank my parents and friends. My parents were always happy to help and opened their doors for me when I needed a quiet and cozy study place. Most of my friends were also graduating and therefore able to perfectly understand me and cheer me up when times were hard. A special thanks to Britt, Juliette, Robin, Kato and Danaï for your support.

I am looking back with a lot of enjoyment and I am looking forward to my next adventure!

Enjoy and all the best,

Simone de Bruin
March 14th, 2022

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CO_2	Carbon dioxide
RE	Renewable energy
DH	District heating
CHP	Combined heat and power
4GDH	Fourth generation of district heating
IES	Integrated energy system
EFA	Energy flow analysis
PV	Photovoltaic
CSP	Concentrating solar power
PtH	Power-to-heat
COP	Coefficient of performance
Qhp	Heat output
Wcomp	Electrical energy input
SPF	Seasonal performance factor
E-boiler	Electric boiler
WtE	Waste-to-energy
SCW	Super-critical water gasification
ASHP	Air source heat pump
GSHP	Ground source heat pump
WSHP	Water source heat pump
TES	Thermal energy storage
AEB	Afval Energie Bedrijf
SVP	Stadsverwarming Purmerend
RES	Regional Energy Strategy
TVH	Transition Vision for Heat
RSH	Regional Structure of Heat
SPSE	Service Point for Sustainable Energy
CoSEM	Complex Systems Engineering and Management

1 INTRODUCTION

1.1 RESEARCH PROBLEM

In the Paris Climate Agreement, 196 parties including the Netherlands, consented to limit global warming to 2 degrees Celsius while pursuing means to limit the global temperature increase even further to 1.5 degrees [UNFCCC, 2015]. Therefore, The Dutch Climate Mitigation Act obliges to reduce carbon dioxide (CO2) emissions in the Netherlands with 49% by 2030 and with 95% to 100% by 2050, compared to 1990, by implementing the National Climate Agreement [Rijksoverheid, 2019]. The Climate and Energy Outlook provides an overview of the potential future Dutch energy system, while considering national policy [PBL, 2020b]. Currently, the estimated reduction in CO2 emissions in 2030 is 34% compared to 1990, indicating 15% emission reduction below the target. Therefore, the rate of CO2 emission reduction must double in the next ten years in order to achieve the national climate goals, causing the road to a low carbon energy system to be long and bumpy [PBL, 2020b].

1.1.1 Decarbonizing Energy Sectors

Urgent and significant changes in all parts of the current Dutch energy system are required in order to reach national climate goals. Energy efficiency improvements and the substitution of fossil fuels with renewable energy (RE) sources are tools for reducing CO2 emissions within energy sectors, such as electricity and heating [Aunedi et al., 2020; Papadis and Tsatsaronis, 2020]. Currently, the Netherlands is highly dependent on fossil fuels as natural gas is the primary energy carrier in these sectors [PBL, 2020b]. Reducing the use of natural gas can be beneficial for the government, energy companies and consumers. Less than ten years ago, the Netherlands was an important and stable natural gas exporter [PBL, 2020b]. However, due to the closure of the Groningen gas field, the Netherlands is completely dependent on daily market prices for imports, which are currently reaching unprecedented heights [NOS, 2022]. There are thus societal benefits for reducing the dependency on fossil fuels and specifically natural gas in the Dutch energy system.

More than half of the final energy consumption in the Netherlands was used for heating purposes in 2019, while approximately one fifth of the final energy consumption in the Netherlands was used for electricity [PBL, 2020b]. In the relatively large heating sector, efforts are made regarding energy efficiency improvements in order to reduce the national heat demand. However, regarding the share of RE sources, the heating sector is lagging behind compared to the electricity sector. The Climate and Energy Outlook expects an increase in the share of renewable electricity production from 18% in 2019 to 75% in 2030, while the share of renewable heat is expected to merely increase from 7% in 2019 to 13% in 2030. Hence, the estimated growth rate for renewable heat is much lower than the target indicated in the 'Renewable Energy Directive' [PBL, 2020b]. Heat demand is dominant in three main sectors: the built environment, industry and the agricultural sector [Jimenez-Navarro et al., 2020]. As the built environment accounts for the highest share of final energy consumption in the Netherlands with 46%, it has a relatively large potential for reducing CO2 emissions [PBL, 2020b].

1.1.2 District Heating Systems

In order to decarbonize the heating sector, the implementation of district heating (DH) systems in the built environment could play an important role [Liu et al., 2016; Lund et al., 2018a; Jimenez-Navarro et al., 2020]. DH systems distribute heat from heat production plants to consumers through pipe networks [Jimenez-Navarro et al., 2020]. Therefore, DH systems are dependent on the heat supply source with which they are connected. DH systems are perceived to help reduce emissions, meet rising urban energy needs, provide cost-effective temperature control and improve efficiency and flexibility, once RE sources are used as a source for heat supply [IRENA, 2017].

However, the transition from a traditional to a renewable DH system is not a straight forward process. Current fossil DH sources, such as natural gas, need to be substituted with renewable DH sources, such as geothermal, ambient heat and industrial waste heat [Liu et al., 2016; PBL, 2020b]. Some of these current and future DH sources use energy technologies that function as coupling elements between the electricity and heating sector, such as combined heat and power (CHP) plants and heat pumps [Liu et al., 2016; Mitridati and Pinson, 2016]. Through coupling elements, changes implemented in the heating sector affect the electricity sector and vice versa. Therefore, the substitution of current fossil-based DH sources with renewable DH sources within the heating sector causes uncertainties to arise in the changing dynamics of both the electricity and heating sector [Ziemele et al., 2016; Liu et al., 2021]. The specific impact of the shift away from fossil DH within an integrated energy system is thus important to explore in advance. Lake et al. [2017] state that "making informed decisions about the planning, construction and operation of DH systems are key to insuring sustainability of these systems for future generations". It is thus critical for future energy system designs to improve the understanding of the complexities arising from the shift to renewable DH. This could provide relevant lessons for policy-makers and project developers regarding the realization of DH projects and the electricity and heat transition overall.

1.2 RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

This thesis aims to explore the impact of the transition from traditional to renewable DH on the Dutch electricity and heating sector on both a national and regional level by analyzing future national energy scenarios and regional energy plans. This thesis is exploratory and aims at description and understanding of the transition within a larger context. Therefore, this paper aims to answer the following research question:

What is the impact of the transition from traditional to renewable district heating on the Dutch electricity and heating sector?

In order to answer the main research question, the following sub-questions are answered:

SQ1: *What are possible interconnections between energy sources, technologies and uses of the Dutch electricity and heating sector?*

SQ2: *How are the Dutch electricity and heating sector expected to transition according to the trends of existing national energy scenarios for 2050?*

SQ3: *What is the expected impact of the transition to renewable district heating on the Dutch electricity and heating sector according to the trends of existing national energy scenarios for 2050?*

SQ4: *How are the electricity and heating sector expected to transition according to the regional energy plans in a specific Dutch region?*

SQ5: *What is the impact of the transition to renewable district heating on the electricity and heating sector according to the regional energy plans in a specific Dutch region?*

SQ6: *How do the transitions of the national and regional electricity and heating sector compare?*

The main research question aims to explore the impact of the transition from current to future renewable DH on the Dutch electricity and heating sector for the built environment. In the first sub-question possible interconnections between energy sources, technologies and uses of the Dutch electricity and heating sector are determined. This way, a clear overview is provided of how different energy components are related within and between the electricity and heating sector. In the second sub-question, the transition of the current national energy system into the future national energy system is explored by the analysis of various scenarios regarding the future Dutch energy system for 2050. The focus is on exploring and comparing the national transition pathways available to the Dutch electricity and heating sector. By comparing the future energy systems among each other and with the current national energy system, scenario trends can be identified. In the third sub-question, current and future national interconnections between the electricity and heating sector are determined. Subsequently, the impact of the transition from current to future renewable DH on the electricity and heating sector is indicated according to these trends on a national scale. In the fourth sub-question, the transition of the current regional energy system into the future national energy system is explored. By considering a regional scale and regional energy plans, more concrete observations can be done. In the fifth sub-question, current and future regional interconnections between the electricity and heating sector are determined. Subsequently, the impact of the transition from current to future renewable DH on the electricity and heating sector is indicated according to these trends on a regional scale. In the last sub-question, the regional and national energy system analysis are compared in order to determine how the regional future energy system fits within the national future energy scenarios.

1.3 ROLE OF VATTENFALL

Independence from third party interests is critical for conducting an objective research that complies with academic standards. However, this thesis is carried out at the company Vattenfall. Although Vattenfall's contacts, resources and expertise on energy systems are used for this thesis, the research is independent from the individual interests of Vattenfall. The research design and outcomes are not influenced in favor of the company. Vattenfall is an energy utility company with a clear goal: to enable fossil-free living within one generation. Vattenfall currently has approximately 2 million connections in the Netherlands. Their core activities include the production, trading and supply of electricity, natural gas and district heating [Vattenfall, 2021b]. The transition from current to future renewable DH has a high societal relevance considering the ongoing energy transition. Like many other actors in the heating industry, Vattenfall is interested in future trends in the Dutch heating sector and the development of DH systems and sources in the Netherlands in the coming years.

1.4 REPORT OUTLINE

The remainder of this report will have the following outline. In Chapter 2 the theoretical basis of this thesis is provided. In Chapter 3 the research approach and methodology will be discussed. Subsequently, Chapter 4, Chapter 5, Chapter 6 and Chapter 7 will present the findings from applying the research methodology. Lastly, Chapter 8 discusses the main findings, the implications of the findings and the limitations of this thesis.

2 THEORETICAL FRAMEWORK

In this chapter, a theoretical framework is constructed that enables the exploration of the transition from traditional to renewable DH within an integrated energy system. This theoretical framework determines how this thesis is embedded within existing literature and defines key concepts and theories, providing the scientific basis of this thesis. The framework provides a definition and conceptualization of the energy system design and transition pathways theories.

2.1 DISTRICT HEATING WITHIN EXISTING LITERATURE

The DH technology has been integrated into many energy systems, especially in Europe. In literature, DH systems are often associated with a specific generation [Mazhar et al., 2018]. Since 1880, three generations of DH systems have passed. Table 2.1 is adapted from Lake et al. [2017] and shows the three generations of DH and their common DH source, technology and peak period.

	1st Generation	2nd Generation	3rd Generation
Peak Period	1880-1930	1930-1980	1980-2020
DH Technology	Collective boilers	Collective boilers, CHP	CHP
DH Source	Coal	Coal, oil	Biomass, waste, fossils

Table 2.1: Generations of DH, adapted from Lake et al. [2017]

Over the last four decades, the literature regarding DH has evolved considerably. During the 1980s, most research focused on the basic characteristics of DH networks and the integration of co-generation systems and CHP plants [Marchand et al., 1983; Potts and Draaijer, 1985; Rudig, 1986]. From 1990 up until the early 21st century, research mostly focuses on the optimization of DH systems to enhance associated energy efficiencies. Efficiently balancing demand and supply, supply temperatures and optimizing transmission networks were focused upon. Moreover, many techno-economical studies were conducted [Benonysson et al., 1995; Bojic and Trifunovic, 2000; Curti et al., 2000]. During the early 21st century, the focus within DH systems shifted to sustainability. Scientific studies focused on renewable heating technologies and the reduction of carbon emissions within DH systems [Agrell and Bogetoft, 2005; Lund et al., 2010; Difs et al., 2010].

Over the last couple of years, a future fourth generation of district heating (4GDH) is the subject of research [Averfalk and Werner, 2017; Lake et al., 2017; Mazhar et al., 2018; Li and Nord, 2018; Tereshchenko and Nord, 2018; Volkova et al., 2018; Lund et al., 2018b; Leurent et al., 2018; Asim et al., 2020]. According to the literature, the future 4GDH technology should include lower distribution temperatures, assembly-oriented components and more flexible materials [Lund et al., 2018b]. Furthermore, 4GDH should involve strategic and innovative planning [Tereshchenko and Nord, 2018; Volkova et al., 2018]. Overall, 4GDH aims to take advantage of various heat sources, modern measuring equipment, thermal storage and advanced information technology in order to provide flexibility, reliability, intelligence and competitiveness [Li and Nord, 2018; Asim et al., 2020]. The traditional idea ”to use local fuel or heat resources that would otherwise be wasted”, now shifts to ”also recycle heat from low-temperature sources and integrate RE sources such as geothermal and solar energy" [Lund et al., 2014]. Moreover, 4GDH can be linked to to a more integrated and large-scale approach on *energy system design* (see section 2.2) [Lund et al., 2018a; Nielsen et al., 2020; Østergaard et al., 2021]. In some cases, literature focuses on the advantageous implementation of DH within an *integrated energy system* (see section 2.2.1), in which the electricity and heating sector are interconnected [Lund et al., 2018b; Yu et al., 2018; Askeland et al., 2019; Li et al., 2020; Wang et al., 2021; Golmohamadi et al., 2022]. This literature focuses mainly on the technological aspects of the DH technology without considering local future developments.

There is a lack of studies that consider the impact of the transition to renewable DH on the electricity and heating sector within an integrated energy system while considering local concrete conditions. This observation is in line with the knowledge gap identified by Lund et al. [2018a] and Mazhar et al. [2018], who provide a literature review of the development of DH and their role in integrated energy systems. Moreover, in-depth case studies of this subject in the context of the national and regional Dutch energy system are non-existent. This thesis aims to contribute to the state-of-the-art literature by exploring the impact of the transition from a traditional to a renewable DH system on the Dutch electricity and heating sector. Both a national and regional level are included by analyzing future national energy scenarios and regional energy plans.

2.2 ENERGY SYSTEM DESIGN

In this thesis, current and future *energy system designs* are explored both on a national and regional level. The design of the energy system determines the way the components of the system interact. Moreover, the way the components of the energy systems interact determines the overall effectiveness of the energy system [Sanaei and Nakata, 2012]. There are countless possible configurations of political, technical, economic and social system components for the design of an energy system. This thesis focuses mainly on the technical energy system design.

On a technical level, an energy system includes various energy sources, technologies and end-demand purposes with certain interconnections. Mathiesen et al. [2015] present several different types of energy systems that meet certain end-demands. These types of energy systems are not exhaustive, as there are many more configurations possible. Figure 2.1 and figure 2.2 are adapted from Mathiesen et al. [2015] and illustrate two examples of types of energy systems. The 'traditional energy system' illustrated by figure 2.1, supplies heat by individual boilers. Electricity is provided by power plants and additional RE sources, such as wind and solar. The electricity and heating sector are thus not interconnected. Moreover, figure 2.2 illustrates the 'integrated energy system', which supplies both electricity and heat by CHP plants. Additionally, RE sources, such as wind and solar generate electricity. Moreover, heat pumps additionally produce heat using electricity as input. The electricity and heating sector are thus interconnected.

In the system diagrams included within this thesis, the same colour indication is used for the energy components (square) and flows (arrows). Renewable sources are indicated with green, while conventional sources are indicated with blue. Electricity and heat supply are indicated with yellow and red respectively. The black arrows represent fuel flows, dotted black arrows represent wind or solar energy flows, yellow arrows represent electricity flows and red arrows represent heat flows.

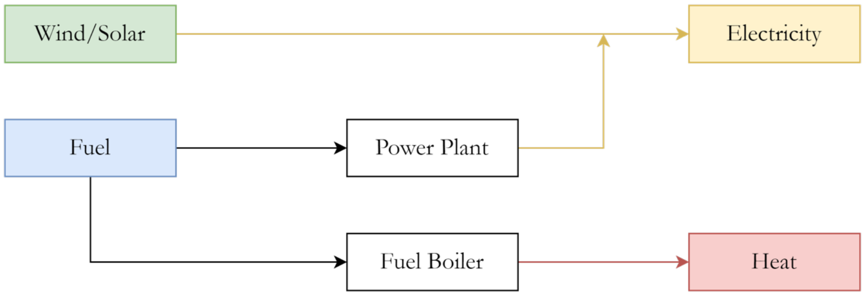


Figure 2.1: System diagram of a traditional energy system, adapted from Mathiesen et al. [2015]

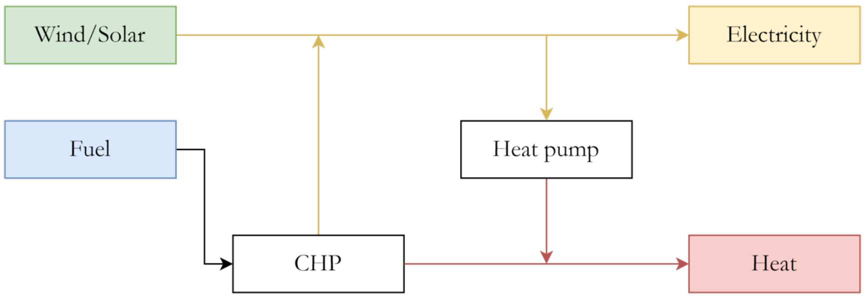


Figure 2.2: System diagram of an integrated CHP energy system, adapted from Mathiesen et al. [2015]

2.2.1 Integrated Energy Systems

In recent years, a global transition away from traditional energy systems has occurred. The integrated energy system (IES), also known as multi-carrier energy system or multi-energy system, is under rapid development in recent years on both a practical and academic level [Pan et al., 2016; Shao et al., 2018]. Integrated energy utilization is viewed as an effective way to improve energy efficiency and flexibility, and increase the share of RE sources [Pan et al., 2016; Connolly et al., 2016; Zhang et al., 2021; Papadis and Tsatsaronis, 2020]. The EU strategic long-term vision for a climate neutral economy by 2050 emphasizes the importance of an IES approach in order to achieve climate objectives [EC, 2018]. Generally, the concept of IES provides an interconnection between at least two individual energy subsectors, such as the electricity and heating sector, as shown in figure 2.2. This approach is commonly referred to in literature with the term 'sectoral coupling' [Jimenez-Navarro et al., 2020; Pan et al., 2016; Liu et al., 2016]. From a policy perspective, the integration of specifically the electricity and heating sector is recognised as a key issue [Jimenez-Navarro et al., 2020].

The sectoral coupling of subsectors into an IES occurs through 'coupling components', such as CHP units and heat pumps [Pan et al., 2016]. In chapter 4, the energy technologies involved in the current en future energy system are further elaborated upon. Some of these technologies are coupling elements between electricity and heating. Through these coupling elements, changes implemented in the heating sector affect the electricity sector and vice versa. Therefore, with the shift away from fossil fuels in one of these sectors, the supply and demand balances of both sectors are expected to change.

2.3 TRANSITION PATHWAYS

A particular renewable energy system configuration as discussed in section 2.2 is the result of a *transition pathway*. In this thesis, transition pathways of the Dutch energy system up to 2050 are analyzed by the use of scenarios and specific regional plans. There are many possible transition pathways resulting in the desired decarbonized energy system that achieves the climate objectives. These transition pathways are shaped by many possible interconnections and uncertainties. Therefore, it is challenging to forecast specific transition pathways and the structure of the energy system at any given year [TNO, 2020a]. In this thesis, the concept of the *scenario funnel* is used to illustrate how the scenarios relate to the current and future energy system. Furthermore, the concepts of *lock-in* and *path dependency* are used to provide an explanation as for how the current energy system and future energy systems are shaped.

2.3.1 Scenario Funnel

According to Timpe and Scheeper [2003], the range of possible transition pathways for complex systems can be simplified by the use of a *scenario funnel*. Figure 2.4 depicts an adapted scenario funnel as proposed by Timpe and Scheeper [2003].

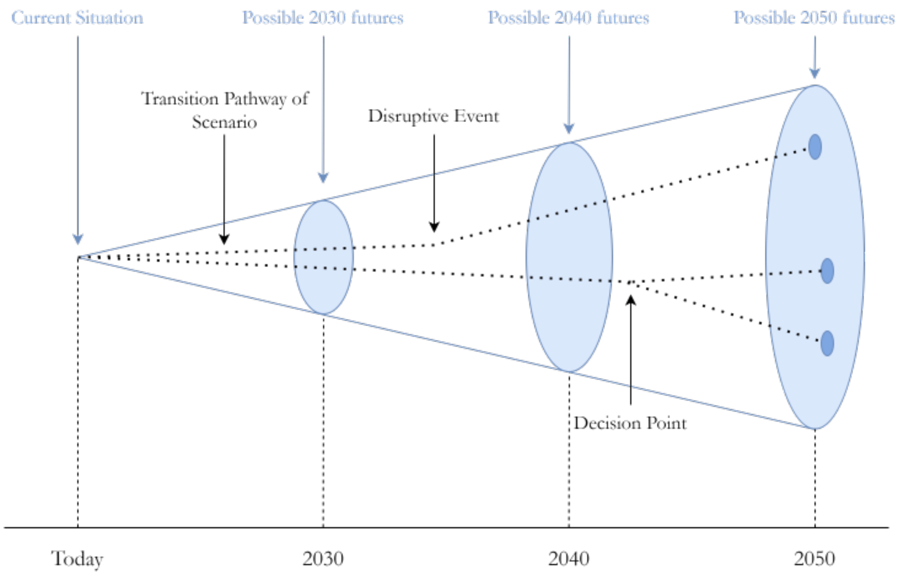


Figure 2.3: Scenario funnel, adapted from Timpe and Scheeper [2003]

The blue circles in the scenario funnel represent the possible realistic futures in a given year. Moreover, the dotted lines represent the various transition pathways of the scenarios. Therefore, the scenario funnel illustrates that the range of possible futures is much larger than a limited number of scenarios. Moreover, the notion can be derived that "the uncertainty of the future usually increases with the distance from the present" [Timpe and Scheeper, 2003]. Besides this, the scenario funnel shows that the possible transition pathways are usually not linear. They might be impacted by 'disruptive events' and 'decision points'. A disruptive event represents an event that that prevents the transition pathway to continue accordingly. At a decision point, a choice exists between several transition pathways [Timpe and Scheeper, 2003].

2.3.2 Lock-In and Path Dependency

Which energy transition pathway or scenario becomes reality is the result of various political, technical, economic and social aspects impacting the disruptive events and decision points. Energy transitions are conceptualized in the theoretical framework of Cherp et al. [2018] in figure 2.4, as a result of three autonomous and co-evolving perspectives: I) the policy perspective (composed of energy-related policies), II) the techno-economic perspective (composed of energy flows and markets), III) the socio-technical perspective (composed of knowledge, practices and networks associated with energy technologies). The course of energy transition can be explained by the developments and interactions of these three perspectives [Cherp et al., 2018; Brauers et al., 2021].

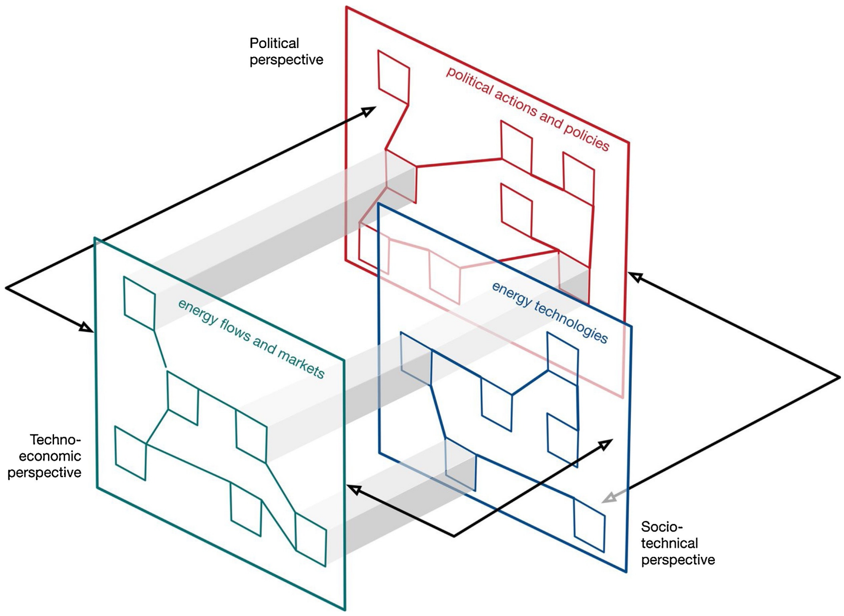


Figure 2.4: Co-evolving systems in energy transitions, reprinted from Cherp et al. [2018]

The concepts of *lock-in* and *path dependency* consider the manner in which large-scale systems, such as energy systems, become embedded in society [Kotilainen et al., 2019]. The lock-in concept refers to a transition pathway or system becoming self-reinforcing. Arthur [1994] defines lock-in as ”increasing returns derived from adoption of a certain technology giving incumbent technologies an advantage over new entrants”. In literature, three types of lock-in are distinguished: *the institutional lock-in*, *infrastructural and technological lock-in* and *behavioural lock-in* [Brauers et al., 2021]. These lock-ins are embedded within the political, techno-economic and socio-technical perspective respectively. The institutional lock-in refers to existing institutions hindering the energy transition [Thelen, 1999]. Moreover, the infrastructural and technological lock-in exist as investments in an existing infrastructure or technology lead to a lock-in to preserve their profits [Bertram et al., 2015; Johnson et al., 2015]. In a behavioural lock-in, current practices through individual decisions and choices are continued. These practices are influenced by social norms and cultural values [Brauers et al., 2021]. Eventually, lock-in can cause path dependency. The path dependency concept refers to a limitation of options regarding actors, institutions and networks [Kotilainen et al., 2019]. The concepts of lock-in and path dependency are used to provide an explanation as for how the current Dutch energy system is shaped following from past Dutch national energy policy in section 5.1. Moreover, these concepts are used to explain how current Dutch energy policy and regional plans shape the future energy system on a regional level in section 6.4.

In the scenario funnel discussed in section 2.3.1, the transition pathways are thus impacted by lock-ins or path dependencies of a political, technical, economic and social nature. Therefore, history shapes current transition pathways and current transition pathways may cause lock-ins for potentially several decades [Vadén et al., 2019]. This causes complexities to arise in the transition from a current to a future renewable energy system. Path dependency causes resistance to change, even if the business as usual pathway seems to be increasingly maladaptive [Barnett et al., 2015]. Hence, it becomes very challenging to re-orient such path-dependent transition pathway [Kotilainen et al., 2019]. According to Barnett et al. [2015] change of transition pathways is always possible, although sometimes slowly. However, time is of the essence with regard to transition pathways involving climate change.

2.4 CONCLUSION

This thesis aims to fill an identified scientific knowledge gap by exploring the impact of the transition from traditional to renewable DH on the Dutch electricity and heating sector. Therefore, the energy system design theory is used. Current and future energy system designs are explored and mapped with regard to their interconnections and quantified energy flows. As energy systems are increasingly becoming more integrated through coupling elements, it is beneficial to view the energy system as an integrated energy system. Moreover, the transition pathways theory is used as various transition pathways of the Dutch energy system up to 2050 are analyzed within this thesis. The range of possible transition pathways for complex systems is depicted via the scenario funnel. Moreover, associated concepts such as lock-in and path dependency are used to provide an explanation as for how the current and future Dutch energy system are shaped.

3 METHODOLOGY

In this chapter, the research approach and its rationale is presented. Subsequently, the research strategy per sub-question is provided. Following from this, the case study methodology, methods for data collection and methods for data analysis are extensively discussed.

3.1 RESEARCH APPROACH

This thesis considers the transition from current to future renewable DH on a Dutch national scale and within a specific Dutch region in order to answer the following main research question: *What is the impact of the transition from traditional to renewable district heating on the Dutch electricity and heating sector?*. The research approach is exploratory and aims at description and understanding of the transition from traditional to renewable DH within a larger context. This larger context is provided by the national energy scenarios in which the regional energy plans take place. Moreover, the larger context is provided by considering the transition to renewable DH within an integrated energy system.

Given the goals of this thesis, the research problem is approached in a mixed methods manner. Both qualitative and quantitative methods are included. The primary reason for using a mixed methods approach is that by combining qualitative and quantitative methods, a more complete understanding of the research subject is provided than either method alone [Creswell, 2003]. The mixed methods approach is well suited for this thesis as it allows to further examine the complex problem at a 'deeper' level. The qualitative strand reveals what the quantitative strand leaves out and vice versa [Edmonds and Kennedy, 2020]. The quantitative methods focus on mapping the current and expected energy system by the use of numerical data. The qualitative methods add to this as they have the benefit of considering the complexities of the transition. Combined, these methods result in in-depth information needed to explore the transition from current to renewable DH on a national and regional scale.

3.1.1 Research Scope

Within the energy system, the electricity and the heating sector are considered, as DH systems play a role in the sectoral coupling of these two sectors specifically. The involvement of other sectors is out of scope. Moreover, the end-demand for electricity and heating considers the built environment, as this is the end-demand sector in which district heating is most relevant. The built environment consists of households and services i.e. a residential and non-residential sector respectively [TNO, 2020a]. Furthermore, the impact of the transition on the electricity and heating sector is explored. As 'sector' is a broad concept, this thesis focuses on the impact in terms of energy flows specifically. Moreover, the transition of the DH sources is studied over a time span of 30 years and the thesis therefore includes various energy scenarios and strategies up to the year 2050.

3.1.2 Research Strategy per Sub-Question

This thesis can be divided into a nationally focused part and a regionally focused part with a case study. The nationally focused part comprises of sub-question 2 and 3, while the regionally focused part considers sub-question 4 and 5. A visualization of the research strategy is provided in figure 3.1. In the remainder of the chapter, the case study methodology (section 3.2) and the associated methodologies for data collection (section 3.3) and analysis (section 3.4) are discussed.

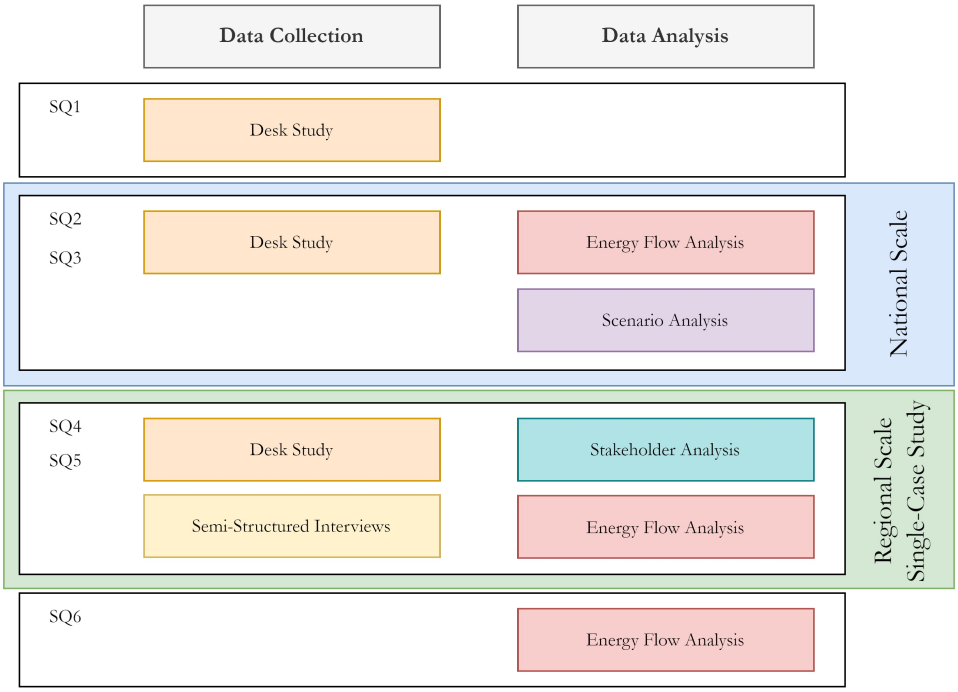


Figure 3.1: Research strategy per sub-question with associated methods

SQ1: What are possible interconnections between energy sources and technologies of the Dutch electricity and heating sector?
In order to answer the first sub-question, a desk study is conducted for data collection regarding the characteristics of current and future energy sources and technologies of the Dutch electricity and heating sector. By determining these characteristics, the interdependencies between the various energy components are determined. A clear overview is provided of how the energy components are related within and between the electricity and heating sector by conducting an energy flow analysis (EFA).

SQ2: How are the Dutch electricity and heating sector expected to transition according to the trends of existing national energy scenarios for 2050?
For answering the second sub-question, a desk study is conducted for data collection regarding Dutch national energy policy and the current Dutch electricity and heating sector on a national level. Moreover, a desk study and and a scenario analysis are conducted regarding future scenario reports for the national energy system of 2050. Subsequently, an EFA is conducted in order to determine the current and future interconnections of the national electricity and heating system and to quantify the energy flows. By comparing the future energy systems among each other and with the current national system, scenario trends can be identified.

SQ3: What is the expected impact of the transition to renewable district heating on the Dutch electricity and heating sector according to the trends of existing national energy scenarios for 2050?
To answer the third sub-question, the EFA of sub-question 2 is used to determine the current and future interconnections of the national energy system between the electricity and heating sector. Subsequently, the changing role of DH within the integrated energy system is analyzed. Therefore, the impact of the transition to future DH on the electricity and heating sector is indicated according to these trends on a national scale.

SQ4: How are the electricity and heating sector expected to transition according to the regional energy plans in a specific Dutch region?
To answer the fourth sub-question, a case study as described in section 3.2 is conducted regarding the electricity and heating sector of a specific Dutch region. Within the case study, a desk study is conducted for data collection regarding the current status of the Dutch electricity and heating sector on a regional level. Moreover, a stakeholder analysis is conducted in order to determine the relevant actors involved in the regional energy system. Stakeholder reports regarding regional energy plans are analyzed in order to determine how concrete the plans are and what they entail. Moreover, expert interviews are conducted with the various identified stakeholders to gather additional data. Subsequently, an EFA is conducted in order to determine the current and future interconnections of the regional electricity and heating system and to quantify the energy flows. By comparing the current and future regional energy systems, the expected transition can be determined.

SQ5: What is the impact of the transition to renewable district heating on the electricity and heating sector according to the regional energy plans in a specific Dutch region?
The fifth sub-question is also part of the case study as described in section 3.2. The EFA of sub-question 4 is used to determine the current and future interconnections of the regional energy system between the electricity and heating sector. Subsequently, the changing role of DH within the integrated energy system is analyzed. The regional energy plans place this changing role in a multi-actor context. Therefore, the impact of the transition to future DH on the electricity and heating sector is indicated according to these trends on a regional scale.

SQ6: How do the transitions of the national and regional electricity and heating sector compare?
For answering the last sub-question, the EFAs of the national and regional analysis are compared. Therefore, it can be determined how the current regional energy system fits within the national energy system. Subsequently, it can be compared how the regional future energy system fits within the national future energy scenarios.

3.2 SINGLE-CASE STUDY METHODOLOGY

Sub-question 4 and 5 are answered in chapter 6 by the use of the single-case study methodology. A case study is defined as "an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used." [Yin, 2009]. By using a case study approach, data within a specific context can be closely examined and a rich picture of a particular phenomenon can be generated. Concerns of case study research regard researchers to not providing enough depth, not follow systematic procedures or have biased views influencing the direction of the findings and conclusions [Yin, 2009].

According to Yin [2009], there are three types of case studies:

- Exploratory: the case study is used to explore a particular phenomenon within its context.
- Descriptive: the case study is used to describe a particular phenomenon within its context.
- Explanatory: the case study is used to provide an explanation for a particular phenomenon within its context.

In this thesis, the single-case study is utilized to gain a deep understanding of one particular case [Seawright and Gerring, 2008]. The regional transition from traditional to renewable DH is explored and in-depth research is conducted into concrete regional impacts of this transition. Therefore, an exploratory analysis is conducted. Moreover, Yin [2009] states that some case study research uses a mix of quantitative and qualitative methods. This approach is applicable to this case study, in which the qualitative analysis aims at providing additional information to the quantitative data analysis.

3.2.1 Case Selection

Case selection is an important part of the case study. Often, a specific geographical area is considered to provide the boundaries of the case [Yin, 2009]. As the supply of heat is a very local phenomenon, the regional area North-Holland South is selected for this case study. This region has been selected for two main reasons. First, the regional energy plans of this region are developed to a large extent. Second, Vattenfall has a large interest in this specific region, as the regional district heating grid is largely under their operation. Within the case study, the current and future regional electricity and heating sector and the involved stakeholders are under consideration.

3.3 DATA COLLECTION

In order to collect data for answering the sub-questions, data collection methods are applied. The methods involve desk research, including literature and desk studies, and semi-structured interviews.

3.3.1 Desk Study

A desk study is conducted in order to collect the data serving as input for data analysis, see section 3.4. First, a literature review is done regarding energy sources and technologies within the Dutch electricity and heating sector as input for the EFA to answer sub-question 1. Moreover, various national energy reports are studied in order to collect data regarding the current Dutch electricity and heating sector on a national and regional scale. This data will serve as input for the EFA of the existing energy systems in sub-question 2 and 4. Furthermore, in order to gather data on the future Dutch electricity and heating sector on a national scale, various scenario reports are studied. The scenarios from these reports will serve as a basis for the scenario analysis in sub-question 2. Lastly, data regarding the future regional electricity and heating sector is gathered by studying various regional energy plans. The data regarding these plans serve as input for the EFA of the future regional energy systems in sub-question 4.

3.3.2 Semi-structured interviews

Semi-structured interviews with several stakeholders are conducted in order to collect and verify data serving as input for data analysis, see section 3.4. Semi-structured interviews are conducted among the stakeholders involved in the transition to renewable DH sources within the regional level (case study) in chapter 6 for answering sub-question 4 and 5. Three types of interviews can be used for conducting interviews: structured, semi-structured and unstructured [Bolderston, 2012]. Structured interviews mostly contain pre-determined closed questions for which the interviewee is often limited to pre-coded responses. In contrast, unstructured interviews have very little structure at all. Questions are often open-ended and not pre-determined as successive questions are framed according to the interviewee's previous response [Mathers and Nick Fox, 1998]. A semi-structured interview is the most suitable method for this thesis. Semi-structured interviews involve a series of open-ended questions. The open-ended nature of the questions enable the topic under investigation to be defined but opportunities are provided for both the interviewer and interviewee to discuss some topics in more detail and investigate other areas. This may lead to potentially important new data, which a useful addition to the scenario and regional energy flow analysis. However, conducting semi-structured interviews also has several limitations. Conducting the interviews can be time-consuming, analyzing the interview data from open questions can be labour intensive and the success of an interview depends on the willingness of the interviewees to cooperate [Mathers and Nick Fox, 1998; Bolderston, 2012]. These limitations are addressed as for each interview a pre-determined duration is stated. Furthermore, the pre-determined questions are standardized for all interviewees, which causes data analysis to become easier and faster, see section 3.4.4. The interview guide is included in appendix C.

Interviewees

Table 3.1 depicts the conducted interviews and the associated interviewee, organization, function and reference.

Interviewee	Organization	Function	Interview Reference
Pim van Herk	Province North-Holland	Policy Consultant Renewable Energy	Provincie Noord-Holland [2022]
Milan van Schendel	Municipality of Amsterdam	Strategy Consultant Renewable Energy	Gemeente Amsterdam [2022]
Bart de Hue	Vattenfall	Program Manager Green Heat	Vattenfall [2022a]
Floor de Kleijn	Vattenfall	Public & Regulatory Advisor	Vattenfall [2022b]
Frank de Vries	Vattenfall	Director of Concession Management	Vattenfall [2022c]
Richard van den Broek	Vattenfall	Portfolio Director Heat	Vattenfall [2022d]
Martin Buijk	Westpoort Warmte	COO Westpoort Warmte	Westpoort Warmte [2022]
Hans van der Geest	Liander	System Operator	Liander [2022]
Hans Coenen	Gasunie	VP Corporate Strategy & Business Developer	Gasunie [2022]

Table 3.1: Conducted interviews

Several stakeholders involved in the transition to renewable DH within the regional level (case study) are interviewed in order to analyse the case from different perspectives. The interviewees were selected based on the conducted stakeholder analysis. In the stakeholder analysis, organizations that are involved with or responsible over the energy flows within the regional electricity and heating sector are included. The main organizations are identified and representatives of these organizations are invited as interviewees. Furthermore, the interviewees are asked if there are other interviewees that are recommended. The viewpoints of the stakeholders identified within the stakeholder analysis are included in chapter 6. This has been done in order to form a representative and widespread understanding of the transition to renewable DH within the region. Therefore, the chance of one-sided and biased information was reduced.

3.4 DATA ANALYSIS

In order to analyse data for answering the sub-questions, data analysis methods are applied. The methods involve energy flow analysis, scenario analysis and stakeholder analysis.

3.4.1 Energy Flow Analysis

An energy flow analysis (EFA) is conducted in in chapter 4, 5, 6 and 7 for answering all sub-question in order to map the interconnections and the energy flows between the technical components of the electricity and heating sector. As the coupling between different energy subsectors is important in this thesis, traditional methods that study energy subsectors as individual subsystems are not suited [Liu et al., 2016; Connolly et al., 2016; Pan et al., 2016]. An EFA offers the possibility to consider the electricity and heating sector as an integrated whole [Papadis and Tsatsaronis, 2020]. In research, EFA has been widely used for tracking the energy balance of industrial clusters, cities and nations. Most EFAs concern energy flows in combination with economic processes within a top-down assessment framework. The energy indicators involved in EFA often include energy import, exports and socio-economic stocks. In this thesis, the physical energy flows of different electricity and heating sources to final end uses in the built environment are included. This also includes imported and exported electricity. With the input data collected by desk study, the involved energy flows are calculated, converted to PJ and assembled using Microsoft Excel [Microsoft, 2010a]. This provides the possibility to track different types of sources used in the energy system, which is important for understanding the energy infrastructure [Chen and Chen, 2015]. Moreover, the EFA gives a sense of scale across the system [Lupton and Allwood, 2017]. The EFA may help policy and decision-makers, researchers and others to understand the energy flows in the electricity and heating sector from source to final end uses in the built environment [Subramanyam et al., 2015].

In this thesis, the EFA is visualized by the means of system and sankey diagrams of the considered energy systems. The system diagram visualizes the interconnections between the technical components and the direction of the energy flows and is created in Microsoft [2019]. The sankey diagram depicts the energy flows of the system in a quantified manner and is created in SankeyMatic [2020]. Sankey diagrams have been used as an effective tool to analyze energy flows and their specific distribution across various energy sectors. The diagram is represented by arrows, for which the width represents the magnitude of the flow [Soundararajan et al., 2014].

3.4.2 Scenario Analysis

A scenario analysis is conducted in chapter 5 for answering sub-question 2, which focuses on the national scale. The key idea of scenario analysis is to explore alternative future developments [Duinker and Greig, 2007]. The scenario analysis is not intended to draw conclusions regarding the best climate-neutral future for our society. However, the purpose of this scenario analysis is to explore the national transition pathways available to the Dutch electricity and heating sector. A scenario analysis is defined as ”a procedure covering the development of scenarios, comparison of scenario results, and evaluation of their consequences” [Alcamo and Henrichs, 2008]. In this thesis, scenarios are not developed. However, various existing scenarios from different sources are compared and analyzed. Each scenario plausibly describes an alternative future, in a qualitative and quantitative manner. Scenario analysis does not focus on making predictions or forecasts, but rather on describing and analyzing images of the future in order to broaden perspectives [Duinker and Greig, 2007]. Key to successfully conducting a scenario analysis is to avoid becoming attached to a particular scenario. According to Duinker and Greig [2007] ”understanding the implications of each scenario permits insightful analysis of the uncertainties that the future holds”.

Alcamo and Henrichs [2008] identifies five main elements of a scenario analysis:

- The initial situation
- An image of the future
- Driving forces (drivers of change)
- Alternative pathways to the future (scenarios)
- Changes

Each of these elements is included within the research by answering sub-question 2 in chapter 5. The current status of the Dutch electricity and heating sector is determined on a national scale. Moreover, the scenarios from the reports gathered in the desk study, will provide an image of the future and alternative pathways to the future. Moreover, the qualitative story lines behind the scenarios will be studied in order to determine the driving forces. Driving forces are the main factors influencing future developments of a system described in a scenario. Main categories of driving forces in environmental scenarios include technological, political, demographic, economic and social-cultural drivers [Alcamo and Henrichs, 2008; Postma and Liebl, 2005]. The scenarios will be explored and compared by the results of the EFA. The EFA will be used to identify changes and particular trends for every scenario.

3.4.3 Stakeholder Analysis

A stakeholder analysis is conducted in chapter 6 for answering sub-question 4 in order to determine the relevant actors involved in the transition from fossil to renewable DH sources within the case study and thus at a regional level. Policy-makers increasingly recognise the need to understand the so-called stakeholders, those who are affected by the decisions and actions they take, and who have the power to influence their outcome [Reed et al., 2009]. Stakeholder analysis is defined as ”a process that: i) defines aspects of a social and natural phenomenon affected by a decision or action; ii) identifies individuals, groups and organisations who are affected by or can affect those parts of the phenomenon (this may include non-human and non-living entities and future generations); and iii) prioritises these individuals and groups for involvement in the decision-making process”. [Reed et al., 2009].

In this thesis, relevant stakeholders will be identified as part of the case study. Stakeholder identification is usually an iterative process. However, if the boundaries of the phenomenon itself are clearly defined, then stakeholders can be relatively easily identified. A risk is the accidental omission of certain stakeholders by the lack of thoroughness. However, a line must be drawn at some point, based on criteria established by the researcher. Such criteria may be for instance of a geographical or demographic nature, depending on the focus of the analysis [Reed et al., 2009]. In this thesis, the boundaries of the phenomenon are defined by the geographical boundaries of the studied case, as described in 3.2.1. More specifically, the stakeholders that are involved with or responsible over the energy flows within the boundaries of the case study's electricity and heating sector are included. As heat supply is a very local issue, the geographical boundaries are easier to determine than for electricity. For electricity, a line is drawn at imported electricity. The stakeholders involved with the regional supply, transmission, distribution and end use of electricity are included. However, the stakeholders that only supply imported electricity are not included.

3.4.4 Interview Data Analysis

An analysis of the data collected by conducting the interviews is performed. This data is relevant for the exploration of regional energy plans in chapter 6 for answering sub-question 4 and 5. While the interviews are conducted, the interview is recorded with permission of the interviewee. Subsequently, the interview is transcribed using Microsoft Word [Microsoft, 2010b]. According to McLellan et al. [2003], the text selected for transcription should take into account the analytical contribution it will provide to the overall study. What to include should thus always be driven by the research question involved [McLellan et al., 2003]. Therefore, in this thesis the interviews are globally transcribed without including mispronunciations, elisions, slang, nonverbal sounds (e.g., laughs, sighs), grammatical errors and background noises. Sentences, paragraphs, passages and stories relevant to the research question are included. Subsequently, the transcribed data is used additionally to the regional energy plans of the involved actors gathered via desk study.

3.5 CONCLUSION

This thesis is divided into a nationally focused part and a regionally focused part in order to answer the main research question: *What is the impact of the transition from current to future renewable district heating sources on the Dutch electricity sector?* The research approach is exploratory and aims at description and understanding of the transition from fossil to renewable DH sources within a larger context. This larger context is provided in two ways: I) by the national energy scenarios and II) by considering the transition to renewable DH within an integrated energy system.

First, overall possible interconnections between energy technologies and sources are determined by collecting data via a desk study and analyzing data using an EFA. Subsequently, a desk study is used for data collection regarding the nationally focused part. A scenario analysis is conducted to determine national energy trends and these trends are analyzed by an EFA. Furthermore, a desk study and semi-structured interviews are used for data collection regarding the regionally focused part. This part includes a single-case study, in which the region North-Holland South is studied by using data analysis methods such as EFA, stakeholder analysis and interview data analysis.

In chapter 4, the possible interconnections between the various energy components are determined. Subsequently, chapter 5 focuses on the national analysis, while chapter 6 focuses on the regional analysis and include the case study of the region North-Holland South. Lastly, 7 compares the national and the regional analysis.

4 ENERGY TECHNOLOGIES AND SOURCES

As discussed in section 2.2, an energy system includes various energy sources, technologies and end-demand purposes. In this chapter, the characteristics of current and future energy technologies and sources of the Dutch electricity and heating sector are discussed. The end-demand purposes are considered to be the electricity and heat demand of the built environment. Following from these characteristics, the interconnections between the various energy components are determined. The first sub-question *What are possible interconnections between energy sources and technologies of the Dutch electricity and heating sector?* is answered within this chapter by applying the methods discussed in chapter 3.

4.1 ENERGY TECHNOLOGIES

A description of the energy technologies that play a role in the current and future energy system is provided in this section. The district heating technology is part of this energy system. However, the district heating technology is discussed separately in section 4.3.

4.1.1 Power Plants

Sarat Raju and Karunya [2018] define a power plant as ”a machine or assembly of equipment that generates and delivers a flow of mechanical or electrical energy”. The main technical component for the generation of electricity is the generator. By coupling the generator to a prime mover, the electricity is generated. The type of prime move determines the type of power plant [Sarat Raju and Karunya, 2018]. Power plants can be fueled by coal, natural gas, hydrogen, nuclear and green gas. Currently, operators typically rely on conventional power plants (e.g. coal- and natural gas-fired power plants) to balance demand and supply, as they are dispatchable [González-Gómez et al., 2014]. This implies that the electricity can be supplied on demand. The associated energy sources are discussed in section 4.2. Figure 4.1 provides a schematic overview of this energy technology’s interconnections.

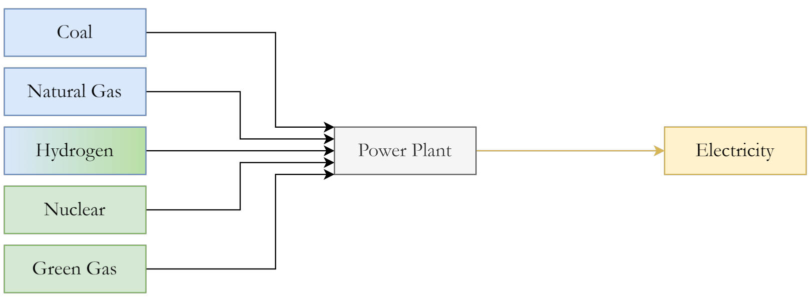


Figure 4.1: System diagram of the interconnections of the power plant technology with renewable and conventional energy sources and supply

4.1.2 Wind Technology

The wind energy generation technology generates renewable electricity. Wind energy is converted to electricity by the use of wind turbines. These wind turbines can be realized on a small-scale or on a large-scale, in which case wind farms are established. The siting of wind turbines can occur onshore or offshore [Pareek et al., 2020]. Figure 4.3 provides a schematic overview of this energy technology's interconnections.

Figure 4.2: System diagram of the interconnections of the wind and solar technology with renewable (green) energy sources and supply

However, there are challenges involved regarding the implementation of large-scale wind energy. First, the realization of on- and offshore wind farms on a large-scale brings along challenges regarding costs, operation and public acceptance [Ladenburg et al., 2020]. Moreover, the electricity generation by wind is location specific, highly intermittent, non-dispatchable and only predictable to a limited extent [Collins et al., 2017]. This causes challenges to occur with grid operators when scheduling power generation. Wind turbines are among the most capital-intensive and lowest cost to operate [González-Gómez et al., 2014]. Once the turbines are realized, the least-cost approach is to run them as much as possible. As electricity supply and demand must always balance, electricity systems require technologies that can offer generation flexibility in response to wind. Generation flexibility refers to the extent to which power technologies can respond to changes in the residual load on different timescales [González-Gómez et al., 2014].

4.1.3 Solar Technology

Solar energy generation technologies also generate renewable electricity. Solar energy can be used to generate electricity via technologies like photovoltaic (PV) panels and concentrating solar power (CSP) [Pareek et al., 2020]. Solar energy systems range from large-scale solar farms to small-scale application for buildings. Therefore, solar energy systems can be either centrally or decentrally generating electricity, providing the possibility for consumers to deliver electricity back to the grid [Devabhaktuni et al., 2013]. Figure 4.3 provides a schematic overview of this energy technology's interconnections.

Figure 4.3: System diagram of the interconnections of the wind and solar technology with renewable (green) energy sources and supply

However, similar to with wind energy, there are challenges involved regarding the implementation of large-scale solar energy. Similarly, the realization of solar farms on a large-scale brings along challenges regarding costs, operation and public acceptance [Ladenburg et al., 2020]. Furthermore, the implementation of decentralized solar requires investments of homeowners and an adapted electricity grid. Moreover, the same challenges apply as mentioned in the previous section with regard to the intermittent nature of wind and solar energy and therefore flexibility technologies are required.

4.1.4 Combined Heat and Power Plants

The utilization of CHP plants as a source for both electricity and heat supply is very common and therefore the technology is mature. CHP plants produce both electricity and usable heat and are therefore a coupling element, as discussed in 2.2.1. Chemical energy from fuels is conversed to mechanical and thermal energy. The mechanical energy provides power to the generator, while the thermal energy is used for DH systems or to produce high-pressure steam for further systems operations. The ratio between the generated electricity and thermal energy can be controlled by the system operator [Mazhar et al., 2018]. Compared to conventional, separated electricity and heat production, CHP plants achieve a higher energy efficiency, less fuel consumption and less carbon footprint [Sayegh et al., 2017]. Similar to power plants, operators rely on CHP plants to balance demand and supply, as they are dispatchable. CHP plants are often operating as base load producers and can cost-effectively supply heat and electricity during summer and winter [Winterscheid et al., 2017]. Times with high power prices will create good market conditions for CHP plants [Werner, 2017]. CHP plants can be fueled by natural gas, coal, waste, biomass and green gas. These energy sources are discussed in section 4.2. Figure 4.4 provides a schematic overview of this energy technology's interconnections.

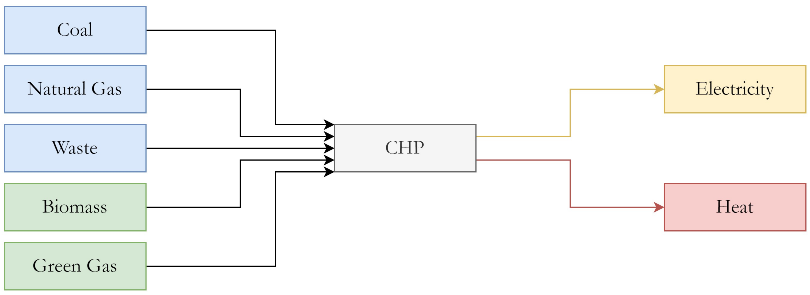


Figure 4.4: System diagram of the interconnections of the CHP technology with renewable (green) and conventional (blue) energy sources and supply

4.1.5 (Hybrid) Heat Pumps

Heat pumps transfer or "pump" heat from a heat source to a heat sink, as they lift low exergetic heat to a higher temperature by running a vapour compression cycle [Fischer and Madani, 2017]. Electric heat pumps use electricity as an energy input and therefore are a power-to-heat (PtH) technology and a coupling element, as discussed in 2.2.1. Parameters such as the temperature, volume and flow of the heat source will determine the possible efficiency of the heat pump [Lund and Persson, 2016]. Furthermore, the coefficient of performance (COP) is a widely used indicator for assessing the energy efficiency of heat pumps. The COP of a heat pump in the heating mode is the ratio of the heat output (Qhp) of a heat pump to its electrical energy input ($Wcomp$), as follows [Hepbasli, 2018]:

$$COP = Qhp/Wcomp \tag{4.1}$$

Air-source heat pumps generally have COPs ranging from 2 to 4, while water- and ground-source heat pumps have COPs ranging from 3 to 5 [Dincer and Rosen, 2021]. If both consumed energy and usable energy are summed during a season, the seasonal COP, which is also referred to as the seasonal performance factor (SPF) is used. Within the EU, heat pumps are classified as renewable when their SPF is greater than 2.5. Moreover, the EU definition aims to ensure that heat pumps are merely classified as renewable, whenever their output exceeds the potentially non-renewable primary energy input [Fawcett et al., 2015]. Figure 4.5 provides a schematic overview of this technology's interconnections. A distinction can be made between individual and collective heat pumps.

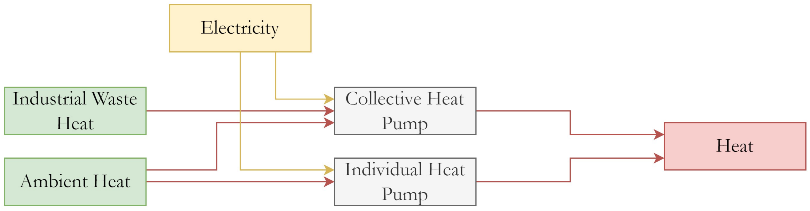


Figure 4.5: System diagram of the interconnections of the heat pump technology with renewable (green) and conventional (blue) energy sources and supply

In order to individually supply heat, individual heat pumps can be used. In this case, heat is supplied in a decentralized manner by implementing heat pumps in buildings. In order for the individual heat pump to function properly, buildings must be well insulated and have sufficient space. The benefits of the heat pumps include high efficiency and socio-economic competitiveness [Hedegaard and Münster, 2013]. The most considered source for individual heat pumps is ambient heat. This energy source is discussed in section 4.2. Some individual heat pumps use additional gases besides their main heat source. These heat pumps are defined as hybrid heat pumps. A hybrid heat pump combines a conventional heat pump and a condensing boiler. Therefore, the hybrid heat pumps is able to switch from electricity to gas and reciprocally in order to satisfy heating demand, according to primary energy minimization target or economic signals [Vuillecard et al., 2011]. These additional gases could be hydrogen or green gas. These energy sources are discussed in section 4.2.

Collective heat pumps can serve as input for DH systems. The lower supply temperature needed from the heat pump, the higher efficiency [Lund and Persson, 2016]. Collective heat pumps can contribute to increasing the flexibility of the electricity supply as the DH network offers available heat storage capacity. Whenever alternative options of DH sources are available, heat pumps can be operated when electricity prices are low and shut down when prices are high [Averfalk et al., 2017]. The use of heat pumps as integrated production units in DH systems can provide an efficient and stable heat supply [Sayegh et al., 2017]. The most considered sources for collective heat pumps are ambient heat and low-temperature industrial waste heat. These energy sources are discussed in section 4.2.

4.1.6 Boilers

A conventional boiler or heat-only boiler is a device that boils water to produce steam. A boiler thus converts the chemical energy in fuel into the heat energy in steam, or, when no firing is involved, the boiler converts the heat energy of hot gases into the heat energy in steam. Boilers are made in various shapes and sizes in order to burn various fuels. Boilers are a mature energy technology, the earliest form of a boiler is a kettle. The use of boilers do not require buildings to be as well insulated compared to when heat pumps are used [Rayaprolu, 2009]. Boilers can be fueled by natural gas, hydrogen, solar, biomass and green gas. These energy sources are discussed in section 4.2. Whenever green hydrogen is used as a source for boilers, an interconnection can be formed between the electricity and heating sector, as green hydrogen is produced with electricity surpluses. Moreover, boilers can also use electricity as an energy source, in which case the boiler is an electric boiler (E-boiler). An E-boiler converts electricity into heat and therefore is a PtH technology and a coupling element, as discussed in 2.2.1. The E-boiler can provide flexibility to the electricity grid. Whenever electricity surpluses are available and the heat demand is low, the E-boiler stores the heat in a buffer. E-boilers are characterized by a relatively low investment, but are much more sensitive to the electricity price because they are expected to have an efficiency of 99,99% (COP of 1) [Vattenfall, 2021a]. Figure 4.6 provides a schematic overview of this energy technology's interconnections.

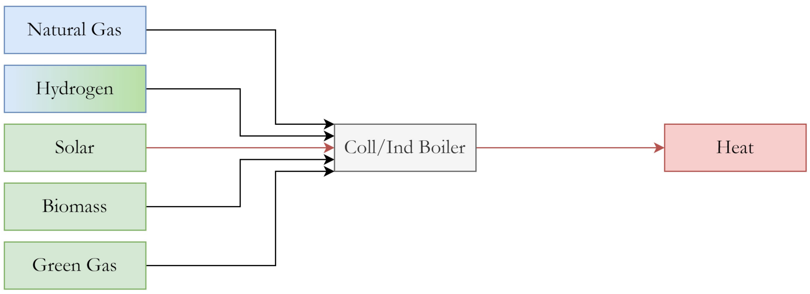


Figure 4.6: System diagram of the interconnections of the boiler technology with renewable (green) and conventional (blue) energy sources and supply

A distinction can be made between individual and collective boilers. In order to individually supply heat, individual boilers can be used. In this case, heat is supplied in a decentralized manner by implementing boilers in buildings [Rayaprolu, 2009]. In this report, for simplicity the use of biomass in individual boilers represents the individual combustion of biomass for heat. For boilers, buildings are required to implement much less extensive insulation compared to for individual heat pumps and DH. Moreover, collective boilers can be connected to a DH network in order to supply heat. Collective boilers provide a way to supply heat for large scale-application [Rayaprolu, 2009].

4.1.7 Hydrogen Production and Storage Technology

The production and storage of hydrogen are energy technologies that can be involved in the future energy system. The main challenge in utilizing hydrogen as a fuel is its production in pure form. There are different technologies used for production of pure hydrogen. A distinction is made between green, blue and gray hydrogen. Green hydrogen involves hydrogen produced with RE sources, blue hydrogen involves hydrogen produced with conventional energy sources in combination with CCS, and gray hydrogen involves hydrogen produced with conventional energy sources [Pareek et al., 2020]. Hydrogen can be produced from a wide variety of sources such natural gas, coal, biomass and electricity [Quintel, 2019]. These energy sources are discussed in section 4.2.

Steam reforming is a highly developed hydrogen production process to extract hydrogen from fossil fuel stocks, such as natural gas and coal. Methane reacts in the presence of a catalyst with steam at a high temperature to provide a mixture of hydrogen and other gases. The unwanted gases (including CO2) are then separated by further reactions and the hydrogen thus obtained is purified to meet the industrial standard. This technique is already being used extensively, but mainly to produce hydrogen for industrial use. Furthermore, biomass gasification is a mature technology for the production of hydrogen from biomass. Moreover, hydrogen can be produced from electricity surpluses generated by wind and solar energy through electrolysis. In this technology, water is splitted into oxygen and hydrogen using electric current [Quintel, 2019; Pareek et al., 2020]. Therefore, the production of hydrogen through electrolysis can provide flexibility in the electricity sector. In this research, a power-to-hydrogen efficiency of 66% is assumed for 2050 according to Quintel [2019].

The storage of hydrogen can provide flexibility to the energy system and aid in balancing energy supply and demand. Energy storage becomes increasingly important with the increase of the share of fluctuating RE sources, such as wind and solar. Finding a cost-effective method of storing hydrogen remains an indomitable challenge. Currently, hydrogen can be stored as compressed hydrogen, liquid hydrogen and as storage material [Pareek et al., 2020; Niaz et al., 2015]. Figure 4.7 provides a schematic overview of this energy technology's interconnections.

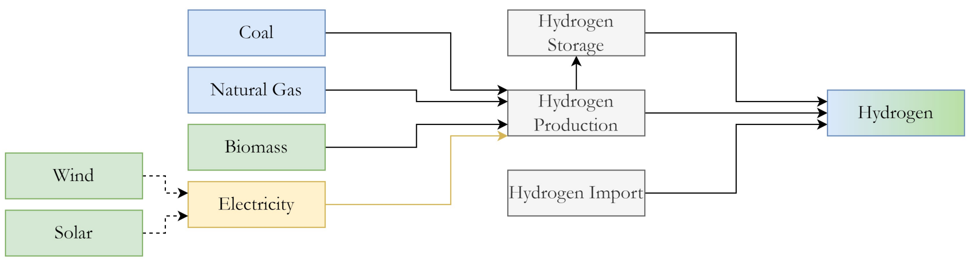


Figure 4.7: System diagram of the interconnections of the hydrogen technology with renewable (green) and conventional (blue) energy sources and supply

4.2 ENERGY SOURCES

The energy technologies discussed in section 4.1 require the input of associated energy sources in order to generate usable electricity or heat. In the following sections, a description of the energy sources that play a role in the current and future energy system is provided.

4.2.1 Natural Gas

Natural gas can be used as an energy source for power plants, CHP plants, boilers and hydrogen production. Natural gas is considered to be the cleanest fossil energy source [Mac Kinnon et al., 2018]. However, natural gas combustion cause higher emissions of GHG and pollutants than RE sources. The usage of natural gas as an energy source can play a role in supporting renewable resource integration by providing load balancing services, and supporting the use of gaseous RE sources via the existing infrastructure of the natural gas system [Mac Kinnon et al., 2018].

4.2.2 Coal

Coal can be used as an energy source for power plants, CHP plants and hydrogen production. Coal is worldwide the most abundant energy source. However, it is a high-emitting energy source, mostly composed of carbon and hydrocarbons, which have a high energy density released through combustion [Gasparotto and Da Boit Martinello, 2021]. Depending on the type of coal the combustion causes various pollutants to be emitted. Although new coal-fired power plants use modern technologies that filter the flue gases in stacks, pollutants are still being emitted in several times higher amounts than natural gas fired and other power plants [Shahzad Baig K and Yousaf M, 2017].

4.2.3 Nuclear

Nuclear energy can be used as an energy source for power plants. Nuclear energy is sometimes viewed as a major opportunity for the decarbonization of energy systems as it is a low-carbon energy source. In nuclear power plants, electricity is efficiently obtained from nuclear fission processes, due to the usage of the cohesion of the subatomic particles of radioactive materials [Obregón et al., 2019]. The energy produced by nuclear is viewed as renewable. Nuclear power plants include built-in physical barriers to prevent the escape of radioactive isotopes into the environment. However, safety issues and the radioactive waste that nuclear generates still bring about public concerns. These concerns are mainly caused by the occurrence of nuclear accidents, such as the well-known Chernobyl (1986) and Fukushima Daiichi (2011) events that released high amounts of radioactive isotopes into the environment. Moreover, nuclear waste is highly radioactive and can not be stored in an easy, safe and permanent manner. High-level radioactive waste persists in the environment for up to one hundred thousand years, which makes safe storage almost impossible [Prăvălie and Bandoc, 2018]. According to Prăvălie and Bandoc [2018] the role of nuclear in the energy system is uncertain as climate and energetic advantages are outweighed by the disadvantages associated to radioactive pollution.

4.2.4 Biomass

Biomass can be used as an energy source for CHP plants, boilers and hydrogen production. Biomass is a collective term for a wide range of various biomass fuels and is considered to be a RE source. Biomass is used as a fuel in form of wood fuels, forest waste, biofuels and biogas [Sayegh et al., 2017]. Biomass can be used as an energy source in a stand-alone or hybrid manner. Most research and studies focus on techno-economic analysis of the substitution of conventional sources with this renewable source [Mazhar et al., 2018]. However, recent debates regarding the use of biomass as a renewable energy source point to a lack of public support [PBL, 2020a]. The following two sections discuss waste and green gas. These sources relate to biomass, as part of the waste used for waste incineration is biogenic and green gas is produced from biomass. However, it has been chosen to discuss these two sources separately, as their fuel flows are separately included within the system diagrams.

4.2.5 Waste

Waste can be used as an energy source for CHP plants. European waste management has the clear aim to "move up the waste hierarchy". Therefore energy recovery from waste or waste-to-energy (WtE) could be beneficial in order to avoid landfills. WtE technology involves any waste treatment process that uses waste as a fuel in order to produce energy in the form of heat and power [Rudra and Tesfagaber, 2019]. Commonly, waste incineration plants are constructed as CHP plants providing the possibility to both generate electricity and recycle the heat output [Werner, 2017]. Waste is combusted at high pressure in a boiler or furnace, forming hot combustion gas, oxygen, flue gas, and ash. Hot flue gas products are subsequently used to generate electricity and heat. This technology is widely used in developing and developed countries [Consonni et al., 2017]. The combustion of waste is classified by the Dutch government for 51% as renewable, in proportion to the biogenic part of the waste [RSW, 2022].

4.2.6 Green Gas

Green gas can be used as an energy source for power plants, CHP plants and boilers. Sometimes green gas is considered to become part of the future energy system, not merely as an energy carrier, but also as a means to balance supply and demand of energy [Bekkering et al., 2015]. Green gas can be produced through biomass fermentation and dry or wet gasification. Biomass fermentation produces biogas, which can be used directly for heat or electricity supply, but can also be upgraded to green gas before being introduced into the gas network. In dry gasification, dry biomass is gasified at high temperatures, a kind of combustion with a shortage of oxygen. The gasification route offers a lot of flexibility when it comes to possible follow-up routes and end products to be manufactured (green gas, hydrogen, transport biofuels and more). In the case of green gas production, gasification is followed by methane synthesis and upgrading to natural gas quality green gas. Wet gasification or super-critical water gasification (SCW) converts wet biomass into green gas under a higher pressure and temperature [Quintel, 2019]. However, as green gas is produced from biomass, a similar lack of public support is involved [PBL, 2020a].

4.2.7 Hydrogen

Hydrogen can be used as an energy source for power plants and boilers. Hydrogen is the highest heat-burning gas of all-natural fuels and is considered a non-renewable or renewable source depending on the production process. Therefore, as mentioned before, a distinction is made between green, blue and gray hydrogen. An important characteristic of hydrogen is that the molecules do not contain other chemical elements. Therefore, the combustion product is solely water, causing hydrogen to be viewed as an ideal clean energy resource. In recent years, the scientific community has been involved in facilitating the introduction of hydrogen into energy systems. Hydrogen power plants can be deployed flexibly and can therefore play a role in balancing the sustainable energy system of the future [Wang et al., 2019]. The production and storage of hydrogen is discussed in section 4.1.7.

4.2.8 Wind

Wind can be used as an energy source for wind turbines. Wind energy has an intermittent nature. The winds are mainly produced by the convective effect that is induced by solar heating of earth's surface. Therefore, wind energy largely depends on geological location and season [Pareek et al., 2020].

4.2.9 Solar

Solar can be used as an energy source for solar technologies. Similar to wind, its nature is intermittent. Solar energy is obtained from the natural resource the sun. Therefore, solar energy also largely depends on geological location and season [Pareek et al., 2020].

Moreover, solar thermal heat can serve as input for boilers. Solar thermal heat produces hot water from sunlight by the absorption of solar irradiation. Solar energy is captured by solar collectors, of which two main types of collector are used: flat plate and evacuated tube collectors. Subsequently, the solar energy is converted to heat via a heat-transfer fluid, such as propylene glycol. The fluid is often circulated through the system by the use of an electric pump and transfers the heat to a storage cylinder where it is used to produce hot water [Greening and Azapagic, 2014]. Efficiency improvements are required to increase the amount of generated heat, especially in regions with low solar irradiation [Mazhar et al., 2018].

4.2.10 Ambient Heat

Ambient heat can be used as an energy source for individual and collective heat pumps. There are multiple types of ambient heat such as air, ground and water (aquathermal). Therefore, air source heat pumps (ASHP), ground source heat pumps (GSHP) and water source heat pumps (WSHP) are developed. The ASHP absorbs energy from the air, while the GSHP and WSHP absorb energy using a dedicated borehole or network of buried pipes [Fischer and Madani, 2017].

4.2.11 Industrial Waste Heat

Industrial waste heat can be used as an energy source for DH either directly (high-temperature) or via the use of collective heat pumps (low-temperature). According to the principle of the trias energetica, the industry first focuses on saving energy consumption, then on the efficiency of its own energy consumption and finally on internal reuse of own residual heat [RES Noord-Holland Zuid, 2021]. The high-temperature industrial waste heat that is left after this can be used for DH. If the temperature of the industrial waste heat is lower than the temperature level in the DH network, a heat pump is required in order to increase the temperature to the required level [Lund and Persson, 2016]. Industrial waste heat can be available from industry, data centers and other companies. The recovery of industrial waste heat could increase the efficiency of the industrial sector and the DH system in a cost-efficient way while reducing carbon en pollutant emissions [Fang et al., 2013].

4.2.12 Geothermal

Geothermal heat can be used as an energy source for DH. Geothermal energy uses the thermal energy stored in the ground in order to supply heat. Typical geothermal systems consist of heat exchangers, a compression or absorption ground source heat pump and a peak water boiler [Sayegh et al., 2017]. In order to function, the plants are installed in depth of 800–3000 m underground. The temperatures at that depth ranges between 30 and 90 °C with low salt levels. Most research focuses on efficiency improvements and the hybrid use of geothermal heat [Mazhar et al., 2018]. Geothermal heat sources have relatively low efficiency, partly since they are used in indirect heating. Moreover, they are often available at remote areas. Therefore the heat is required to be transported to urban centres, which eventually increases losses. Furthermore, geothermal heat sources require substantial investments due to the drilling and equipment needed [Mazhar et al., 2018].

4.3 DISTRICT HEATING SYSTEMS

In section 4.1 and 4.2, the energy technologies and associated sources of the current and future electricity and heating sector of the built environment are discussed. DH is part of these energy technologies. According to Werner and Frederiksen [2013], the traditional idea of DH is "to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place". DH thus enables energy technologies and sources to be connected to the heat demand via DH networks. All DH systems can be divided into a generation, transmission and distribution side [Mazhar et al., 2018]. At the generation side, one or more DH sources provide heat, with water as the medium of heat transfer. These DH sources are connected to a transmission network of pipes. The transmission network covers the distance to the distribution grid, where the heat is used by end-consumers. The size of a typical DH grid may range from an entire city or region to a housing scheme connected to a few houses. The implementation of a DH network requires the use of the subsoil. Therefore, the use of DH in places with little space in the subsoil (historic city centers) is viewed as unattractive [Mazhar et al., 2018].

4.3.1 District Heating Sources

The main advantage of DH systems is its flexibility in the sources of heat at the generation side [Sayegh et al., 2017; Mazhar et al., 2018]. Different DH sources can be utilized in a common cycle, resulting in a hybrid system. This provides a significant technological advantage and the potentials of further development [Sayegh et al., 2017]. The design of a DH system requires a case-by-case approach in order to fully take advantage of the available local energy. Various decentralized and centralized DH sources can be used for the operation to a DH grid [Mazhar et al., 2018]. These sources for DH are described in the sections above: CHP plants (section 4.1.4), collective boilers (section 4.1.6), collective heat pumps (section 4.1.5), industrial waste heat (section 4.2.11) and geothermal energy (section 4.2.12). By including coupling elements such as CHP plants and heat pumps, DH is involved in the sectoral coupling of the electricity and heating sector [Liu et al., 2016; Mitridati and Pinson, 2016]. Usually DH systems combine RE sources with conventional energy sources and thermal storage [Ericsson and Werner, 2016].

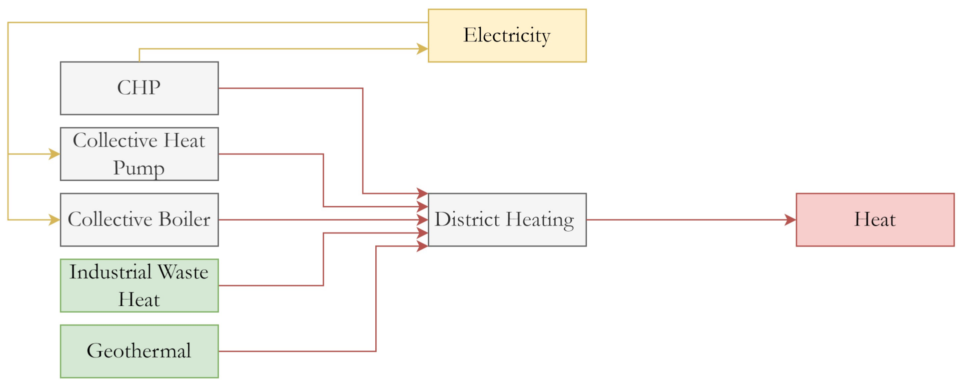


Figure 4.8: System diagram of the interconnections of the district heating technology with other energy technologies, renewable (green) energy sources and supply

It is important to note that the lower the temperature of the DH network is, the more insulation measures are required in connected buildings. DH sources such as CHP plants, high-temperature industrial waste heat and geothermal result in a high-temperature DH network. Low-temperature DH sources such as low-temperature industrial waste heat or ambient heat are often connected to collective heat pumps before connecting to the DH network [Werner and Frederiksen, 2013].

4.3.2 Thermal Storage

Two main gaps between thermal energy demand and supply exist in DH systems. First, a gap is formed caused by the time difference between the generation and consumption of thermal energy. This gap is caused by the integration of unpredictable fluctuating RE sources and by the difference in cost of the thermal energy during the day [Sayegh et al., 2017]. Secondly, a gap exists regarding the distance between the generation plants and the consumers [Guelpa and Verda, 2019]. In order to manage the gaps between thermal energy demand and supply, additional thermal energy storage (TES) systems could be included in the DH system. A TES consists of a storage medium, used to store thermal energy. DH provides several sources of flexibility: the heat of the heat carrier, thermal storage devices and thermal inertia of the buildings connected to the system. TES can serve as a heat source at times of peak demand and as heat sink at times of low demand [Mazhar et al., 2018]. Moreover, TES can be used for long term usages (seasonal storage) in order to store the surplus heat in summer times for transition or winter times, although this is currently relatively inefficient. One of the main barriers for the integration of seasonal storage in urban DH networks is their high investment costs and the connected investment risk considering long payback periods [Köfinger et al., 2018].

Storing heat is much easier and cheaper than storing electricity [Luc et al., 2020]. Due to the potential of heat storage capacity, DH could offer possibilities for increasing the flexibility of the electricity system. Whenever PtH coupling elements, such as collective heat pumps and E-boilers, are involved, electricity can be converted into heat and stored within the TES. Collective heat pumps and E-boilers have different roles within the energy system. Collective heat pumps are expensive, but are less dependent on the electricity price compared to collective E-boilers because of their higher energy efficiency. They must therefore be able to run relatively many hours to recoup the high investment. E-boilers are characterized by a relatively low investment, but are much more sensitive to the electricity price because they have a very low efficiency. This means that an E-boiler is only used during those hours when the electricity price is very low, whenever there is much energy from solar and wind. This is only a limited number of hours on an annual basis [Luc et al., 2020; Kiviluoma and Meibom, 2010].

4.4 CONCLUSION

In this chapter, the characteristics of the various energy technologies and sources result in interconnections between them, which are visualized in the system diagrams. This chapter thus provides an overview of the potential interconnections between energy sources and technologies. The first sub-question *What are possible interconnections between energy sources and technologies of the Dutch electricity and heating sector?* is answered as follows:

Power plants, wind and solar technologies and CHP plants can be interconnected with various energy sources. Therefore, these energy technologies can generate electricity which results in an interconnection between these technologies and electricity supply. CHP plants, heat pumps, boilers and DH systems can also be interconnected with various energy sources. Therefore, these energy technologies can produce heat which results in an interconnection between these technologies and heat supply.

Furthermore, there are also multiple interconnections between the electricity and heating sector, through coupling elements. First, CHP plants supply both electricity and heat and thus can function as a coupling element between these sectors. Moreover, heat pumps demand electricity to produce heat and therefore also function as a coupling element. Third, hydrogen can by used as an energy source for boilers. Green hydrogen can be produced by electricity surpluses generated by wind and solar energy. As hydrogen boilers produce heat, an interconnection can thus be formed between the electricity and heating sector. This is also the case with E-boilers. Lastly, it is important to note that DH systems can use other energy technologies and various energy sources as input. Therefore, some coupling elements can form an interconnection with DH systems. The usage of DH systems in combination with CHP plants, heat pumps and hydrogen/E-boilers thus can increase the interconnections between the electricity and heating sector. Whenever heat pumps and E-boilers are connected to a DH network, a relatively large heat buffer (TES) can be available. Therefore, these coupling elements can increase the flexibility of the electricity supply.

5 TRANSITION OF THE NATIONAL ENERGY SYSTEM

In this chapter, following from Dutch energy policy, the current Dutch electricity and heating sector are mapped on a national scale. Subsequently, an analysis of various scenarios regarding the future Dutch energy system of the built environment for 2050 is provided. The focus is on exploring and comparing the national transition pathways available to the Dutch electricity and heating sector in order to identify scenario trends. Therefore, the second sub-question *How are the Dutch electricity and heating sector expected to transition according to the trends of existing national energy scenarios for 2050?* is answered. These expectations are used to determine the impacts of the transition of DH. The third sub-question *What is the expected impact of the transition to renewable district heating on the Dutch electricity and heating sector according to the trends of existing national energy scenarios for 2050?* is answered. The methods as discussed in chapter 3 are applied.

5.1 NATIONAL ENERGY POLICY

Energy policy is a subset of foreign policy, economic policy, and national and international security policy. Traditionally, the public goals for Dutch energy policy are affordability, reliability and environmental responsibility [Kohl, 2004]. Therefore, the National government aims to design the Dutch energy system in such a way that these goals are achieved. According to the concepts of lock-in and path dependency discussed in section 2.3, energy policy shapes the current and future energy system. Some important developments in energy policy have occurred in order to steer the Dutch transition pathway.

5.1.1 Natural Gas Dependency

Until recently, Dutch energy policy was dominated by natural gas policy, since natural gas has been the leading fuel in the Dutch economy. In the 1960s, the Groningen natural gas field was discovered in the northeast of the Netherlands. This discovery resulted in a large national dependency on low caloric natural gas. Moreover, the Netherlands was an important natural gas supplier in North-West Europe, due to the historic quantities of natural gas in the Dutch sub-soil [Miedema et al., 2018]. In 2005, the Dutch government announced its aim of turning the Netherlands into the 'gas roundabout' of Europe. The gas roundabout refers to "a hub to which gas is transported and then stored for distribution to foreign buyers" [Algemene Rekenkamer, 2012]. With this gas roundabout, the Dutch government wanted to position the Netherlands as a hub at the centre of international gas flows and as the gas distribution centre for northwest Europe. Therefore, the long-term supply of natural gas to the Netherlands could be secured. Moreover, it could strengthen the international competitiveness of the Netherlands and increase employment opportunities [Algemene Rekenkamer, 2012]. However, in 2018 the Dutch government decided to gradually phase out gas extraction as the consequences of gas extraction in Groningen are no longer socially acceptable. Therefore, the Dutch export position has changed into a net dependency on natural gas imports. The dependency on natural gas has led to an infrastructural lock-in of the Dutch energy system, which causes change to be difficult [Miedema et al., 2018]. The current electricity and heating sector are mainly built on an infrastructure dependent on natural gas. The infrastructure includes plants, transmission and storage systems, transport systems and city structures [Vadén et al., 2019].

5.1.2 National Energy Agreement

In 2013, the National Energy Agreement was established with the aim to supply more renewable energy in the Netherlands. Important pillars were the increase of the share of RE sources, energy efficiency improvements and decentralized energy generation. With a share of 4% renewable energy, the Netherlands was lagging behind in Europe. With a successful implementation of the agreement, the Netherlands planned to get back on track, achieve European goals and boost the economy and employment [SER, 2013]. In recent years, governments have provided incentives to support these pillars, such as the SDE subsidy [Pareek et al., 2020].

5.1.3 National Climate Agreement

Currently, the Dutch Government is aiming to achieve substantial carbon emission reductions, in line with the Paris Agreement [UNFCC, 2015], established in 2015. The Dutch Climate Mitigation Act obliges the Netherlands to achieve 49% carbon emission reduction by 2030 and 95% by 2050, compared to 1990. To implement climate measures, the Dutch National Climate Agreement was implemented in 2019 by the Dutch governments. The Dutch National Climate Agreement Agreement builts further on the National Energy Agreement [Rijksoverheid, 2019]. In this agreement, it is stated that the Dutch national government aims for 'no-regret' alternatives, which are alternatives that do not involve hard trade-offs with other policy objectives and are cost-effective now and under a range of future climate scenarios. The national objectives are meant to be achieved by phasing-out fossil energy sources and increasing the share of RES. For electricity supply, wind and solar are stimulated. Furthermore, an integrated national hydrogen system is desired to be realized. The National Climate Agreements states that in the long term (2050), hydrogen will have to fulfill a number of crucial functions in the energy system including adjustable renewable electricity generation, energy storage for longer periods, and energy transport over longer distances.

5.2 CURRENT NATIONAL ELECTRICITY AND HEATING FLOWS

National energy policy as described in the previous section has shaped the current Dutch energy system. In this section, the electricity and heating sector of the built environment are mapped. The year 2019 is considered the base year of this analysis, as this is the most recent year with a complete data set. The energy system of the base year will be referred to as the current energy system.

5.2.1 Interconnections of System Components

In order to present an overview of the current energy system, a system diagram is depicted in figure 5.1, which visualizes the interconnections between the system components and the direction of the energy flows. The colour indication as discussed in section 2.2 is used for all system diagrams.

The current Dutch energy sources are of a conventional (blue) or renewable (green) nature. Fluctuating RE sources, such as wind and solar generate electricity which feeds into the electricity grid (yellow). Moreover, nuclear, coal, natural gas and

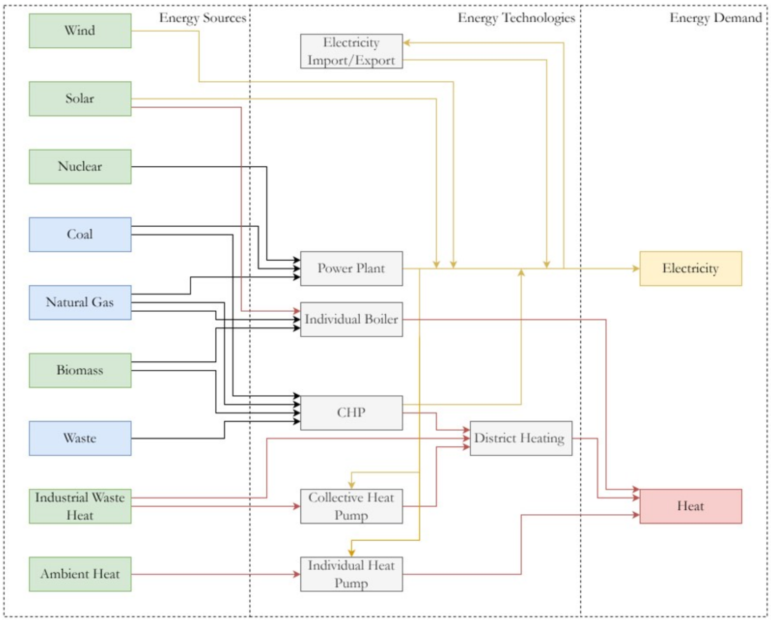


Figure 5.1: System diagram of the interconnections between the system components of the Dutch electricity and heating sector for the built environment in 2019. Data sources: PBL [2020b]; TNO [2020c]; Eurostat [2019]

biomass are energy sources utilized in power plants. Furthermore, coal, natural gas, biomass and waste incineration energy sources are connected to CHP plants, which generate both electricity and usable heat. The electricity feeds into the electricity grid, while the heat is utilized within the DH network, with water as the medium of heat transfer. The generated electricity is used for fulfilling electricity demand, electricity import/export supports in balancing supply and demand. The heat generated by the CHP provides the heat supply for the DH network. Industrial waste heat is either connected to heat pumps or directly connected to the DH network. The DH network eventually provides heat to supply the heat demand. Furthermore, ambient heat is provided to individual heat pumps, which can supply heat to fulfill heat demand. Both types of heat pumps additionally require electricity from the electricity grid. Lastly, natural gas, solar and biomass are used as a source for heat supply via boilers or directly.

5.2.2 Quantified Energy Flows

In order to visualize the energy flows of the system in a quantified manner a sankey diagram is depicted in figure 5.2. It becomes evident that the dependency on natural gas discussed in section 5.1.1 in the current energy system still shows. However, various RE sources are used for both the supply of electricity and heat. The use of RE source is mainly present within the DH system. In every sankey diagram, the vertical red line represents the heat demand, the vertical light blue line represents the electricity demand and the vertical dark blue line represents electricity export.

The final energy supply for electricity in the built environment currently consist largely of natural gas-fired plants with a share of 55%. Furthermore, several sources for electricity are coal, wind, solar, nuclear and biomass, of which coal contributes the most. Besides wind and solar, these sources all generate electricity via power plants. 14% of the supplied electricity is imported. The share of RE sources within the electricity sector of the built environment on a national scale is 19%.

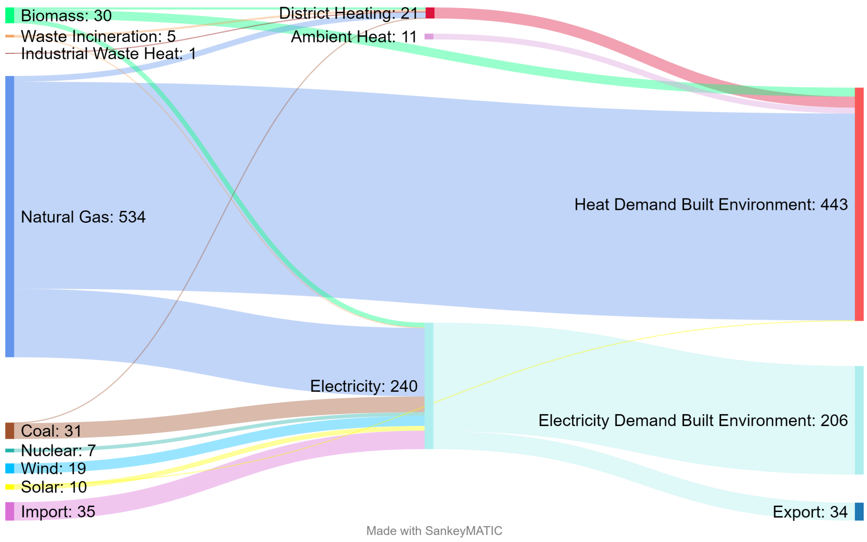


Figure 5.2: Sankey diagram of the energy flows in PJ between the system components of the Dutch electricity and heating sector for the built environment in 2019. Left side represents supply, right side represents demand. Data sources: PBL [2020b]; TNO [2020c]; Eurostat [2019]

The biggest energy source for supplying heat is also natural gas with 89%, provided by individual boilers. Furthermore, DH, biomass, individual heat pumps using ambient heat and solar boilers provide heat. The share of RE sources within the heating sector of the built environment on a national scale is 7,5%.

Multiple sources are used in different amounts for the DH supply, namely natural gas, biomass, waste incineration, coal and industrial waste heat. Natural gas-fired CHP plants are the largest contributor to DH supply with 52%. Moreover, biomass- and waste incineration-fired CHP plants both contribute to the DH supply with 19%. Furthermore, 5% of the DH supply is contributed by coal-fired CHP plants and industrial waste heat (via collective heat pumps). According to TNO [2020c], the data regarding industrial waste heat is not separately publicly available due to the small number of suppliers and unpublished data by CBS. However, TNO [2020c] deduced from the heat labels that in 2018 the contribution of industrial waste heat was approximately 1 PJ. This data is therefore also used for 2019. The share of RE sources within district heating on a national scale is 33,5%.

5.3 FUTURE NATIONAL ENERGY SYSTEM SCENARIOS

Now that the current national energy system is mapped, it is of interest how the future national energy system is expected to function. Therefore, various energy scenarios for 2050 are analyzed derived from scenario reports. The considered energy reports are 'Klimaatneutrale energiescenario's 2050' by Berenschot & Kalavasta [2020] and 'Scenario's voor een Klimaatneutraal Energiesysteem' by TNO [2020b]. The two scenario reports provide an image of the future for the entire Dutch energy system. These reports are chosen specifically for three main reasons. First, they focus on long-term scenarios (2050) for the Netherlands. Second, they are published in 2020 and therefore include the most recent policy, economic and technical developments. Third, these reports are published by independent research groups. The sections below provide a short description of the reports.

5.3.1 Klimaatneutrale Energiescenario's 2050 by Berenschot & Kalavasta (2021)

The report 'Klimaatneutrale Energiescenario's 2050' by Berenschot & Kalavasta [2020] is requested by the Dutch Ministry of Economic Affairs and Climate. This report considers four carbon neutral scenarios for 2050: the Regional, National, European, and International scenario, created within the Energy Transition Model by Quintel [2019]. The scenarios are designed to show the four corners of the energy system playing field, between which development can move in practice. They differ with regard to the scale level at which the Dutch energy transition is mainly managed and how residents and companies respond to this. [Berenschot & Kalavasta, 2020].

5.3.2 Scenario's voor Klimaatneutraal Energiesysteem by TNO (2021)

Moreover, the report 'Scenario's voor Klimaatneutraal Energiesysteem' by TNO [2020b] will be considered in which TNO has created two carbon neutral scenarios: ADAPT and TRANSFORM. The scenarios were used to study the major changes in the Dutch energy system that are required to occur in order to reach the national climate goals for 2050. The difference between the ADAPT and TRANSFORM scenario lies in the difference in intrinsic motivation of residents and companies. In the ADAPT scenario, the Netherlands builds on the current economic strength and decisions are based on protecting and preserving the present lifestyle. In the TRANSFORM scenario, the Netherlands is prepared to drastically change behavior and switch to a clean, energy-efficient economy with new innovative technologies. This causes the Netherlands to become less energy-intensive.

5.4 DRIVING FORCES OF THE SCENARIOS

The qualitative story lines behind the scenarios are studied in order to determine the driving forces for every scenario. Driving forces are the main factors influencing future developments of a system. Main categories of driving forces in environmental scenarios include political, demographic, economic, technological and social-cultural drivers [Alcamo and Henrichs, 2008]. In all scenarios, there are some drivers that are overarching.

- Political driver: achievement of the national climate objectives
- Political driver: closure of all nuclear and coal-fired power stations [1]
- Demographic driver: population growth
- Economic diver: economic growth
- Technological driver: technological development (efficiency improvements and innovation)

5.4.1 Regional Scenario

In this scenario, the Dutch government outsources the governance of the energy transition largely to provinces and municipalities. The objective is to fully decarbonize and become self-sufficient. Provinces and municipalities are given the resources and responsibility to lead the energy transition. The regional authorities take a lot of initiatives to maximize regional potential, but regions are not necessarily autonomous in their energy supply. Due to the regional management, energy projects with large investment costs are less obvious. Because the provinces and

1 The use of nuclear power plants within the national Dutch energy system is currently subject of discussion with the National government. This development is not included within the national scenarios.

municipalities are committed to being self-sufficient, storage is available on a large scale in this scenario. Moreover, due to the regional focus, residents are highly aware of the environment and local initiatives. Residents and companies are actively involved in projects initiated by local government bodies, such as solar PV, collective district heating and geothermal. Moreover, residents and companies are supported by the local government to realize sustainable initiatives, such as home insulation. The pressure from society and regions on the national government to impose strict regulations in terms of sustainability and circularity, will increase [Berenschot & Kalavasta, 2020]. The following driving forces are thus identified:

- Political driver: governance on a local level (provinces and municipalities)
- Political driver: self-sufficient
- Socio-cultural driver: high level of public environmental awareness

5.4.2 National Scenario

In this scenario, the national government takes the lead. Objectives are to achieve high levels of self-sufficiency, sustainability and circularity. A result of this is a decrease in the number of small-scale initiatives that are initiated by residents and companies. A clear climate-neutral vision up to 2050 will enable large-scale projects to be realized in which the national government covers the risks. This will lead to projects with high start-up costs, such as large-scale offshore wind and a national hydrogen infrastructure. This has major implications for the spatial policy of provinces and municipalities. The construction of large-scale onshore and offshore wind farms and solar farms are examples of measures that can have a significant spatial impact [Berenschot & Kalavasta, 2020]. The following driving forces are thus identified:

- Political driver: governance on a national level
- Political driver: high level of self-sufficiency
- Economic driver: national government covers risks of large-scale projects

5.4.3 European Scenario

In this scenario, the focus lies more on European governance, which is a political driver. A CO2 tax will be introduced on a European scale. This tax concerns all sectors and therefore goes beyond the current ETS, which is only for energy-intensive industry and electricity producers. The CO2 tax will increase progressively towards 2050. The speed of the energy transition is therefore directly correlated with the increase in the CO2 tax and the availability and price of renewable alternatives. Europe supports its own industries and mutual solidarity between countries is high. This strengthens the pentalateral electricity market. The Netherlands will import energy from abroad, with a preference for renewable energy of European origin. Projects and initiatives will only come about if this can be substantiated by a positive business case. Hydrogen in combination with CCS plays a role in resolving electricity imbalances [Berenschot & Kalavasta, 2020]. The following driving forces are thus identified:

- Political driver: governance on an European level
- Political driver: dependent on imported energy
- Economic driver: European CO2 tax
- Economic driver: open European energy market (electricity, hydrogen, biomass)

5.4.4 International Scenario

This scenario is based on a fully open international energy market at global level, with a strong climate policy being pursued. The Netherlands is not self-sufficient and thus dependent on imports. There will be strong international collaborations and no import tariffs, quotas or other measures in place inside or outside Europe that could hinder trade. Therefore, there will be an advanced international infrastructure (within Europe) for the exchange of energy carriers. The Netherlands will have infrastructures with strategic reserves to enable the transport and storage of various renewable energy carriers in very large volumes, such as biomass and hydrogen. The Netherlands focuses on its knowledge economy. The technologies developed here can be used abroad and therefore the Netherlands exports knowledge and imports renewable energy carriers on a large scale. Renewable energy is generated on a large scale at techno-economically strategic locations worldwide. Within the Netherlands, this means that offshore wind will mainly be realized. Outside the Netherlands, for example, this results in large-scale solar farms and/or biomass production in sparsely populated areas. Hydrogen in combination with CCS plays a role in resolving electricity imbalances [Berenschot & Kalavasta, 2020]. The following driving forces are thus identified:

- Political driver: governance on a global level
- Political driver: dependent on imported energy
- Economic driver: fully open international energy market (electricity, hydrogen, biomass)

5.4.5 ADAPT Scenario

In this scenario, the Netherlands is building on its current strengths. There is a conservative attitude. For decades, oil, coal and gas have provided a strong industry, a strong transport and logistics sector, a reliable electricity supply and comfortably heated houses. As residents opt for security, sustainability is considered less important. Therefore, the current system is adapted and optimized. National and local governments take the lead and guide residents and companies with concrete policy measures. In this scenario, there are no major social objections to use of fossil fuels in combination with CCS. Also, import of biomass is socially accepted [TNO, 2020b]. The following driving forces are thus identified:

- Political driver: governance on a local and national level
- Socio-cultural driver: conservative attitude
- Socio-cultural driver: medium level of public environmental awareness

5.4.6 TRANSFORM Scenario

In this scenario, the Netherlands and Europe are leading the way in the transition to a renewable energy system. There is a progressive attitude and a high level of awareness. The awareness of the residents regarding their energy use and their CO_2 footprint leads to behavioral change and all kinds of sustainable initiatives, which are supported by the local governments. The Netherlands has a strong knowledge infrastructure and innovative businesses. Because residents being more environmentally aware and acting accordingly, the energy demand decreases. Companies are also taking initiatives to an ambitious transformation by replacing existing processes with sustainable alternatives. There is no public support for CCS and the import of biomass stays limited [TNO, 2020b]. The following driving forces are thus identified:

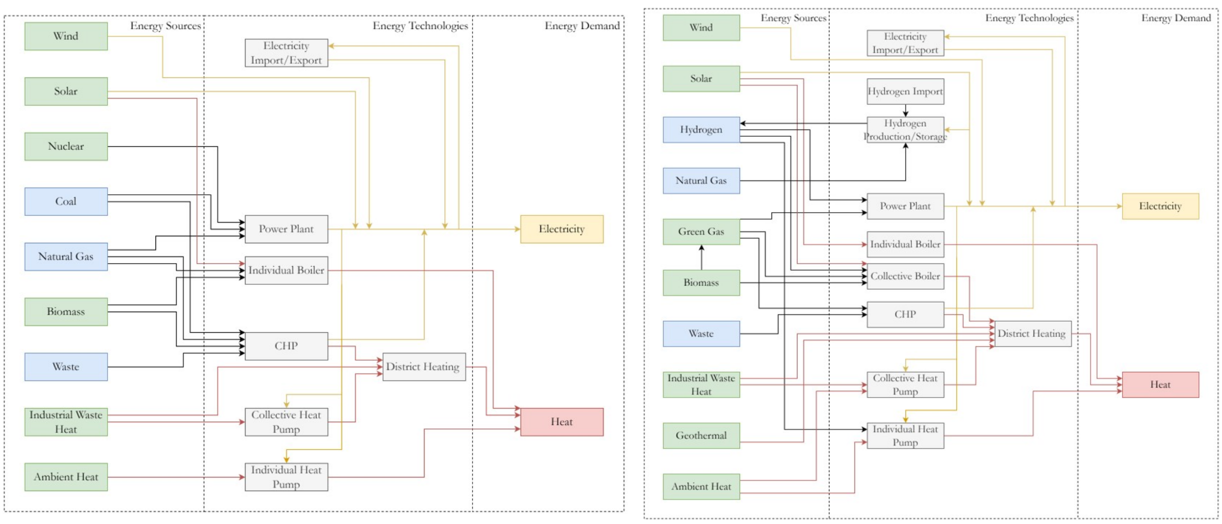
- Political driver: governance on a local, national and European level
- Socio-cultural driver: progressive attitude
- Socio-cultural driver: high level of public environmental awareness

5.5 TREND IDENTIFICATION

The driving forces of the scenarios addressed in section 5.4 shape the structure of the scenario's energy systems. In this section, the current energy system (base case) discussed in section 5.2 is compared with the energy systems of the six scenarios. Resulting from this comparison, various scenario trends are identified. The scope of the scenarios from the reports includes the total energy demand of the Dutch energy system. However, the scope of this scenario analysis is the heat and electricity demand of the built environment specifically (see section 3.1.1).

5.5.1 Energy Systems of the Scenarios

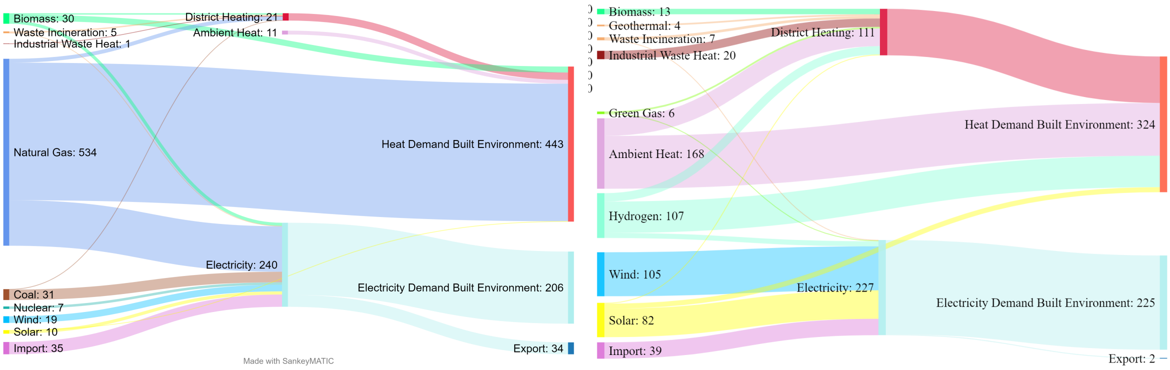
The energy systems of the scenarios are presented both in terms of the interconnection of system components and quantified energy flows in appendix A. Figure 5.3 shows the comparison between the system diagrams of the current energy system (base case) and the international scenario energy system. This comparison is chosen as an example, as this scenario also includes all interconnections that are included in the the other scenarios. Only the connection between green gas and individual heat pumps is not included in this scenario. The figure illustrates that major system changes can be required for a future decarbonized energy system. Figure 5.4 shows the comparison between the sankey diagrams of the current energy system and the international scenario energy system. This figure illustrates the major differences between the two energy systems in terms of quantified energy flows. By comparing the diagrams of all of the scenarios with the base case and among each other, certain trends can be determined. The following sections will elaborate on the identified trends regarding final energy demand, electricity supply, heat supply and DH supply.



(a) Base Case (2019)

(b) Future International Scenario (2050)

Figure 5.3: System diagrams of the interconnections between the system components of the Dutch electricity and heating sector for the built environment in the base case and international scenario for 2050



(a) Base Case (2019) **(b)** Future International Scenario (2050)

Figure 5.4: Sankey diagrams of the energy flows in PJ between the system components of the Dutch electricity and heating sector for the built environment in the base case and international scenario for 2050. Left side of each diagram represents supply, right side represents demand.

5.5.2 Final Energy Demand

The diagrams of the scenarios as presented in appendix A show clear trends with regard to the energy demand of the built environment. Both the total final energy and the heat demand are lower for all scenarios compared to the current energy system and thus decrease. Moreover, the final electricity demand for the built environment is higher in all scenarios and thus increases. Figure 5.5 presents the final energy, electricity and heating demand for the base case and the scenarios.

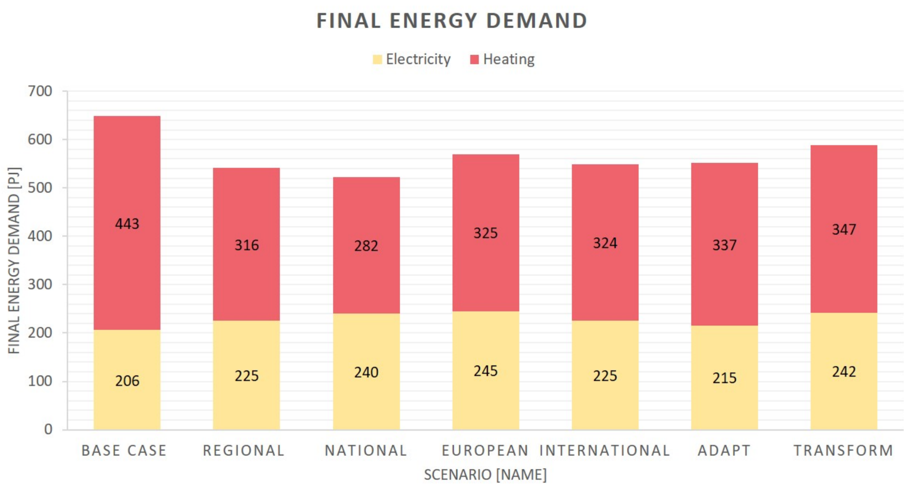


Figure 5.5: Final energy demand of the built environment in the base case (2019) and scenarios (2050)

The identified trends regarding the final energy demand in 2050 are summarized below:

- Decrease in the final energy demand
- Increase in the final electricity demand
- Decrease in the final heat demand

Reflection

The expected decrease of the final energy demand can be explained by technological development such as efficiency improvements. Currently, energy efficiency measures are increasingly promoted by policy makers and environmental associations [Ebrahimigharehbaghi et al., 2019]. The past years, a decrease in energy demand of the Dutch built environment has been observed by CBS [2019a]. The expected decrease is thus plausible. The level of public environmental awareness can also play a role in this [Steg et al., 2018]. However, unexpectedly the scenarios which are driven by a high level of public environmental awareness, do not experience the largest decrease in energy demand. This can be the result of other contextual factors, such as institutional arrangements and access to technology, products, services [Steg et al., 2018]. The decrease in heating demand can be explained by the electrification of the heating sector through the implementation of large-scale electric heating alternatives, which explains the increase of the electricity demand. The scenarios all assume the electricity grid to have sufficient capacity for the increased electricity demand and associated supply. However, upgrading the grid causes challenges regarding investments and planning [Netbeheer Nederland, 2019].

5.5.3 Energy Sources for Electricity Supply

The energy sources used for electricity supply vary per scenario. Figure 5.6 presents the energy sources for electricity supply for the base case and for every scenario. An important trend is the decrease of natural gas-fired plants. Only in the ADAPT and TRANSFORM scenario these plants still contribute a little to the electricity supply. Besides the reduction in the use of natural gas, the elimination of coal and biomass power and CHP plants and nuclear power plants is a trend in all scenarios. Lastly, the scenarios vary heavily with regard to the imported electricity.

The electricity supply gap that emerges due to these trends is filled by renewable sources, especially wind and solar. Both of these sources experience a significant increase in all scenarios. Therefore, the scenarios show a unanimous expectation for the functioning of wind and solar as backbone for the future electricity supply. In five out of six scenarios, the contribution of solar to the electricity supply is larger then the contribution of wind. This is mainly due to the large expected increase in decentralized solar PV installations in the built environment, as depicted in figure 5.7. Moreover, some scenarios additionally expect waste incineration, green gas and hydrogen to contribute to the electricity supply. These contributions are relatively insignificant in terms of percentages. However they do affect the system's interconnections. Two scenarios (regional & national) involve green hydrogen as a relatively small source for electricity generation and storage. The hydrogen is produced with electricity surpluses. One scenario (international) involves blue hydrogen as a source for electricity generation and storage, in which the hydrogen is produced mainly from natural gas in combination with CCS. The identified trends regarding energy sources for electricity supply in 2050 are summarized below:

- Large decrease in the contribution of natural gas fired power and CHP plants to the electricity supply
- Elimination of coal and biomass power and CHP plants and nuclear power plants as a source for electricity supply
- Increase in the contribution of wind and solar to the electricity supply, especially decentralized solar
- Additional electricity supply through waste incineration and green gas CHP plants, hydrogen power plants and import, in order to compensate imbalances

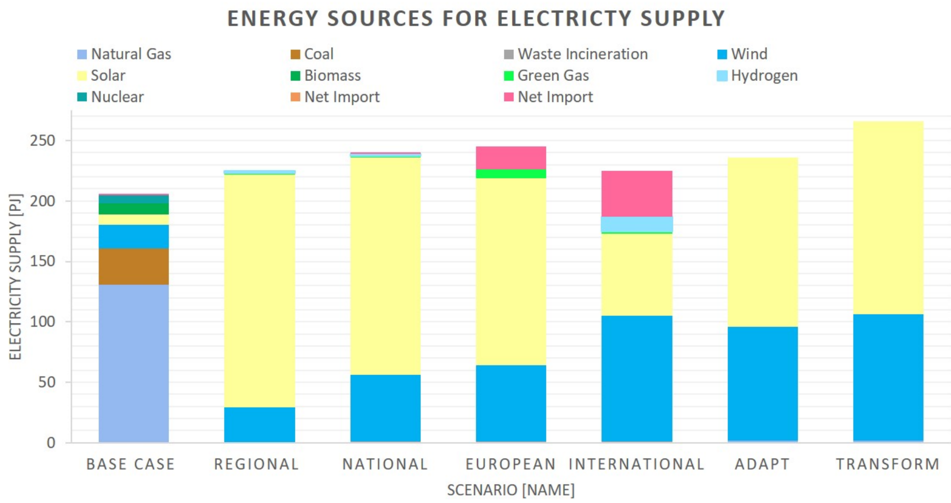


Figure 5.6: Mix of energy sources for electricity supply in the base case (2019) and scenarios (2050)

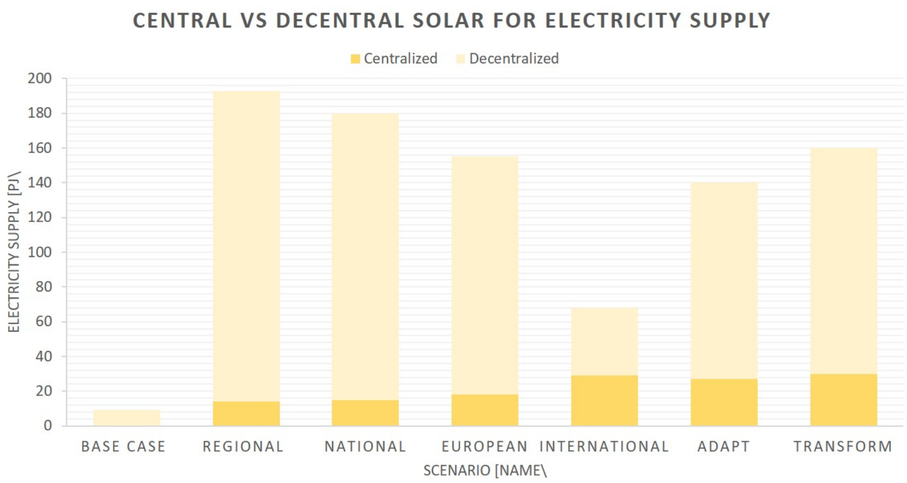


Figure 5.7: Centralized and decentralized solar energy for electricity supply in the base case (2019) and scenarios (2050)

Reflection

The scenarios all expect electricity generation through fossil fuels and biomass to be phased out. The elimination of biomass plants can by caused by the lack of public support regarding the use of biomass [PBL, 2020a]. Even scenarios assuming a low/medium level of public environmental awareness, eliminate biomass as an electricity supply source. The large decrease in the contribution of natural gas plants to the electricity supply and the elimination of coal and nuclear energy plants are explained by the political driver of all scenarios to achieve the national climate objectives [Rijksoverheid, 2019].

This also explains the increase in the contribution of wind, solar, green gas, and hydrogen to the electricity supply. These future sources all have challenges as discussed in section 4.1. Taken this into account, the expected necessary wind and solar capacities are remarkable. A minimum of 10 GW onshore and 27,5 GW offshore wind capacity is expected. As in the base case this capacity is approximately 3,5 GW and 1 GW respectively this seems like quite a challenge [CBS, 2019b]. Especially, considering that national wind capacity objectives of 2020 were not achieved

[RVO, 2020]. Moreover, solar energy is mainly expected to generate electricity in a decentralized manner and the minimum contribution is expected to increase about fourfold. The international scenario expects solar to be a less important contributor, as a driver is a fully open international market at global level. Therefore, RE is generated on a large scale at techno-economically strategic locations. Within the Netherlands, this means that solar panels are not attractive to install, while offshore wind farms are [MacKay, 2013]. In other scenarios the solar increase leads up to 18 times the current capacity. This raises questions considering the feasibility of the required solar panel capacity. The increase of solar can be explained by the high environmental awareness of residents, which may stimulate homeowners to install solar panels. The expected contribution of decentralized solar is even high in scenarios in which a conservative attitude and a low level of public awareness is assumed. In this case homeowners can still be stimulated due to financial benefits. Currently, the 'salderingsregeling' is in place, which stimulates homeowners to implement solar panels. This regulation causes small scale consumers to receive benefits on their energy bills [Rijksoverheid, 2020]. Lastly, the scenarios all assume a well functioning electricity grid. However, the increased integration of fluctuating RE sources can cause challenges for electricity grid operators [Netbeheer Nederland, 2019].

Interestingly, it becomes evident that there is variation in the manner in which to provide flexibility in the electricity system. The options are limited to batteries, green gas, hydrogen and import. The variation in additional electricity supply sources is partly explained by the level of openness of the energy markets. Resulting from this, an advanced international infrastructure for the exchange of energy carriers (hydrogen, biomass, electricity) is needed, which brings along challenges. According to the IEA [2021] "Attaining hydrogen strategy targets will necessitate much faster hydrogen transmission development". Moreover, the need for imported energy increases the dependency on other countries, which could jeopardize the energy security of supply. The extent to which the import of energy is possible, is very dependent on how other countries design their future energy system. A risk occurs when other countries are not able or willing to export energy for a fair price (or not at all), while the Dutch energy supply can not fulfill demand [Escribano Francés et al., 2013]. Considering the fact that batteries, hydrogen and green gas are currently not implemented on a large scale, the dependency on imported electricity could increase.

5.5.4 Energy Sources for Heat Supply

Figure 5.8 presents the energy sources for heat supply for the base case and for every scenario. Up until now, the scenarios were quite consentient regarding the identified trends. However, regarding the sources for heat supply, they vary more. Again, an important trend is the decrease of natural gas, here in individual boilers. Only in the ADAPT and TRANSFORM scenario these individual boilers still contribute a little to the heat supply. Regarding the use of biomass as a source for heat supply the scenarios vary. Four scenarios report an elimination of biomass, while two scenarios expect an increase for 2050.

The heat supply gap that emerges mainly due to the decrease in natural gas use in individual boilers, is filled by several renewable sources. A clear trend is identified regarding the use of DH networks for heat supply. In the base case the contribution of DH is 5%, while all scenarios notably expect a large increase in the use of DH, ranging from 34% to 56%. Moreover, such a trend can also be identified for the use of ambient heat in individual heat pumps. In the base case, individual heat pumps using ambient heat account for a share of 2%. However, in all scenarios, the contribution of individual heat pumps using ambient heat increases, ranging from 21% to 51%. DH and ambient heat are the most important heat sources in all scenarios and seem to substitute each other. Whenever the share of DH is lower, the share of ambient heat is higher and vice versa. Moreover, some scenarios additionally expect green gas, biomass, natural gas and hydrogen through individual boilers and hybrid heat pumps to contribute to the heat supply. These contributions are relatively lower in terms of percentages. However they do affect the system's interconnections.

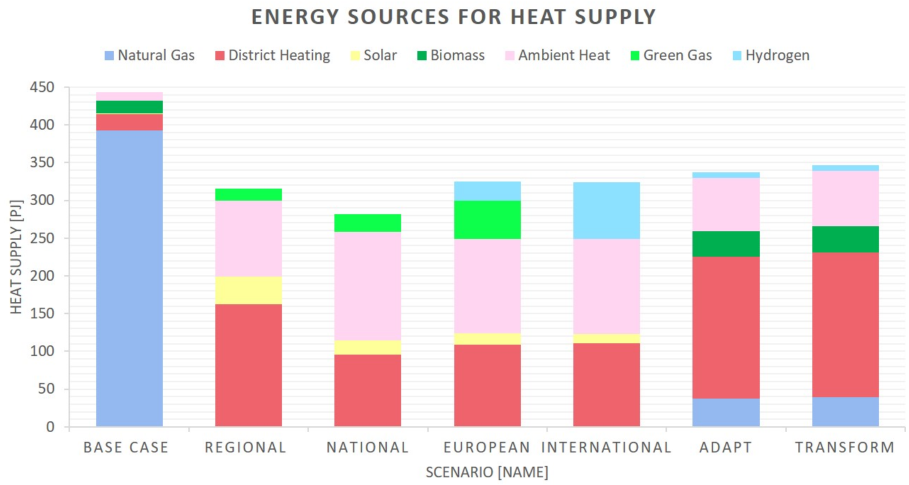


Figure 5.8: Mix of energy sources for heat supply in the base case (2019) and scenarios (2050)

The identified trends regarding energy sources for heat supply in 2050 are summarized below:

- Large decrease in the contribution of natural gas fired individual boilers to the heat supply
- Increase in the contribution of DH and individual heat pumps using ambient heat to the heat supply
- Additional heat supply by natural gas, green gas, hydrogen and solar through individual boilers and heat pumps and direct combustion of biomass

Reflection

Regarding heat supply, there is consent between the scenarios with regard to what must be eliminated, namely fossil fuels and especially natural gas. The large decrease in these sources can be explained by the political driver in all scenarios to achieve the national climate objectives [Rijksoverheid, 2019]. In order to substitute these sources, mainly an increase in the contribution of DH and individual heat pumps is expected. Interestingly, the combination of these two alternatives has the largest contribution to the heat supply in every scenario, despite their different assumptions. According to the scenario reports, there are places where DH networks are less obvious, such as with newly constructed buildings and buildings in areas with a lower housing density. In those cases electric individual heat pumps using ambient heat will provide households with heat. The ratio in which these two main alternatives contribute varies. In the regional, ADAPT and TRANSFORM scenario, the share of DH is the highest. In these scenarios, a political driver is the local governance of the energy system, which causes DH networks to be realized. However, the capacity for DH is not only dependent on the governance level, but naturally also on available DH sources, as discussed in section 4.3.

Moreover, other expected heat sources are hydrogen, green gas and biomass. The variation in these sources is partly explained by the level of openness of the energy markets. Therefore, part of the hydrogen and biomass required for the production of green gas is imported, which increases the dependency on other countries. The associated challenges were mentioned before. Interestingly, green gas and biomass are both included in scenarios that assume a high level of public environmental awareness. Therefore, a contradiction can be identified. As discussed in section 4.2, recent debates regarding the use of biomass as a renewable energy source point to a lack of public support [PBL, 2020a]. Since green gas is produced from biomass, the same lack of public support may be applicable. Therefore, the use of these sources in these specific scenarios is improvident and can cause for public disapproval.

5.5.5 Energy Sources for District Heating Supply

Figure 5.9 presents the energy sources for DH supply for the base case and for every scenario. It could be derived from this graph that the scenarios are the least unanimous with regard to the sources for DH supply. However, a clear trend is identified again regarding the decrease in natural gas CHP plants. In the base case, more than half of the DH supply is fulfilled by natural gas CHP plants. In all scenarios, the use of natural gas as a DH source is eliminated. Moreover, all coal-fired CHP plants are also eliminated.

The DH supply gap that emerges is expected to be filled by several renewable sources. However, clear trends are hard to identify as the energy sources for DH supply vary a lot. Two of the scenarios (ADAPT & TRANSFORM) expect the entire DH supply to be delivered by industrial waste heat. Moreover, the remaining scenarios provide a mix of geothermal, green gas, ambient heat, biomass, hydrogen, industrial waste heat and waste incineration. Green gas and waste incineration are connected to CHP plants. Green gas, solar, biomass and hydrogen are connected to collective boilers. Ambient heat and industrial waste heat are partly connected to collective heat pumps. In these scenarios a trend in the use of geothermal and collective heat pumps using ambient heat is identified. As either geothermal or collective heat pumps using ambient heat are the most important heat sources in these scenarios, they seem to substitute each other. The contribution of green gas in collective boilers can also be significant in these scenarios.

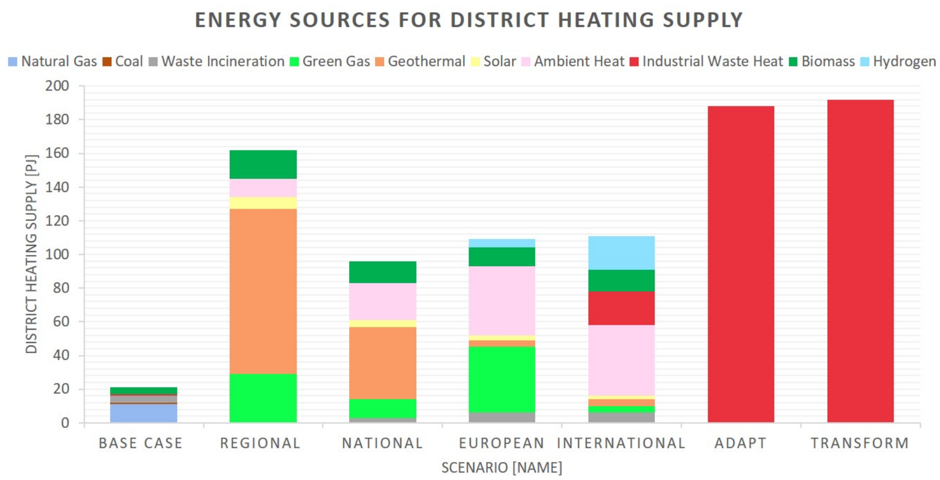


Figure 5.9: Mix of energy sources for district heating supply in the base case (2019) and scenarios (2050)

The identified trends regarding the energy sources district heating supply for 2050 are summarized below:

- Elimination of natural gas and coal CHP plants as a DH source
- Increase in the contribution of geothermal, hydrogen/solar/biomass/green gas-fired collective boilers, industrial waste heat/ambient heat collective heat pumps and green gas/waste incineration CHPs to the DH supply
- Large variation in renewable DH sources per scenario

Reflection

The elimination of natural gas and coal CHP plants from the DH supply is again explained by the political driver in all scenarios to achieve the national climate objectives [Rijksoverheid, 2019]. Therefore, fossil fuels need to be decreased and the share of RE sources increased. This explains the increase in the contribution of RE sources to the DH supply. The large variation in DH sources is explained by multiple driving forces.

First, the use of hydrogen, biomass and green gas can be partly explained again by the level of openness of the energy markets. These sources are partly imported as a DH source in all of the scenarios that use them, resulting in a dependency on other countries. Moreover, green gas and biomass are again included in scenarios that assume a high level of public environmental awareness. Therefore, the same line of reasoning regarding public disapproval is applicable here. Furthermore, it is assumed in the scenarios that local governments will undertake action and search for locally available DH sources, such as geothermal, to make heat available to their residents. This explains the high share of geothermal in the regional scenario. Additionally, it was assumed that municipalities jointly realize larger-scale heat networks, in order for municipalities with less geothermal potential to have sufficient available heat. These larger-scale heat networks also explain the high share of geothermal in the national scenario, in which the national government takes the lead and supports large-scale projects. Lastly, the use of industrial waste heat is prominent in the ADAPT and TRANSFORM scenario and present in the international scenario. It is not evident from the scenario reports which driving force plays a role with regards to this, as industrial waste heat can be viewed as a local heat source. Therefore, it is surprising that this source is not involved in the scenarios in which geothermal also plays a role.

The assumption that the possibilities of DH sources such as geothermal and industrial waste heat are explored, does not mean that these DH sources are actually available and achievable. This notion is strengthened by the fact that the transportation of heat over long distances is very inefficient [Mazhar et al., 2018]. There is still a lot of uncertainty regarding the availability of geothermal and industrial waste heat in the right areas [Milieucentraal, 2020]. Therefore, the scenarios that expect a large contribution of geothermal and industrial waste heat can be viewed as uncertain.

5.5.6 Overall Reflection

The current energy system is compared with the energy systems of the six scenarios and many trends are determined and reflected upon. The scenarios all are driven by different forces as discussed in section 5.4. However, they all have the same aim: to achieve the national climate objectives as discussed in section 5.1.3. First of all, from the analysis it becomes evident that major changes in the entire energy system are necessary in order to achieve these national climate objectives. From the scenario funnel discussed in section 2.3.1, it became evident that the Dutch transition pathway is impacted by disruptive events and decision points. As unexpected events can occur and decisions need to be made (often cooperatively), the scenarios and their assumptions thus bring along much uncertainty. Naturally, the questions arise if the Dutch energy system is able to implement the necessary changes in time or even at all, and what the future Dutch energy system will look like.

5.6 INTERCONNECTIONS BETWEEN ELECTRICITY AND HEAT

The current and future energy systems have been analyzed with regard to their electricity and heat sources. In this section, the focus lies on the interconnections between electricity and heat. Several coupling elements can be identified that form interconnections. These interconnections experience a transition along with the energy system.

5.6.1 National Coupling Elements

In the current national energy system, the three following specific interconnections are identified:

- Individual heat pumps function as a coupling element between heat supply and electricity demand.
- CHP plants function as a coupling element between heat supply and electricity supply. The heat is delivered via DH networks.
- Collective heat pumps function as a coupling element between heat supply and electricity demand. The heat is delivered via DH networks.

In the future national energy system, the same coupling elements as included in the current energy system are expected to play a role. However, one additional coupling element is included:

- Collective hydrogen boilers function as a coupling element between heat supply and electricity demand. The heat is delivered via DH networks.

The first coupling element, the individual heat pump, supplies heat while to a certain extent competing with DH. These heat pumps use ambient heat and demand electricity to function. It is expected that in the future, hybrid heat pumps can be used using green gas and hydrogen. Section 4.1.5 noted that the COP of air-, water- and ground-source heat pumps currently ranges from 2 to 5. Therefore, a current average COP of 3.5 is assumed. For future energy systems, an average COP of 4 is assumed according to Quintel [2019].

Furthermore, the second coupling element, the CHP plant, supplies heat via the DH system. The CHP plant is the only coupling element that also contributes to the electricity supply, both in the current and future energy system. Currently, CHP plants use natural gas, biomass, waste incineration and coal. In the future energy system, green gas and waste incineration CHP plants are expected to contribute.

Moreover, the third coupling element, the collective heat pump, supplies heat via the DH system. In the current system, the collective heat pump uses a small amount of low-temperature industrial waste heat to supply heat via the DH system. In the future energy system, heat pumps are expected to be used in combination with low-temperature industrial waste heat and ambient heat. Collective heat pumps require electricity input. For collective heat pumps using ambient heat, the same average COPs are assumed as with an individual heat pump (current average COP of 3.5 and future average COP of 4). Moreover, for collective heat pumps using industrial waste heat, a current average COP of 3.7 and a future average COP of 4.2 were assumed, based on a research regarding the use of low-temperature industrial waste heat from datacenters [Pärssinen et al., 2019]. For collective heat pumps using low-temperature industrial waste heat a higher COP is thus assumed. As the temperature of low-temperature industrial waste heat is expected to be higher, the temperature difference between the waste heat source and the user is lower.

Lastly, in future energy systems, collective hydrogen boilers are able to supply heat via the DH system. As discussed in section 4.1.7, an average electrolysis efficiency of 66% is assumed. Therefore, the electricity demanded from collective hydrogen boilers can be excessively high.

5.6.2 Quantified Interconnections

Figures 5.10, 5.11 and 5.12 compare the contributions of the coupling elements for the base case and the scenarios to the heat supply, electricity demand and electricity supply respectively.

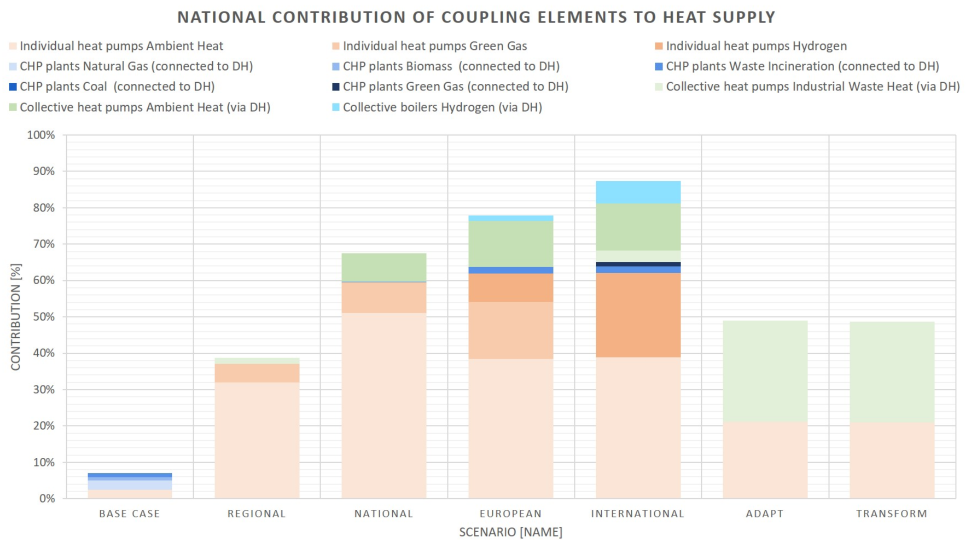


Figure 5.10: National contribution of coupling elements to the heat supply for the built environment

Figure 5.10 shows that currently, the contribution of coupling elements to the heat supply is relatively small. This is mainly caused by individual natural gas boilers being the dominant source for heat supply. All scenarios expect the contribution of the coupling elements to the heat supply to increase substantially, as a minimum sixfold increase is observed. This observation confirms that in the future, an increased IES approach is expected to be taken in order to achieve climate objectives, as discussed in section 2.2.1. In the most extreme scenario, almost 90% of the heat supply technologies are connected to the electricity sector. Mainly, individual heat pumps (orange colours) and collective heat pumps (green colours) contribute to this. It is noteworthy that in all scenarios, the individual heat pump using ambient heat is expected to contribute significantly.

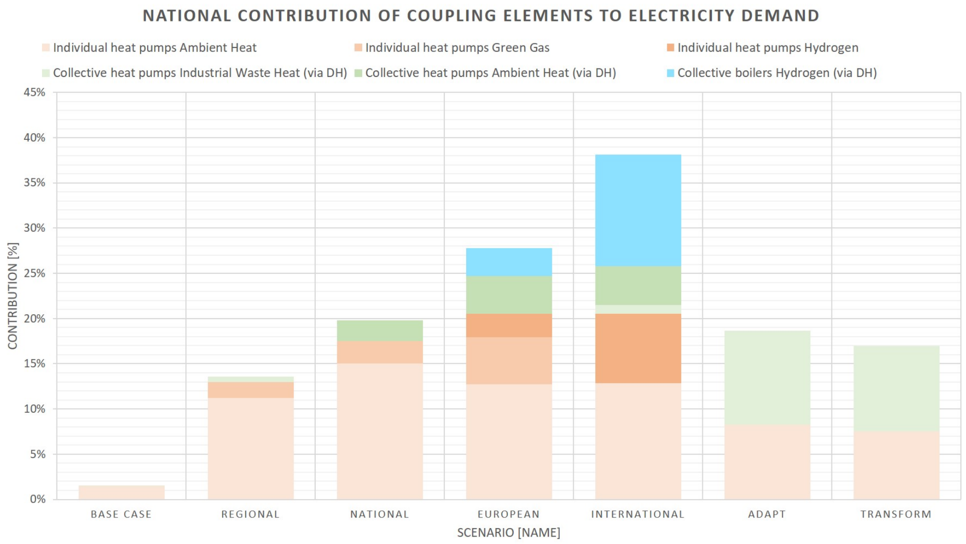


Figure 5.11: National contribution of coupling elements to the electricity demand for the built environment

From figure 5.11 it can be derived that all scenarios expect the contribution of the coupling elements to the electricity demand to increase substantially. Here, the increase is expected to be minimally ninefold, indicating an increased electrification of the heat sector. Again, the contribution of individual heat pumps (orange colours) and collective heat pumps (green colours) is noticeable. Note that the collective heat pumps (green colours) and collective boilers (bright blue colour) are connected to the DH network. In the most extreme scenario, almost 40% of the electricity is demanded by coupling elements delivering heat. In this scenario, individual hydrogen boilers (bright blue colour) are mainly responsible for this electricity demand. This is caused by the efficiency of the electrolysers to convert electricity into hydrogen. The conversion of electricity into hydrogen and hydrogen into heat causes a lot of energy to be lost and therefore is quite inefficient.

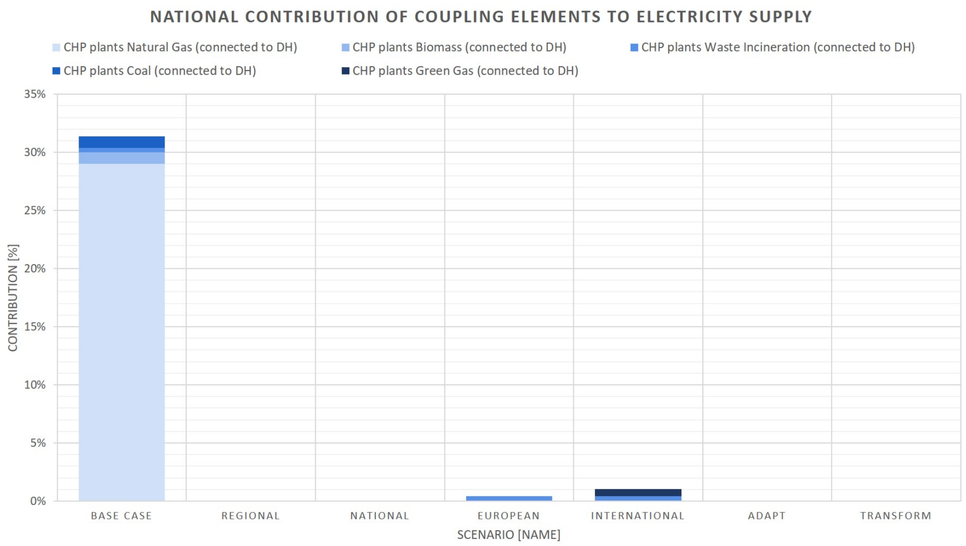


Figure 5.12: National contribution of coupling elements to the electricity supply for the built environment

From figure 5.12 it becomes evident that the contribution of the coupling elements to the electricity supply is expected to decrease extremely. Currently, CHP plants (blue colours) supply more than one third of the total electricity supply. The decrease is mainly caused by the expected elimination of natural gas-fired CHP plants. Two scenarios expect CHP plants using waste or green gas to play a minor role in the future electricity supply. However, this contribution is almost negligible to the current electricity supply by CHPs.

Overall, it can thus be concluded that the contribution of coupling elements to the heat supply and electricity demand is expected to increase greatly, while the contribution to the electricity supply is expected to decrease to almost 0%. Therefore, the heating system transitions from a system that has a connection with electricity supply, to a system that is largely connected with electricity demand.

5.7 CONCLUSION

5.7.1 National Energy Transition

In this chapter, the second sub-question *How are the Dutch electricity and heating sector expected to develop according to the trends of existing national energy scenarios for 2050?* is answered as follows:

The current national energy system is primarily based on natural gas. Mainly natural gas-fired power plants supply electricity, while mainly individual natural gas boilers supply heat. Therefore, the system is currently experiencing an infrastructural natural gas lock-in. This lock-in complicates the transition to a renewable future energy system. An analysis of six scenarios for the Dutch national energy system of 2050 resulted in several trends regarding energy demand, electricity supply, heat supply and DH supply. The scenarios were all based on the same political driver: to achieve the national climate objectives. Additionally, the scenarios varied with regard to the governance level of the energy transition, the level of self-sufficiency and the level of public environmental awareness.

Overall, there is much consent in the scenarios with regard to wind and solar energy being the backbone of the electricity supply. Moreover, the results indicate a potential role for hydrogen, green gas and imported electricity as means for providing flexibility. However, there are still challenges with regard to the realization of a fully renewable electricity supply. Enormous wind and solar capacities need to be realized, most of the flexibility alternatives are not fully developed yet and the electricity grid is required to be adapted.

On the contrary, the scenarios show a great deviation in renewable heating alternatives. However, all scenarios include large supplies of DH and individual heat pumps. The preference for DH seems to be driven by a local governance level and high levels of self-sufficiency and public awareness. Sources for DH vary greatly per scenario and are quite uncertain. The deviation and uncertainty indicates that there is still dubiety regarding how to realize the heat transition and regarding its feasibility.

5.7.2 National District Heating Transition

Subsequently, the third sub-question *What is the impact of the transition to renewable district heating on the Dutch electricity and heating sector according to the trends of existing national energy scenarios for 2050?* is answered as follows:

Impact on the Heating Sector

- Increased DH supply: As the contribution of renewable DH to the heat supply is expected to increase, current sources for heating can be substituted. While DH is currently a minor contributor to the heat supply (5%), it is expected that DH will become one of the, if not the most, important heating alternatives (34-56%). The increased contribution of renewable DH causes a shift away from the currently dominant natural gas-fired individual boilers.

- Competition with other heating alternatives: The remainder of the heat supply can be delivered by a large variety of other heating alternatives, with which DH competes to a certain extent. The main alternative to DH is expected to be (hybrid) individual heat pumps using hydrogen or green gas. Individual green gas/solar/natural gas boilers or direct biomass combustion can supply heat in cases in which both DH and individual heat pumps are not feasible alternatives.

- Varying and uncertain DH sources: DH sources are expected to shift from mainly natural gas-fired CHP plants to renewable alternatives. A wide variety of future DH sources is presented in the scenarios. It can be derived that CHP plants are eliminated as the most important DH source. Geothermal, green gas/biomass/hydrogen/solar collective boilers and industrial waste heat/ambient heat collective heat pumps are mentioned as substitutes. As the DH supply is expected to increase substantially, the supply balances of some of these specific sources can be very ambitious. None of the expected future sources are currently applied on a large-scale and their potential is yet to be explored.

Impact on the Electricity Sector

- Increased electricity demand: The increased contribution of renewable DH can cause for increased electricity demand, due to the increase in collective heat pumps and hydrogen boilers. However, since the expected contribution of the interconnections are based on diverging scenarios, there is much variety in the value of the increase. Furthermore, the main alternative for DH, individual heat pumps, require electricity. Therefore, DH can limit the electricity demanded by the individual heat pump to a certain extent by competing. Overall, it can be stated that it is expected that the future heating sector will demand more electricity than in the current energy system. This is one of the causes for the electrification of the future energy system. It depends on the used DH sources if this is also the case for DH specifically.

- Decreased electricity supply: In the current system, the natural gas-fired CHP plant is the largest coupling element and contributor to both the DH and electricity supply. As these plants are expected to be mostly eliminated, a gap will appear in the electricity supply. In the future energy system, green gas and waste incineration CHPs can have a small contribution to the DH supply. However, the electricity generated by these CHP plants is not expected to be sufficient to substitute the eliminated fossil-fired CHP plants from the current energy system. Therefore, the interconnection between DH supply and electricity supply is expected to decrease.

5.7.3 Overall Conclusion

The changing role of DH within the national integrated energy system is analyzed. According to the trends, it was determined that the shift to renewable DH can potentially cause for an increased DH supply, competition with other heating alternatives, varying and uncertain DH sources, an increased electricity demand and a decreased electricity supply. In conclusion, these trends combined cause the transition from traditional to renewable DH to not be the most obvious choice. The most important source, the natural gas-fired CHP plant, is eliminated, while finding feasible alternative DH sources seems difficult. Therefore, DH sources demanding electricity can increase, which subsequently puts pressure on the electricity supply.

It can be observed that there is little variation with regard to the expected electricity sources within the scenarios. However, there is much variation with regard to the expected heat sources, specifically DH sources. As the supply of heat is a very local issue, it is of interest to explore local plans in order to determine if there is more clarity to the implementation of DH alongside a renewable electricity supply in a specific region. The next chapter aims to explore 'what happens on the ground' in the region North-Holland South.

6 CASE STUDY: TRANSITION OF THE REGIONAL ENERGY SYSTEM

In this chapter, the current Dutch electricity and heating sector of the built environment are mapped on a regional scale in order to conduct more concrete observations. Subsequently, regional energy plans are explored in order to estimate how the current regional energy system is planned to transition into a future energy system. The fourth sub-question *How are the electricity and heating sector expected to transition according to the regional energy plans in a specific Dutch region?* is answered. These expectations are used to determine the impacts of the transition to renewable DH. Subsequently, the fifth sub-question *What is the impact of the transition to renewable district heating on the electricity and heating sector according to the regional energy plans of a specific Dutch region?* is answered. The methods as discussed in chapter 3 are applied.

6.1 REGION NORTH-HOLLAND SOUTH

The region under consideration for the case study is region North-Holland South. The National Climate Agreement distinguishes thirty 'energy regions' in the Netherlands [Rijksoverheid, 2019], of which North-Holland South is one. The North-Holland South region is divided into six sub-regions: Amstelland, Amsterdam, Gooi & Vechtstreek, Haarlemmermeer, IJmond & South Kennemerland and Zaanstreek/Waterland. Each of these sub-regions consist of various municipalities [RES Noord-Holland Zuid, 2021].

Figure 6.1: Region North-Holland South, adapted from RES Noord-Holland Zuid [2021]

6.2 CURRENT ACTIVITY OF REGIONAL ACTORS

The liberalization of the Dutch energy market has separated its value chain, which used to be largely integrated. This causes for many different actors to control different parts of the energy system [Tanrisever et al., 2015]. Therefore, different actors are involved with the electricity and heating sector of the built environment of region North-Holland South. Similar to in chapter 5, the year 2019 is considered the base year of this analysis. The energy system of the base year will be referred to as the current regional energy system. Below, a description is given of the actors and their activities within the current regional energy system. Later in this chapter, the regional plans of these specific actors are explored.

6.2.1 Governmental Parties

The government is involved on different levels with the governance of the electricity and heating sector in the region North-Holland South. The governmental parties involved are the national government, province North-Holland, 3 regional water authorities and 29 municipalities of the region. These governmental parties implement energy policy with guidelines and incentives in order to achieve established climate objectives [RES Noord-Holland Zuid, 2021].

6.2.2 Electricity and Heat Producers

In the region North-Holland South, there are several electricity producers. Table 6.1 presents an overview of existing power generation plants adapted from CE Delft [2019]. Furthermore, wind and solar energy contribute to the electricity supply. There are a large range of wind electricity producers, such as Vattenfall, Eneco, E.ON, Engie and local initiatives. Electricity from solar energy is generated decentrally by end-users. Besides these large plants, there are also some small scale natural gas-fired CHP plants available in the region.

Moreover, some of the power plants from table 6.1 are CHP plants and thus also provide usable heat. These plants are indicated with an asterisk (*) in the electric capacity column, which indicates an additional availability of heat capacity. Moreover, individual natural gas-boilers, biomass combustion and individual heat pumps are also contributors the the heat supply. In this case, end-users produce their own heat.

Producer	Plant	Location	Energy Source	Capacity [MW]
Vattenfall	Hemweg-8	Amsterdam	Coal	630
Vattenfall	Hemweg-9	Amsterdam	Natural Gas	435
Vattenfall	Diemen-33	Diemen	Natural Gas	266*
Vattenfall	Diemen-34	Diemen	Natural Gas	435*
Vattenfall	Ijmond-1	Cluster Velsen	Natural Gas	144*
Vattenfall	Velsen-24	Cluster Velsen	Natural Gas	350*
Vattenfall	Velsen-25	Cluster Velsen	Natural Gas	375
AEB	AEC	Amsterdam	Waste	80*
AEB	HRC	Amsterdam	Waste	60*
AEB	Biomass Plant	Amsterdam	Biomass	8*
Orgaworld	Greenmills	Amsterdam	Biomass	5,5*
SVP	de Purmer	Purmerend	Biomass	44*

Table 6.1: Existing power (and heat) plants in region North-Holland South in 2019. Data sources: CE Delft [2019]; TNO [2020c]

It is important to note that the Hemweg-8 coal-fired power plant has been closed since January 2020. However, since the base year is considered to be 2019, this plant is included in this analysis.

6.2.3 Electricity Network Operators

In the region, the produced electricity is transported and distributed to end-users via regional electricity networks. The electricity network in North-Holland South is connected to the national and international networks (380 kV). The international network has connections with Belgium, Germany, England and Norway, through which internationally bought or sold electricity can be transported [CBS, 2015b]. The management of the grid is a regulated monopoly performed by grid operators TenneT, Liander and Stedin. The national grid operator TenneT manages voltage levels from 380 kV to 110 kV and regional grid operator Liander manages voltage levels from 50 kV and lower. An exception is the electricity grid in the municipality of Heemstede, which is managed by regional grid operator Stedin. The electricity network in North-Holland South is already reaching its capacity limits, especially in the Amsterdam area [CE Delft, 2019].

6.2.4 Gas Network Operators

The main sources for heat supply in the region North-Holland South are individual natural gas-fired boilers. Therefore, there is a provincial gas network in place for the transport and distribution of natural gas. This network has connections to national and international networks. The management of the grid is a regulated monopoly performed by grid operators Gasunie, Liander and Stedin. The national grid operator Gasunie manages the high-pressure grids and the regional grid operator Liander manages the regional grids. The southern part of the coastal region is managed by regional grid operator Stedin. Gasunie's high-pressure networks transport both high-calorific gas and low-calorific Groningen gas [CE Delft, 2019].

6.2.5 District Heating Network Operators

In the region North-Holland South, there are various large-scale DH networks constructed for heat supply to buildings that are operated by different actors. Large-scale DH networks are here defined as networks that annually supply more than 0,15 PJ of heat to end users. In 2019, there are large-scale DH networks within the areas Amsterdam North and West, Amsterdam South and East and Purmerend. Table 6.2 presents an overview of these DH networks reproduced from CE Delft [2019].

DH Operator	DH Location	Heat Supply [PJ/yr]
Westpoort Warmte	Amsterdam North & West	1
Vattenfall	Amsterdam South & East	1,8
SVP	Purmerend	0,8

Table 6.2: Existing DH networks in region North-Holland South in 2019. Data sources: CE Delft [2019]

In the Amsterdam North and West area, the DH network is operated by heat company Westpoort Warmte. This is a joint venture between Afval Energie Bedrijf (AEB) Amsterdam, owned by the Municipality of Amsterdam, and Vattenfall. The DH network of Westpoort Warmte supplies heat to the Westpoort, Nieuw-West, Noord, Houthaven and Zeeburgereiland areas. However, the Zeeburgereiland area is also connected to the DH network of Amsterdam South and East. The main sources of supply of the Amsterdam North and West DH network are the AEB plant, the Orgaworld Greenmills installation and the Diemen power plants, mentioned in figure 6.2 [TNO, 2020c].

In the Amsterdam South and East area, the DH network is operated by Vattenfall. The DH network of Amsterdam South and East (including Amstelveen) supplies heat to the Zuideramstel/Zuidas, Buitenveldert, Stadionbuurt, Zuidoost, Amstelkwartier, De Omval, IJburg, Zeeburgereiland and Amstelveen areas. The main source for DH supply are the Diemen power plants, mentioned in figure 6.2. Furthermore, at some locations, auxiliary heat plants with natural gas-fired boilers supply a limited part of the heat [TNO, 2020c].

In Purmerend, the DH network is operated by Stadsverwarming Purmerend (SVP). SVP is a local heat company in which the municipality is a shareholder. The main source of this DH network is the biomass plant de Purmer, which runs on wood chips from the maintenance of the forests of Staatsbosbeheer and is owned by SVP. In addition, there is a natural gas-fired auxiliary CHP plant for heat supply at peak demand and maintenance times [TNO, 2020c].

6.2.6 Electricity and Heat Suppliers

Energy suppliers supply electricity and heat to end-users. There is a large range of energy suppliers available, such as Vattenfall, Essent, Eneco, ENGIE and Vandebron. Before the liberalization of the energy market in 2004, consumers had no choice between different providers as the energy supplier was determined depending on the place of residence. Since then, the number of energy suppliers has extensively increased. There are energy companies that only supply electricity and/or heat, but do not produce them. These suppliers purchase energy from energy producers in the Netherlands. As electricity can be efficiently transported, electricity can be purchased and important from neighboring countries. However, there are also energy suppliers that additionally produce electricity and/or heat, such as Vattenfall in the region North-Holland South [TNO, 2020c].

6.2.7 End-users in the Built Environment

End-users have a certain demand for electricity and heat. The end-users of the built environment consists of households and services i.e. a residential and non-residential sector, respectively. End-users are responsible for their 'end-user behavior'. The decrease in energy demand and the implementation of renewable energy alternatives through end-user behaviour is of key importance in order to achieve climate objectives [TNO, 2020a].

6.3 CURRENT REGIONAL ELECTRICITY AND HEATING FLOWS

Following from the activities of the involved actors, the current electricity and heating sector of the region North-Holland South for energy supply of the built environment include various connected energy sources, technologies and end-demand purposes. The role of DH in this region can be determined in terms of the position of DH within the system and contribution of DH supply to the national energy flows.

6.3.1 Interconnections of System Components

In order to present an overview of the current energy system, a system diagram is depicted in figure 6.2, which visualizes the interconnections between the system components and the direction of the energy flows.

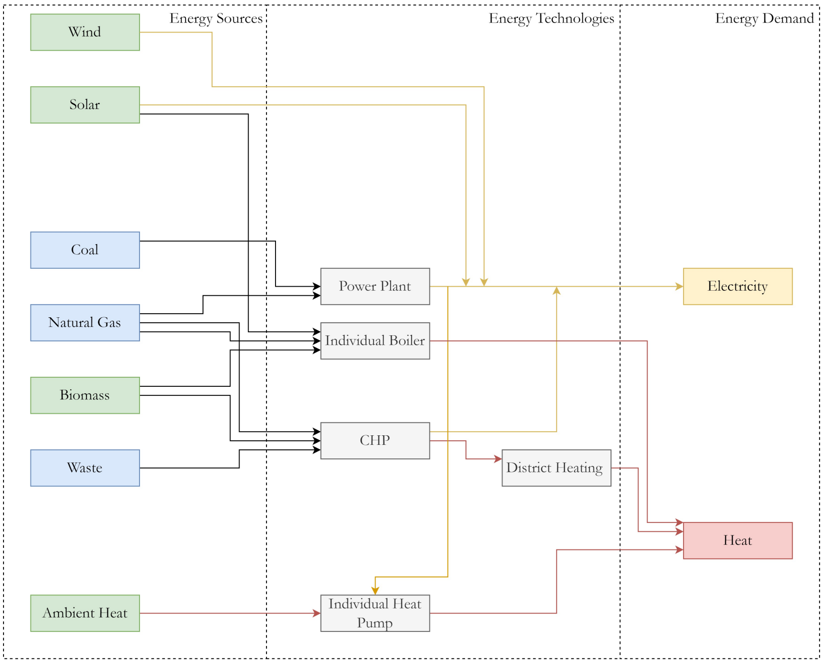


Figure 6.2: System diagram of the interconnections between the system components of the regional electricity and heating sector for the built environment in 2019. The green energy sources are renewable, while the blue energy sources are conventional. The electricity grid is indicated with yellow. Data sources: PBL [2020b]; TNO [2020c]; Eurostat [2019].

The current regional energy sources are of a conventional (blue) or renewable (green) nature. Fluctuating RE sources, such as onshore wind and solar generate electricity which feeds into the electricity grid (yellow). Moreover, coal, natural gas and biomass are energy sources utilized in power plants. Furthermore, natural gas, biomass and waste incineration energy sources are connected to CHP plants, which generate both electricity and usable heat. The electricity feeds into the electricity grid, while the heat is utilized within the DH network, with water as the medium of heat transfer. The generated electricity is used for fulfilling electricity demand, electricity import/export supports in balancing supply and demand. The heat generated by the CHP provides the heat supply for the DH network. The DH network eventually provides heat to supply the heat demand. Furthermore, ambient heat is provided to individual heat pumps, which can supply heat to fulfill heat demand. These heat pumps additionally require electricity from the electricity grid. Lastly, natural gas and biomass are directly used as a source for heat supply.

6.3.2 Quantified Energy Flows

Figure 6.3 depicts a sankey diagram, visualizing the quantified energy flows of the system. The dependency on natural gas as a result of the infrastructural natural gas lock-in, as discussed in section 5.1.1, is also visible within the regional energy system.

The final energy supply for electricity in the built environment currently consist largely of natural gas-fired plants with a share of 70%. Furthermore, sources for electricity are coal, onshore wind, solar, waste incineration and biomass, of which coal contributes the most. Besides wind and solar, these sources all generate electricity via power plants. The share of RE sources within the electricity sector of the built environment on a regional scale is 11%.

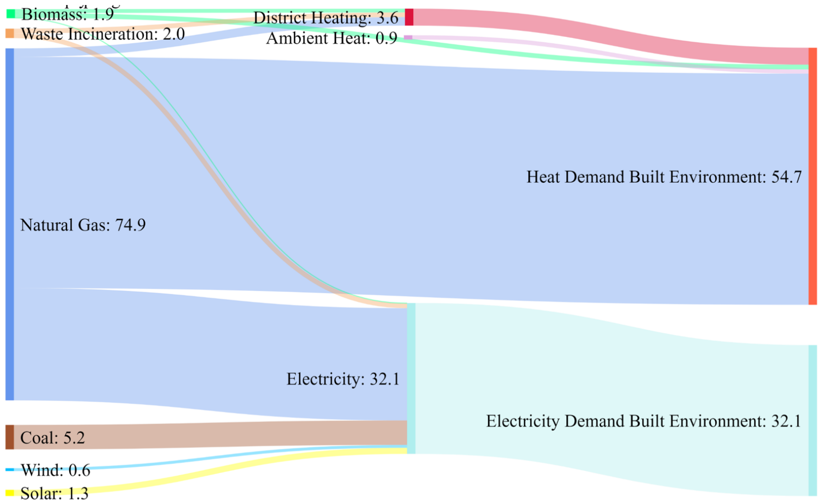


Figure 6.3: Sankey diagram of the energy flows in PJ between the system components of the regional electricity and heating sector for the built environment in 2019. Left side represents supply, right side represents demand. Data sources: PBL [2020b]; TNO [2020c]; Eurostat [2019]

The final energy supply for heat in the built environment also consists largely of natural gas with 90%, provided by individual boilers. Furthermore, other sources are DH, individual biomass combustion and individual heat pumps using ambient heat, of which DH contributes the most. The share of RE sources within the heating sector of the built environment on a regional scale is 6%.

Multiple sources are used for the DH supply, namely natural gas, biomass, and waste incineration. Natural gas-fired CHP plants are the largest contributor to DH supply with 56%. Moreover, biomass- and waste incineration-fired CHP plants both contribute to the DH supply with 22%. Therefore, the share of RE sources within district heating in on a regional scale is 33%.

6.4 REGIONAL ENERGY POLICY

The national government, province North-Holland and 29 municipalities of the region implement energy policy with guidelines and incentives in order to achieve established climate objectives [RES Noord-Holland Zuid, 2021]. The National Climate Agreement states that each energy region in the Netherlands must prepare a Regional Energy Strategy (RES) [RES Noord-Holland Zuid, 2021]. Moreover, the municipalities of these energy regions are required to prepare Transition Vision for Heat (TVH) reports. The RES and TVHs provide guidelines along which involved actors can create concrete plans. Implementation plans regarding concrete actions are constructed on a neighborhood level. There are thus various levels at which energy policy is managed. The following levels can be distinguished [RES Noord-Holland Zuid, 2021]:

- At the national level, the National Climate Agreement considers various national climate objectives and guidelines. This includes plans regarding wind and solar and the flexibility of the power system.
- At the regional level, the potential of onshore wind and solar for electricity generation in the region are mapped in the Regional Energy Strategy (RES). Moreover, the RES includes the Regional Structure of Heat (RSH), which discusses renewable heat sources available in the region.

- At the municipal level, the transition vision for heat (TVH) describes how the municipality aims to phase out natural gas and how the transition to renewable heating sources will occur and at which pace.
- At the neighborhood level, a concrete implementation plan is constructed in order to shape the transition plans together with residents and organizations from the neighborhood. A definitive choice is made regarding the heat alternatives and the associated costs. These agreements for instance end up at the level of a homeowner association.

According to the concepts of lock-in and path dependency discussed in 2.3.2, this energy policy contributes to shaping the future energy system. It can be stated that plans and strategies regarding the heat transition become more concrete as the policy level becomes lower. However, it is important to note that there is always a degree of uncertainty to these plans and strategies. Moreover, new innovations and breakthroughs in the coming years can cause for new insights.

6.4.1 Regional Energy Strategy

In order to implement the agreements made in the National Climate Agreement, the province North-Holland, the region's municipalities, regional water authorities, network operators, social organisations, businesses and residents from the energy region North-Holland South work together on the RES for this region.

Approach

The North-Holland South region has opted for a bottom-up or decentral process. With this approach, the region aims to map out of the many interests and tasks, stimulate collaboration between involved actors and create a solid foundation for the regional energy transition. The focus of the RES is on onshore wind and solar energy for electricity supply and on a renewable heat supply. Part of the RES is the regional structure of heat (RSH), in which the regional heat demand, heat sources, required infrastructure and the supra-municipal opportunities and challenges regarding the heat transition are analyzed [RES Noord-Holland Zuid, 2021]. It is noteworthy that, in preparation of the RES, the province of North-Holland commissioned a research published by CE Delft, which includes an estimated electricity and heat demand for the province North-Holland [CE Delft, 2019].

Regional Electricity Sector

The region North-Holland South expects a very strong growth in electricity demand. This strong growth is caused by economic development and the electrification of the energy system [RES Noord-Holland Zuid, 2021]. The region aims to increase the share of RE sources in the electricity sector and hereby focuses on onshore wind and solar energy. Therefore, various so-called 'search areas' are established in the RES of region North-Holland South. A search area indicates where options for generating wind and/or solar energy are further being investigated. This exploration takes place in consultation with stakeholders. Within the search areas, the RES indicates a current theoretical potential of 10,8 PJ/yr of onshore wind and solar energy for the electricity supply. This potential includes 1,2 PJ/yr of large-scale centralized solar energy, 6,1 PJ/yr of decentralized solar energy, 1,5 PJ/yr of onshore wind energy and 2,0 PJ/yr existing wind and solar. However, search areas can be adjusted and therefore this theoretical potential can change. The RES primarily indicates that decentralized solar energy can count on a lot of support [RES Noord-Holland Zuid, 2021].

Regional Heat Sector

The RSH is part of the RES and focuses on a renewable heat supply. The heat demand of the built environment in the North-Holland South region is expected to decline due to the implementation of energy-saving measures and electrification of the heating supply. However, a transition to a renewable heat supply is still required [RES Noord-Holland Zuid, 2021]. Therefore, various so-called 'heat demand clusters' are established in the RSH. Heat demand clusters are areas where there is sufficient heat demand and density of buildings. According to the RSH, these areas mainly are located in an near large cities, such as Amsterdam. The RSH emphasizes that there is a focus on a collective heat supply in the form of DH networks. In areas where the heat demand is lower, such as the outlying areas in the region, individual electrical heating solutions or heating solutions that use renewable gas are identified as more attractive [RES Noord-Holland Zuid, 2021].

Several heating sources available in the region North-Holland South for individual or collective heat supply are discussed in the RSH: geothermal, industrial waste heat, waste incineration, CHP heat, aquathermal, green gas, hydrogen and biomass [RES Noord-Holland Zuid, 2021]. These sources were elaborated upon in detail in section 4.2. For all sources it is emphasized that further research is required to determine the real potential in the region.

- Geothermal: The RSH expresses a great interest in geothermal as a source for DH supply. It is currently unknown how much heat from geothermal energy is available in the North-Holland South region. To determine this, research is currently being carried out into the presence of suitable earth layers and some exploration permits are granted. Before extraction can take place, a production license must also be granted.

- Industrial waste heat: The RSH also focuses on industrial waste heat as an energy source for DH supply. As discussed in section 4.2, the industry operates according to the principle of the trias energetica. As a result, a major regional impact on the heat supply cannot be expected in advance. However, in Amsterdam, Haarlemmermeer and Amstelland in particular, the RSH determines datacenters to be a promising and possible DH source, providing low-temperature heat.

- Waste incineration: The RSH identifies the AEB waste incineration power plants to be supra-municipal sources. These plants provide high-temperature heat and are connected to DH network Amsterdam North & West, as mentioned in section 6.2.5. The RSH discusses the possibility of expanding this DH network as the heat supply capacity is not yet fully utilized.

- CHP heat: The Diemen power plant is identified by the RSH as a supra-municipal CHP source. This plant provides high-temperature heat and is connected to DH network Amsterdam South & East, as mentioned in section 6.2.5. The RSH also emphasizes the possibility of expanding this DH network as the heat supply capacity of the plant is not yet fully utilized. As the Diemen power plant is natural gas-fired, the region identifies the plant as transition source and uses the slogan "better used than unused". It can enable the construction of DH networks to which sustainable sources can be connected in the future. (Note: a transition source/fuel can be defined as "a substitute low-carbon fuel for higher content fossil fuels (coal and oil) to reduce CO_2 emissions in the near future" Gürsan and de Gooyert [2021])

- Aquathermal: Aquathermal is a form of ambient heat and is expected to be used as a source for collective or individual heat pumps. Heat pumps are required to increase the source temperature to use temperature for heat supply.

According to the RSH, aquathermal energy has a high theoretical potential in the wetlands of North-Holland South.

- Green gas: The RSH plans to use green gas in individual boilers as a heat source for the built environment only where no alternatives are possible (for example, in historic city centers with little space in the subsoil and property that is difficult to insulate). For that reason, the RSH recommends the municipalities to focus on alternative heat sources.
- Hydrogen: The RSH expects that green hydrogen can be produced after 2030, when a lot of green electricity is available. However, the use of hydrogen to heat or electrify homes is inefficient. Applying green hydrogen in the built environment is therefore only identified as a realistic option in the future in cases where there is no sufficient alternative. Hydrogen is not elaborated upon further in the RSH.
- Biomass: According to the RSH, a vast majority of municipalities believe that there is no support for additional installations for the combustion of, in particular, imported biofuels. On the other hand, there is support for the use of local pruning and residual wood in existing installations. No potential is seen for a large biomass installation with supra-municipal capacity.

6.4.2 Transition Vision for Heat

Additionally to the RSH of the RES, in the transition vision for heat (TVH) of the region's municipalities more concrete choices are made regarding which renewable heating sources are implemented on a municipal level.

Approach

The region North-Holland South includes 29 municipalities, of which 15 have published their TVH. The remaining municipalities plan to publish their TVH in 2022. Table 6.3 shows the municipalities with their associated population in 2019 (base year) derived from [CBS, 2019c]. From this table it can be derived that 72% of the population of the region North-Holland South is covered by the currently published TVHs. Therefore, these TVHs are assumed to represent the general regional plans of the municipalities in a reasonably manner.

The 15 municipalities that have published their TVH aim to be natural gas free before 2050. The municipalities have a similar approach to tackle the renewable heat transition. First, for each neighborhood, potential renewable heating options are identified. This choice is primarily based on source availability and social costs. Then, possible 'promising neighborhoods' are identified, for which specific renewable heating options are least uncertain. The municipality views these neighborhoods as a starting point, while other neighborhoods mainly focus on improving the insulation of existing buildings.

Renewable Heating Sources

The TVHs are explored and their planned renewable heat sources determined in appendix B. Establishing the renewable energy mix for heating is a very local issue. However, the municipalities of region North-Holland South seem to identify quite similar sufficient renewable heating sources in line with the RSH.

Municipality	Population	TVH Reference
Aalsmeer	31.728	Not yet published
Amstelveen	90.838	Gemeente Amstelveen [2021]
Amsterdam	862.965	Gemeente Amsterdam [2020]
Beemster	9.748	Not yet published
Beverwijk	41.176	Not yet published
Blaricum	11.202	Not yet published
Bloemendaal	23.410	Not yet published
Diemen	29.196	Gemeente Diemen [2021]
Edam-Volendam	36.099	Not yet published
Gooise Meren	57715	Not yet published
Haarlem	161265	Gemeente Haarlem [2021]
Haarlemmermeer	154.235	Not yet published
Heemskerk	39.164	Gemeente Heemskerk [2021]
Heemstede	27.286	Gemeente Heemstede [2021]
Hilversum	90.238	Gemeente Hilversum [2021]
Huizen	41.273	Not yet published
Landsmeer	11.488	Gemeente Landsmeer [2021]
Laren	11.195	Gemeente Laren [2021]
Oostzaan	9.757	Gemeente Oostzaan [2021]
Ouder-Amstel	13.916	Not yet published
Purmerend	80.117	Not yet published
Uithoorn	29.424	Gemeente Uithoorn [2021]
Velsen	68.348	Not yet published
Waterland	17.315	Gemeente Waterland [2021]
Weesp	19.334	Gemeente Weesp [2021]
Wijdemeren	24.013	Not yet published
Wormerland	16.329	Gemeente Wormerland [2021]
Zaanstad	155.885	Gemeente Zaanstad [2021]
Zandvoort	17.011	Not yet published
Total Population	2.181.670	
Population with TVH	1.571.679	
Population with TVH [%]	72%	

Table 6.3: Municipalities of the region North-Holland South with their current population TVH reference. Data Source: CBS [2019c]

The following three heat alternatives are identified in the TVHs:

- DH networks: The implementation of DH networks is seen as attractive in 14 out of 15 TVHs. Municipalities plan to extend their existing DH network or implement a new DH network. Various local sources are planned to be used for DH supply. Many municipalities consider geothermal energy to be a sufficient source as it provides high-temperature heat. Moreover, aquathermal and industrial waste heat (including waste heat from datacenters) are often considered as sources providing low-temperature heat. Additionally, the municipality of Amsterdam mentions biomass, waste incineration, solar thermal and TES as sources for DH supply. The municipality of Haarlem also mentions solar thermal. However, the remainder of the municipalities do currently not specifically plan for biomass, waste incineration, solar thermal and TES to be used in the future.
- Individual (hybrid) heat pumps: The use of individual (hybrid) heat pumps is mentioned in all TVHs. In old city centers, both a DH network and all-electric solution are often expensive or not suitable for use. Therefore, municipalities view hybrid heat pumps as a feasible option. Hybrid heat pumps use a gas-fired boiler to supply heat at times when the heat demand is high. This gas is planned to be natural gas from the existing gas network at first, which is later substituted by green gas. Therefore, hybrid heat pumps can function as a transition technology. Municipalities thus do not plan to remove the existing gas network straight away.

- Individual green gas boilers: In many TVHs, the use of existing individual boilers fueled by green gas is discussed for areas in which DH networks and hybrid heat pumps are insufficient. However, many TVHs emphasize that this renewable heating option is of a last-resort nature, as there is much uncertainty regarding the availability of green gas in the future energy system.

It becomes evident that the municipalities of region North-Holland South plan to implement two main options for renewable heating: a collective solution in the form of DH networks and an individual solution in the form of (hybrid) heat pumps. However, there is still much uncertainty regarding the implementation of specific renewable heating sources at specific locations and especially regarding the availability of DH sources.

6.4.3 Interviews

The published regional plans stated in the RES and TVHs are explored. Subsequently, interviews with the province North-Holland and the municipality of Amsterdam in order to obtain their viewpoint with regard to their role within the energy transition. The information in this section is obtained through semi-structured interviews with the province North-Holland and the municipality of Amsterdam. The interview protocol can be found in appendix C. The interviews with these governmental actors focused on subject C of the interview protocol (collaboration).

According to an interviewee of the province North-Holland "The province has a small facilitating role in the energy transition of the region North-Holland South" [Provincie Noord-Holland, 2022]. The province has established the Service Point for Sustainable Energy (SPSE), which is a virtual independent entity. The SPSE supports municipalities, regions, housing associations and other stakeholders in the province North-Holland with regards to the energy transition in the built environment. Therefore, this entity provides possibilities for a more integrated approach. Currently, municipalities do not always have the knowledge or experience to manage the heat transition in their designated area. Moreover, the province notices that many local heat initiatives are currently not well aligned. The province North-Holland observes that different levels of government (municipalities, provinces and national government) do not cooperate sufficiently, while this is necessary to make the energy transition a success [Provincie Noord-Holland, 2022]. Moreover, "the national government makes insufficient use of the role that the province can play as a middle government (between municipalities and national government) in the implementation of energy policy by municipalities" [Provincie Noord-Holland, 2022]. Therefore, the province is planning to extend the SPSE with the purpose to support municipalities even more in their local heat transition in an integrated manner. However, municipalities remain responsible for their own heat transition.

According to an interviewee of the municipality of Amsterdam, "the municipalities aim to play the role of facilitator for especially the heat transition" [Gemeente Amsterdam, 2022]. Therefore, the developments regarding the Heat Act 2 are important to consider. Currently, municipalities plead for more options to be able to steer their heat transition. Therefore, in the bill for the Heat Act 2, municipalities designate areas as 'heat plots'. After a transparent allocation procedure, one heat company is ultimately assigned the legal task of supplying heat to everyone in the plot. This approach will result in a large governing capacity for the municipalities, "which is really challenging" [Gemeente Amsterdam, 2022]. For example, with regards to the somewhat monopolistic position of prominent DH network operators. A benchmark is necessary in order to ensure fair energy prices. However, according to an interviewee of the municipality of Amsterdam "the heat transition needs to be managed at a municipal level, as it is a local issue" [Gemeente Amsterdam, 2022].

6.5 REGIONAL ENERGY PLANS OF NON-GOVERNMENTAL ACTORS

In the previous sections, the RES of the region North-Holland South and the TVHs of the region's municipalities are explored. The RES and TVHs provide guidelines along which involved actors can create concrete plans. In this section, the regional energy plans of other involved actors (section 6.2) are discussed. Regional energy plans of these actors regarding renewable heat and electricity sources are relevant. Part of the information in this section is obtained through semi-structured interviews with involved actors. The interview protocol can be found in appendix C.

6.5.1 Electricity and Heat Producers

The main electricity and heat producers in the region North-Holland South are Vattenfall, AEB, Orgaworld and SVP, of which Vattenfall is the largest producer.

Interviews

With regard to electricity generation within region North-Holland South in 2050, Vattenfall expects wind and decentralized solar to be the dominant energy sources. Imported electricity, hydrogen and natural gas are expected to function as a back-up for these fluctuating RE sources [Vattenfall, 2022c,d]. It was mentioned by an interviewee that "ideally to my personal opinion, nuclear energy would also function as an electricity source" [Vattenfall, 2022c]. Currently, concrete plans of Vattenfall include the realization of large-scale offshore wind farms and onshore wind farms in other regions. Moreover, as fossil fuels are planned to be phased-out, Vattenfall has closed the Hemweg-8 coal-fired power plant in January 2020. For the natural gas-fired plants, there are no concrete plans yet for closure, since current energy demand needs to be fulfilled. However, Vattenfall is conducting research regarding the substitution of natural gas with green hydrogen [Vattenfall, 2022c,d]. Moreover, there are no concrete plans regarding the closure of the biomass plants of AEB, Orgaworld and SVP. There is a plan for the construction of a new biomass plant in Diemen. It is expected to be operational in the second half of 2023. However, as biomass is often viewed as a transition source, this can cause for a strong decrease of biomass-fired plants in the future energy system of 2050 [Vattenfall, 2022a,d,c; Westpoort Warmte, 2022].

Furthermore, the waste incineration plants of AEB currently generate electricity and heat. After the maximum amount of raw materials from the waste is removed, a residual flow remains that is used for energy generation. However, a decrease in the amount of waste that is usable for energy generation is expected in the future. This is caused by the objective of the national government to become fully circular by 2050. The decreasing import volumes of waste may lead to the decommissioning of one of the two units (for example, the AEC unit, the oldest of the two installations). However, it is expected that there will be a shift towards more heat production and less electricity production [Westpoort Warmte, 2022].

Moreover, Vattenfall expects energy sources for heat supply to be DH, (hybrid) individual heat pumps and gas-fired individual boilers. Hydrogen is not expected to provide heat in individual boilers and it is expected that green gas will be very scarce due to ongoing public debates [Vattenfall, 2022c,d]. Therefore, there are doubts with regard to the complete elimination of natural gas in the regional energy system of 2050 [Vattenfall, 2022c]. It is expected that part of their natural gas-fired plants are preserved. It is noteworthy that Vattenfall and installation company Feenstra are currently developing a high-temperature individual heat pump. The heat pump system is presented to be a simple and affordable alternative to the natural gas-fired individual boiler. The high-temperature heat pump system has been specially developed for existing homes that are moderately insulated. The first heat pumps are expected to be delivered from 2022 [Vattenfall, 2022b,a,c].

Additional Published Data

- According to the 'Annual and Sustainability Report 2020' published by Vattenfall [2020], Vattenfall is realizing major investment projects regarding on- and offshore wind in the Netherlands. However, not yet in the specific North-Holland South region. Furthermore, Vattenfall is exploring the possibilities for using green hydrogen in existing power plants in a pilot project in Germany. Vattenfall plans to run their Hemweg-9 plant entirely on green hydrogen by 2035. Furthermore, there are plans for the Diemen plants to run on green hydrogen. Moreover, investments are planned for the Green Heat Diemen project, where opportunities for a biomass-fired heat-only boiler (100 MW heat) are explored.
- According to the 'AEB Jaarverslag 2019' published by AEB [2019], AEB aims stimulate the circular economy by taking the lead in turning recovered raw materials into locally applicable products. Moreover, AEB aims to increasingly recover high-quality raw materials from waste by optimizing collection, making use of social employment and applying state-of-the-art technology.

6.5.2 Electricity Network Operators

Electricity network operators in the region North-Holland South are TenneT, Liander and (for the municipality of Heemstede) Stedin, of which the former is the national grid operator and the latter two are regional grid operators.

Interviews

As electricity demand is expected to increase substantially, the electricity network capacity is required to increase [Liander, 2022]. The electricity network in North-Holland South is already reaching its capacity limits, especially in the Amsterdam area. Moreover, many other future capacity bottlenecks are expected to occur in the region North-Holland South. Therefore, the grid operators require to adapt their investment plans in order to increase and maintain grid capacity in strategic areas. According to an interviewee of Liander, "this is challenging due to the large required investments, lack of technicians and regulatory complexity, such as permit applications" [Liander, 2022]. Currently, grid managers are expected to invest efficiently, meaning that investment processes are only set in motion when contracts have been signed with a customer. Pre-investments may not be made on the basis of, for example, expected growth in the demand for grid capacity. This principle, whereby network operators are not expected to invest in advance, is at odds with the need to invest in sustainable alternatives in anticipation of the transition. Therefore, grid operators call for laws that enable quicker network expansion [Liander, 2022]. Moreover, network operators aim to increase the flexibility of the grid by various measures. Liander stimulates demand-response and the use of home-batteries in combination with solar panels as an alternative for delivering electricity back to the grid [Liander, 2022]. Moreover, an interviewee of Liander stated that "DH networks using collective heat pumps or E-boilers could provide options for improving the flexibility of the electricity grid through thermal storage" [Liander, 2022].

Additional Published Data

- According to the 'Infrastructure Outlook 2050' report published by Gasunie and TenneT [2019], further development of the energy transmission infrastructure for electricity is essential for the future energy system. This development needs to be planned timely in an integrated way to find optimal solutions for a faster and affordable energy transition. The network operators require legal and regulatory frameworks to facilitate and steer the transition pathway.
- According to the 'Liander Jaarbericht 2020' report published by Liander [2020], Liander is working together with the municipality of Amsterdam and TenneT on increasing the electricity grid capacity in the Amsterdam area. Moreover, Liander is investigating the impact of the expected electrification on their infrastructure and is trying to coordinate the planning with the capacity and replacement plans of the cables and pipelines.

6.5.3 Gas Network Operators

Gas network operators in the region North-Holland South are Gasunie, Liander and for a very limited area Stedin, of which the former is the national grid operator and the latter two are the regional grid operators.

Interviews

Gasunie and Liander expect green gas and hydrogen to play a role in the future energy system [Gasunie, 2022; Liander, 2022]. According to a Liander interviewee "the transition to green gas and hydrogen can preserve the value of the existing natural gas infrastructure for society" [Liander, 2022]. This applies to (a large part of) the Liander distribution networks, but also to the transmission and distribution networks operated by Gasunie and Stedin. Currently, Liander is exploring possibilities for the use of hydrogen in existing natural gas networks and the conversion of electricity to hydrogen. Several pilots projects have been started [Liander, 2022]. Gasunie and Liander expect the role of natural gas to decrease as the amount of renewable energy increases. Until then, natural gas is viewed as a good transition alternative. However, according to a Gasunie interviewee, the use of large amounts of hydrogen and particularly green gas for future renewable heating may be unrealistic, as much uncertainty is involved [Gasunie, 2022]. Therefore, there is a risk for a natural gas lock-in, whenever the potential of hydrogen and green gas for renewable heating purposes are currently overestimated [Gasunie, 2022].

Additional Published Data

- According to the 'Gasunie Jaarverslag' report published by Gasunie [2020], the transmission infrastructure for green gases are required to be further developed. Gasunie sees hydrogen as an important future energy carrier and therefore intends to realize a 'hydrogen backbone' for hydrogen transport. The backbone can be realized in 2027, but also earlier if needed by allocating (separating) pipes of the current natural gas transport network for hydrogen. Hydrogen is mainly expected to be used for industrial clusters and for balancing the fluctuating electricity supply from wind and solar. In the field of green gas, Gasunie is further developing the technology for supercritical water gasification (a technology for the efficient conversion of wet biomass) and gasification of woody residual flows. Current networks are ready for the large-scale in-feed of green gas. Furthermore, they issue Guarantees of Origin for green gas, produced by market parties. Gasunie expects that green gas may play a role as a heating alternative either through individual boilers or hybrid individual heat pumps [Gasunie, 2020].

6.5.4 District Heating Network Operators

DH network operators in the region North-Holland south are Vattenfall, Westpoort Warmte and SVP, of which Vattenfall operates the largest DH network.

Interviews

Vattenfall and Westpoort Warmte expect DH networks to play an important role supplying heat in the regional energy system of 2050. DH is mainly expected to be an important heating alternative in existing densely built areas. Therefore, an increase in these networks is expected and being prepared for [Vattenfall, 2022a; Westpoort Warmte, 2022].

The Amsterdam North & West and Amsterdam South & East DH networks are planned to be extended and supplied with additional heat sources. Vattenfall and Westpoort Warmte expect the future main DH sources to be geothermal, industrial waste heat and ambient heat (aquathermal) [Vattenfall, 2022c,a,d; Westpoort Warmte, 2022]. According to an interviewee of Vattenfall "it is in some cases desirable to connect multiple geothermal sources to the DH network in order to continuously supply the base load" [Vattenfall, 2022c]. Geothermal is a viable option in areas where the DH demand is above a certain threshold. Together with municipalities, the Province North-Holland and Eneco, Vattenfall is currently exploring the possibilities for geothermal in the region North-Holland South [Provincie Noord-Holland, 2022; Vattenfall, 2022c]. However, besides these main expected DH sources, additional DH sources are required to deliver heat. Therefore, Vattenfall is planning to realize an E-boiler to supply heat to the DH network of Amsterdam South & East. [Vattenfall, 2022c,a,d,b; Westpoort Warmte, 2022]. However, there are still policy challenges involved with this E-boiler, as currently the heat supplied by this boiler is not classified as renewable, but as equally renewable as the electricity supply mix [Vattenfall, 2022a]. Furthermore, it is expected that (part of) the waste incineration plants of AEB will still be available to deliver heat to the DH network and the Diemen power plant could potentially supply heat using green hydrogen [Westpoort Warmte, 2022; Vattenfall, 2022c,d]. The use of the existing biomass plants as a future DH source is debatable [Vattenfall, 2022a,b].

Additional Published Data

- According to the 'Annual and Sustainability Report 2020' published by Vattenfall [2020], Vattenfall is planning major investment in DH networks. Investments are being made in the distribution operations in response to increased capacity requirements, a high number of new connection requests and new renewable production. This includes investments in the Amsterdam South & East DH network, which will enable considerable growth in DH in the region. Additionally, Vattenfall is developing a large 150 MW collective E-boiler in Diemen with an efficiency of 99,9% (COP of 1). This E-boiler is planned to supply heat to 20.000 households per year. The advantage of this location is that there is already a large electricity connection and there is also a large heat buffer in which any excess heat can be stored. Furthermore, Vattenfall is involved in a feasibility study for geothermal heat, waste heat from data centres and heat from various water sources in the region.

- According to the 'AEB Jaarverslag 2019' report published by AEB [2019], AEB sees serious opportunities to contribute to the growth of heat demand in Amsterdam by supplying heat to the DH network of Westpoort Warmte.

- According to the 'Rapportage Systeemstudie Energie-infrastructuur Noord-Holland 2050' published by CE Delft [2019], the estimated potential of high-temperature waste heat sources available within the region is 2,9 PJ/yr.

6.5.5 Electricity and Heat Suppliers

There are many electricity and heat suppliers active in the region North-Holland South, such as Vattenfall, Essent, Eneco, ENGIE and Vandebron.

Interviews

Energy suppliers are dependent on the plans of electricity and heat producers and end-users. Therefore, energy suppliers adapt their plans accordingly with the aim to maintain their competitive position. With the increased supply and demand of renewable energy, the role of energy suppliers change. The increase in decentrally generated electricity and heat causes the role of energy suppliers becomes smaller. Energy suppliers are starting to present themselves more as energy partners, providing customized advice for home-owners wanting to switch to renewable alternatives [Vattenfall, 2022b].

Additional Published Data

- According to the 'Eneco Bestuursverslag 2020' report published by Eneco [2020], customer needs are transforming due to the energy transition. There is pressure on the margin per customer and the loss of 'traditional' energy customer contracts. Eneco wants to create added value for customers and develop new energy services with promising technologies such as solar panels, heat pumps and smart use of data for Smart Home applications.

6.5.6 End-users in the Built Environment

The end-users of the built environment consists of households and services.

Interviews

End-user behavior results in a certain energy demand, energy supplier and, to a certain extend, energy alternatives. End-user behavior or consumer choices can depend on various values, such as affordability, functionality or climate awareness. All of the involved actors are taking measures to change end-user's behaviour in many ways. End-users are increasingly stimulated to become more aware of the energy transition, which can cause for energy to be used more efficiently and renewable energy alternatives to be chosen. An example is the 'salderingsregeling' or energy pricing [Gemeente Amsterdam, 2022]. It is also noteworthy that end-user choices are impacted by the life time of individual energy alternatives. For instance, as the average life time of a gas boiler is 15 years, this means that an end-user who purchases a new gas boiler in 2015 is unlikely to adopt a new heating alternative until 2030.

6.6 REGIONAL ENERGY PLANS REFLECTION

In the previous sections, regional energy policy and plans of the various involved actors are explored. In this section, these plans are compared and reflected upon in order to draw assumptions from them. These assumptions are eventually used to estimate the energy flows of the regional electricity and heating sector of 2050.

6.6.1 Overall Alignment

It can be derived that overall, the RES, TVHs and regional energy plans of non-governmental actors are well aligned. This becomes evident as the regional plans of the province and municipalities are recognized and supported by the regional plans of the other involved actors. It becomes clear that the electricity transition is mainly managed on a national policy level, while the heat transition is mainly managed on a municipal level. From the interviews it can be concluded that the non-governmental involved actors require legal and regulatory frameworks to facilitate and steer the transition pathway. Specifically the TVHs of the municipalities are used as a guideline along which involved actors can create concrete plans for the heat transition. This is confirmed as the regional plans of the TVHs and other actors are well aligned. Moreover, the implementation of the renewed Heat Act 2.0 could provide municipalities with more governing capacity, resulting in even more alignment between governmental and non-governmental heat transition plans. However, the leading role of municipalities in the heat transition is new and requires them to collect new knowledge, expertise and competences, which can cause for difficulties with regard to managing the local heat transition.

6.6.2 Municipalities Approaches

A misalignment can be identified in the municipalities approaches. There is much uncertainty regarding the implementation of specific renewable heating sources substituting natural gas at specific locations and the availability of DH sources. According to the National Climate Agreement, municipalities are expected to present their concrete implementation plan no later than 8 years before the end date of the natural gas supply. Municipalities can choose these end-dates, as long as they are before 2050 [Rijksoverheid, 2019]. This means that theoretically, municipalities have to present their plans no later than in 2042, in order to become natural gas free before 2050. However, there are naturally always risks and uncertainties resulting in delays. Overall, a reluctant and assertive approach to the heat transition can be distinguished. Two examples are the municipality of Laren and the municipality of Amsterdam.

- The municipality of Laren is reluctant to officially determine renewable heating options for specific areas [Gemeente Laren, 2021]. Until 2030, the municipality of Laren plans to continue the heat supply with natural gas-fired individual boilers. This is in line with their basic principle of not forcing residents to take measures. Moreover, this approach provides extra time for conducting research regarding suitable future heat sources [Gemeente Laren, 2021].
- The municipality of Amsterdam is an example of a more assertive municipality. The municipality of Amsterdam plans in their TVH to connect 66% of the buildings to a DH network by 2040 [Gemeente Amsterdam, 2020]. The remainder of the buildings are planned to be connected to a green gas network or heated by individual heat pumps. The DH network is planned to be fed by a mix of heat sources [Gemeente Amsterdam, 2019]. However, it is stated that most of these sources yet need to be developed and connected [Gemeente Amsterdam, 2020].

The approaches (reluctant/assertive) of the municipalities both bring along uncertainties. A reluctant approach may result in delays regarding the transition to a renewable heat supply. Moreover, an assertive approach in times of uncertainty may lead to potential malfunctioning infrastructural lock-ins, such as an implemented DH network without sufficient DH sources. Moreover, different approaches may result in misaligned local initiatives.

6.6.3 Coal and Natural Gas

All of the actors unanimously plan and expect coal to be phased out within the future energy system. Vattenfall has closed the Hemweg-8 coal-fired power plant in 2020 and there are naturally no further plans for using coal as a electricity or heating source. The national government aims for natural gas-fired power plants to be phased-out. However, the province North-Holland, Vattenfall, Gasunie and Liander view these plants as transition sources. There are currently no concrete plans for closing these plants. Therefore, the view of natural gas as a transition source can cause risks, such as a delay in the implementation of 'sufficient' long-term alternatives.

6.6.4 Nuclear

It was mentioned by a Vattenfall interviewee that nuclear energy would also ideally function as an energy source. The use of nuclear power plants in the future energy system was until recently not included in the plans of the national government. However, in the most recent Coalition Agreement, it is planned that the nuclear power plant in Borssele will remain open and two new nuclear power plants will be realized in the future (after 2030). The siting of these plants will in all probability not be within the region North-Holland South [Rijksoverheid, 2022].

6.6.5 Wind and Solar Energy

All of the involved actors expect the electricity demand to increase. This electrification is unanimously expected to be supplied with regional onshore wind energy and decentralized solar energy, for which the RES determined a theoretical potential. The biggest regional electricity supplier, Vattenfall, wishes to realize onshore wind farms in the region. However, only concrete plans for the realization of offshore wind farms sited in the North sea are currently published. Despite this, there are good possibilities to realize the full theoretical potential, which is approximately three times the current capacity. Recent successfully developed onshore wind farms in other regions could accelerate the entire process and could also stimulate other electricity producers to invest in onshore wind. Moreover, the national and regional governments are very motivated. This motivation is also very much required in order to realize the full theoretical potential for decentralized solar, which is approximately eight times higher compared to now. In order to achieve this challenging objective, it is necessary for homeowners to be provided with incentives and for Liander, Stedin and TenneT to adapt their grids. This brings along certain challenges, due to the large required investments, lack of technicians and regulatory complexity. However, currently homeowners are increasingly motivated for improving environmental awareness and the installation of solar panels is popular and financially rewarding. Moreover, grid operators are aware of the plans to increase decentralized solar and are currently working on solutions. For example, home-batteries in combination with solar panels as an alternative for delivering electricity back to the grid are advised.

6.6.6 Hydrogen

As mainly wind and solar are planned to supply future electricity, additional sources are required to function as a back-up due to their intermittent nature. The RES and TVHs do not include any expectations or plans. However, the national government, province North-Holland, Vattenfall, TenneT, Liander and Gasunie expect hydrogen to play a role in this. Hydrogen strategies have been published in collaboration with the province, TenneT and Gasunie. Gasunie intends to realize a 'hydrogen backbone' for hydrogen transport before 2027. This backbone is mainly expected to be used for industrial clusters and for balancing the fluctuating electricity supply from wind and solar. Currently, Vattenfall is conducting research regarding the substitution of natural gas with green hydrogen within the Hemweg-9 plant and possibly within the Diemen-34 plant. However, the use of hydrogen in the future energy system brings along challenges and uncertainties. Most importantly, a sufficient amount of green hydrogen needs to be available. As currently the Vattenfall power plants run on natural gas, their competitive position is relatively poor compared to applications for which green hydrogen substitutes grey hydrogen (industrial clusters). Therefore, high capacities of wind and solar are required to be installed or hydrogen needs to be imported from other countries. As the demand for hydrogen is expected to be high in the future energy system, actors agree that the use of hydrogen for supplying heat to buildings is not an obvious choice.

6.6.7 Waste Incineration

According to the RES, TVH of Amsterdam, Vattenfall, AEB and Westpoort Warmte, the AEB waste incineration plants can contribute to the regional electricity and heat supply in 2050. On one hand, the decreasing import volumes of waste may lead to the decommissioning of one of the two units (for example, the AEC unit, the oldest of the two installations). On the other hand, a shift towards more heat production and less electricity production is expected. Therefore, the AEB plant can still be expected to supply heat to the DH network of Amsterdam North & West.

6.6.8 Biomass

The use of biomass within the future energy system is a debatable topic. According to all involved actors, biomass is viewed as a transition source and therefore is not necessarily expected to deliver electricity or heat in 2050. This includes the province, municipalities and Vattenfall. However, AEB, Orgaworld and SVP have no concrete plans for closing their regional biomass plants. Furthermore, Vattenfall is planning to realize a biomass heat-only boiler in Diemen, which can supply heat to the DH network of Amsterdam West and South. Interestingly, the lack of public support regarding biomass is very visible within this process. The municipality of Diemen stated the following in 2018: "Vattenfall wants to build a biomass boiler within the layout of the power plant in Diemen, which is controversial. Biomass is labeled as 'renewable' by the national government and therefore substantial subsidies are provided. However, the municipalities of Diemen, Weesp, Gooise Meren and the district of Amsterdam-Oost have not asked for this power plant, but will have to deal with its adverse effects. The municipalities are doing everything within their legal possibilities to stop the construction of the power plant. If that fails, they want to legally enforce various agreements through a covenant with Vattenfall." [Gemeente Diemen, 2018]. As for now, the biomass boiler is not realized. The adverse effects that are mentioned represent objections regarding the environmental impact of biomass creating a lack of public support. Clearly, a conflict of interest occurs here. The view of certain sources as a transition source could be problematical as the knowledge exists that the use of the source is not optimal and eventually needs to be substituted. However, the use of biomass can play a viable role in delivering heat to DH networks, while research regarding geothermal energy is conducted. Therefore, a biomass lock-in can occur if the potential for long-term renewable DH sources turns out to be insufficient.

6.6.9 District Heating

According to the RES, TVHs and regional energy plans of Vattenfall and Westpoort Warmte, DH networks are expected to be one of the three main sources for renewable heating in the regional future energy system. 14 out of 15 municipalities plan to implement DH networks and the existing DH networks are expected to be expanded. The main heat sources for the existing DH networks are currently the AEB plants (waste incineration), the Orgaworld installation (biomass) and the Diemen power plant (natural gas). However, the use of the biomass plants is not particularly supported by the municipalities and the public as mentioned before. Moreover, the RES identifies the Diemen plant as a transition DH source. Vattenfall plans to transform this power plant into a green hydrogen plant. However, the use of hydrogen for providing heat is viewed as very inefficient by several actors.

According to the RES, the municipality of Amsterdam and Westpoort Warmte, the waste incineration plants of AEB can play a role as a future DH source. Moreover, the RES identified various DH sources with a large potential, namely geothermal, industrial waste heat and aquathermal. In line with this, almost all municipalities and the dominant DH operator, Vattenfall, expect the same three DH sources to be dominant. Interestingly, the actors seem to have high hopes for geothermal to become the prime DH source in the future energy system. However, there is still much uncertainty regarding its availability in the region. The possibilities for geothermal are currently explored with no break-trough results just yet. Moreover, the high-temperature industrial waste heat sources have been identified. Low-temperature industrial waste heat (datacenters) and aquathermal potential is yet to be explored. Lastly, Vattenfall has currently plans for realizing an E-boiler for delivering heat to the Amsterdam South & East DH network and the municipalities of Amsterdam and Haarlem see potential in solar collective boilers. According to Liander, E-boilers and collective heat pumps could provide flexibility options for the electricity grid. However, currently the heat supplied by the E-boiler is not classified as renewable by the Dutch government.

It can thus be stated that there is currently much uncertainty regarding the three main future DH sources, especially regarding the desired geothermal source. Therefore, it is surprising that the plans of the regional actors are quite well aligned regarding the implementation of DH.

6.6.10 Individual Heat Supply

According to the RES, TVHs and regional energy plans, individual (hybrid) heat pumps and individual gas boilers are the other two main future sources for renewable heating. Boilers are expected to be used as a last resort option, in areas were DH and heat pumps are not possible. Interestingly, all of the published TVHs state that green gas is planned to be used in both the hybrid heat pumps and the boilers. Moreover, Gasunie and Liander expect green gas to play a role in heat provision. However, a misalignment can be identified with regard to the extend of which green gas is expected to be used for heat supply. The RES states clearly that the use of green gas is desired to be limited due to ongoing public debates. Moreover, involved actors such as Gasunie, Vattenfall, Westpoort Warmte expect the potential of green gas to be insufficient for this in the region. Therefore, these actors still expect natural gas to play a role in supplying heat in the future energy system. As currently the regional energy system is locked in a natural gas-infrastructure and it is technically feasible to use green gas within this existing gas-infrastructure, the choice for green gas seems obvious. However, the choice of municipalities for green gas can endanger the phasing-out of natural gas within the system, if its availability eventually turns out to be low. Therefore, the desire to maintain the existing gas-infrastructure to eventually provide green gas for individual boilers and hybrid heat pumps is a risk.

6.7 FUTURE REGIONAL ELECTRICITY AND HEATING FLOWS

Regional energy plans as described in the previous sections will shape the future energy system of region North-Holland South. The future electricity and heating sector for energy supply of the built environment include various energy sources, technologies and end-demand purposes. Naturally, as discussed in section 2.3, it is challenging to forecast specific transition pathways and the structure of the future energy system. However, based on the reflection of the regional energy plans, an estimation of the future energy flows is made.

6.7.1 Assumptions

The estimation regarding the energy flows of the future regional energy system of 2050 is based on various assumptions. These assumptions are derived from the regional energy plans and the reflection. The exact numerical assumptions can be found in appendix D, along with the assumption base. The following assumptions are made:

- The expected electricity and heat demands included in the RES fall within a small range. For the estimation, the highest combination of heat and electricity demand for the region North-Holland South is assumed in order to present the most extreme values.
- Coal and natural gas as a source for electricity and heat supply are assumed to be eliminated, due to the national climate objectives. Coal has been phased out in 2020. Moreover, natural gas is assumed to be gradually phased out.
- No nuclear plants are assumed to be realized in the region North-Holland South.
- The full theoretical regional potential of onshore wind and solar as presented in the RES is assumed to supply electricity.
- In order to provide for the required flexibility in the electricity supply, hydrogen is assumed to play a role. It is assumed that the Hemweg-9 and Diemen-34 plant will be green hydrogen-fired.
- Hydrogen is assumed not to be used as a source for heating of the built environment.
- Biomass as a source for electricity and heat supply is assumed to be fully eliminated, due to the lack of public support.
- The contribution of green gas to the heat supply is assumed to be the maximum amount available stated in the RES for 2030. This also includes the green gas used by hybrid individual heat pumps. As the use of green gas is often mentioned but very uncertain, the maximum amount is assumed for 2050.
- The remainder of the heat demand is assumed to be supplied by DH networks and individual heat pumps. It is assumed that the contribution of DH and individual heat pumps to the heat supply are both equal, as clearly a dominant source can not be identified.
- It is assumed that the existing DH networks Amsterdam North & West and Amsterdam South & East, will be extended. Moreover, it is expected that new DH networks will be developed.

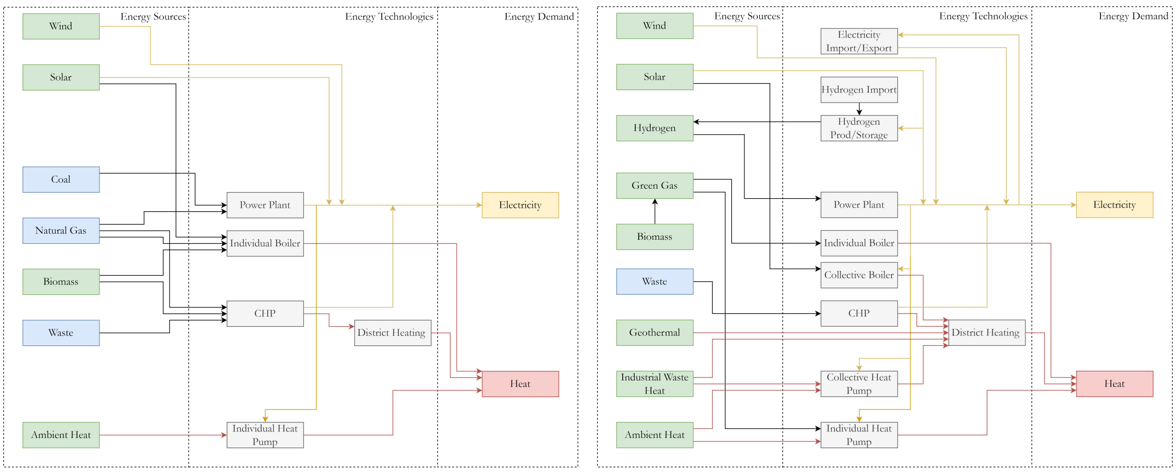
- It is assumed that the contributions of geothermal, industrial waste heat and aquathermal to the DH networks are equal, as the real potential of these expected main future sources is yet to be explored. Moreover, the full identified potential of high-temperature waste heat sources is assumed to supply heat. The remainder of the industrial waste heat is assumed to be low-temperature.
- The remainder of the DH supply is assumed to be filled with waste incineration, an E-boiler and collective solar boilers. Waste incineration is assumed to still contribute to the electricity and heat supply. However, the AEC plant is expected to be closed and there will be a shift towards more heat production and less electricity production, so that the Amsterdam North & West DH network can be supplied. Furthermore, the Diemen E-boiler is assumed to supply heat to 20.000 households per year. Moreover, solar collective boilers are assumed to supply heat to a neighborhood in Haarlem (Ramplaankwartier) and to a comparable neighborhood in Amsterdam.

Validity

The assumptions are based on the regional energy plans and the reflection. From the reflection, it became evident that there is still much uncertainty regarding the exact contribution of renewable electricity and heating sources to the energy supply. Therefore, the contributions can deviate greatly from the assumptions that are made. Resulting from the reflection, the biggest uncertainties are regarding the exact availability of geothermal, low-temperature industrial waste heat and green gas. The absence of the former two DH sources can lead to an increased electrification for heat supply, while the absence of the latter heat source can lead to the use of natural gas or green hydrogen in individual boilers. The use of hydrogen can subsequently result in an increased electricity demand or green hydrogen import.

6.7.2 Interconnections of System Components

Figure 6.4 shows the comparison between the system diagrams of the current regional energy system and the estimated future regional energy system. The system diagrams visualize the differences between the interconnections of the system components and the direction of the energy flows.



(a) Current (2019) national

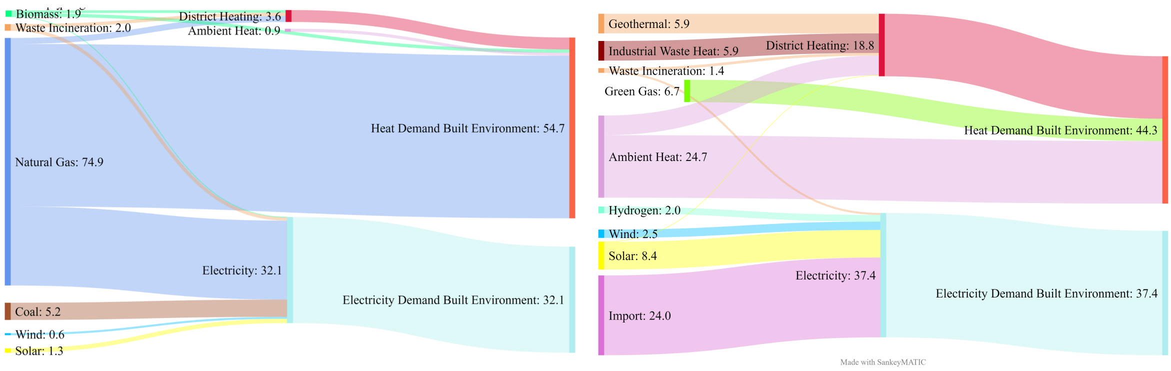
(b) Current (2019) regional

Figure 6.4: System diagrams of the interconnections between the system components of the current and estimated future electricity and heating sector for the built environment of region North-Holland South

In the expected future regional energy system, some of the current components remain. Fluctuating RE sources, such as onshore wind and solar still generate electricity and waste incineration CHP plants still produce both electricity and usable heat for the DH networks. Moreover, ambient heat is used to fulfill heat demand in a decentralized manner through individual heat pumps. However, some additional components contribute to the energy supply in the future energy system. Green hydrogen is produced from electricity surpluses and substitutes coal and natural gas within power plants. Moreover, green gas is produced through biomass fermentation and gasification. The green gas is used as an energy source for individual boilers and hybrid heat pumps. Furthermore, solar is used as a source for collective boilers, which supply heat to the DH network. Lastly, geothermal, industrial waste heat and ambient heat are used as a source for DH, via collective heat pumps in case of low-temperature. Both types of heat pumps additionally require electricity.

6.7.3 Quantified Energy Flows

Figure 6.5 shows the comparison between the sankey diagrams of the current energy system and the international scenario energy system. This figure illustrates the major differences between the two energy systems in terms of quantified energy flows.



(a) Current (2019) **(b)** Future (2050)

Figure 6.5: Sankey diagrams of the energy flows in PJ between the system components of the current and estimated future electricity and heating sector for the built environment of region North-Holland South. Left side of each diagram represents supply, right side represents demand.

The final energy supply for electricity in the built environment experiences a shift from natural gas to mainly import. Furthermore, other sources for electricity are onshore wind, solar, hydrogen and waste incineration of which mainly the contribution of solar increases. The final energy supply for heat in the built environment shifts from natural gas to DH, ambient heat and green gas. All of these three sources experience a substantial growth. Moreover, multiple sources are used for the DH supply, namely geothermal, industrial waste heat, waste incineration, ambient heat and solar. Geothermal, industrial waste heat and ambient heat are the largest contributors. The share of RE sources within the future electricity, heating and district heating supply on a regional scale are all 99%.

6.8 INTERCONNECTIONS BETWEEN ELECTRICITY AND HEAT

In this section, the focus lies on the coupling elements forming interconnections between electricity and heat within the current and future regional energy systems.

6.8.1 National Coupling Elements

In the current regional energy system, the three following specific interconnections are identified:

- Individual heat pumps function as a coupling element between heat supply and electricity demand.
- CHP plants function as a coupling element between heat supply and electricity supply. The heat is delivered via DH networks.

In the future regional energy system, the same coupling elements as included in the current energy system are expected to play a role. However, two additional coupling element are included:

- Collective heat pumps function as a coupling element between heat supply and electricity demand. The heat is delivered via DH networks.
- An collective electric boiler functions as a coupling element between heat supply and electricity demand. The heat is delivered via DH networks.

The first three coupling elements have already been discussed in section 5.6. Their characteristics are also applicable to the regional coupling elements. Therefore, the current and future average COPs as assumed for the individual and collective heat pumps are applied here. The collective electric boiler (E-boiler) was not included in the national energy system. In the future regional energy system, an E-boiler is able to supply heat via the DH system. As discussed in section 6.5, an average COP of 1 is assumed, as all the demanded electricity is converted into heat.

6.8.2 Quantified Interconnections

Figure 6.6 compares the contributions of the coupling elements for the current and estimated future regional energy system to the heat supply, electricity demand and electricity supply. Currently, the contribution of coupling elements to the heat supply is relatively small. However, in the future system, almost 70% of the heat supply technologies are estimated to be connected to the electricity sector. Similar to in the national transition, an increased IES approach is thus expected to be taken in order to achieve climate objectives. The individual heat pumps (orange colours) contribute the most to this substantial increase. Moreover, it can be derived that the contribution of the coupling elements to the electricity demand is estimated to increase substantially. In the current energy system, a negligible interconnection is made with electricity demand through individual heat pumps using ambient heat. This contribution is so small (0,1%) that it is barely visible in the figure. In the future energy system, the contribution to the electricity demand is estimated to increase approximately 180 times. Again, the individual heat pumps (orange colours) mainly contribute to this. Lastly, it becomes evident that the contribution of the coupling elements to the electricity supply is expected to decrease extremely. Currently, CHP plants (blue colours) supply approximately half of the total electricity supply. In the future energy system, natural gas-fired CHP plants are estimated to be eliminated and only part of the waste incineration CHP plant are estimated to contribute to the electricity supply.

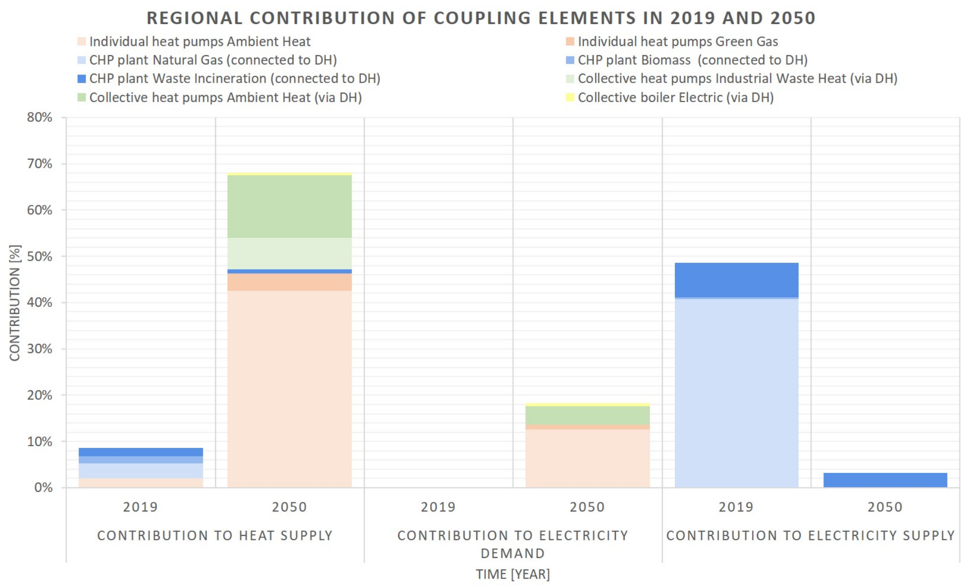


Figure 6.6: Regional contribution of current and future coupling elements to the heat supply, electricity demand and electricity supply for the built environment

Overall, the heating system transitions from a system that has a connection with electricity supply, to a system that is largely connected with electricity demand. The waste incineration plants are estimated to fulfill approximately 16% of the electricity demanded by heat alternatives. The remainder of the electricity demand is required to be fulfilled by other sources.

6.9 CONCLUSION

6.9.1 Regional Energy Transition

In this chapter, the fourth sub-question *How are the electricity and heating sector expected to transition according to the regional energy plans in a specific Dutch region?* is answered as follows:

The electricity transition is mainly managed on a national policy level, while the heat transition is mainly managed on a municipal level. Therefore, municipalities have a lot of responsibility regarding facilitating the local heat transition. However, municipalities lack experience with regard to managing the local heat transition, which can result in misaligned local initiatives, delays or malfunctioning lock-ins in the region North-Holland South. Therefore, the province North-Holland wishes to improve the collaboration of municipalities among each other and with other actors by establishing the Service Point for Sustainable Energy (SPSE). Currently, the overall regional energy plans of the involved actors are well aligned, except for some misalignments regarding municipalities approaches and the use of transition sources, such as natural gas and biomass.

The current regional energy system is primarily based on natural gas. According to the Regional Energy Strategy (RES), Transition Visions for Heat (TVH) and regional energy plans of involved non-governmental actors, an estimation is made of the future energy system of the region North-Holland South. The energy system includes a significant electrification, which is based on a large-scale supply of imported electricity. Moreover, solar, wind and waste incineration supply part of the electricity, while hydrogen functions as a means for providing flexibility. Especially the large planned increase in solar panels can be challenging. The energy system uses DH, (hybrid) individual heat pumps and green gas individual boilers to supply heat. These renewable heating alternatives each have various challenges to overcome before large scale implementation can be realized, regarding infrastructure, source availability and costs. Sources for DH are estimated to be geothermal, industrial waste heat, ambient heat and waste incineration. However, research still is required to confirm the availability of these DH sources.

6.9.2 Regional District Heating Transition

In the national analysis in chapter 5, it was concluded that the national transition to renewable DH can potentially cause for five trends. The regional analysis was conducted in order to explore how these trends are substantiated within the region of North-Holland South. The fifth sub-question *What is the impact of the transition to renewable district heating on the electricity and heating sector according to the regional energy plans of a specific Dutch region?* is answered as follows:

Trend 1: Increased DH Supply

It is expected that DH will become one of the most important heating alternatives increasing its contribution to the heat supply from 7% to 42,5%. The aim is to eventually substitute the current individual natural gas-fired boilers. The implementation and expansion of DH networks seems to be very popular amongst involved actors. Many municipalities have identified neighborhoods in which a DH network is desirable. Municipalities want collaborate with DH network operators and heat producers in order to realize these networks. However, as DH networks are naturally dependent on their DH sources, the availability of these sources in the region determines if the desired DH networks can actually be realized.

Trend 2: Competition with Other Heating Alternatives

Municipalities see potential in (hybrid green gas) individual heat pumps and green gas-fired individual boilers as other heating alternatives. DH and individual heat pumps are preferred over green gas boilers. Green gas boilers are planned to be used only where no alternatives are possible. A misalignment was identified regarding the use of green gas. On one hand, the municipalities and grid operators expect green gas to play a role. On the other hand, the RES, heat producers, grid operators and DH operators do not foresee a sufficient potential for green gas for renewable heat supply. As currently the regional energy system is locked in a natural gas-infrastructure and it is technically feasible to use green gas within this existing gas-infrastructure, the choice for green gas seems obvious. However, the choice of municipalities for green gas can endanger the phasing-out of natural gas within the system, if its availability eventually turns out to be low.

Trend 3: Varying and Uncertain DH Sources

DH sources are expected to shift from mainly natural gas-fired CHP plants to renewable alternatives. From the RES and TVHs it becomes evident that there is no room for coal, natural gas and biomass in the regional energy system of 2050. Heat producers thus prepare to close or re-design these power plants. However, these plans cause for some confusion, as natural gas and biomass are viewed as transition sources. Therefore, heat producers can be reluctant to make decisions regarding closure or re-design, especially when new DH networks are being realized.

As the DH supply is expected to increase substantially, renewable DH sources are desperately required. In the RES, several potential DH sources are described. Many of these DH sources also appear in the TVHs of the municipalities. Geothermal, industrial waste heat and ambient heat are planned to be the biggest DH sources. Additionally, collective solar and electric boilers and waste incineration CHP plants contribute. Municipalities and DH operators are very motivated to discover a sufficient amount of geothermal energy. If there is sufficient potential, geothermal is desired to supply the base load of the DH supply. Therefore, exploratory research is being conducted and permits are pending. However, at this rate, the first geothermal source is not operational before 2030. Moreover, serious delays can occur due to the lack of public support, especially regarding the large-scale application of geothermal. Simultaneously, the potential of industrial waste heat and ambient heat is explored and solar and e-boilers are being developed. The realization of these sources brings along less uncertainties compared to geothermal. However, serious investments and collaboration are required in order to realize these plans. Overall, there is still a long way to go before the future DH sources are actually realized. This stimulates transition sources such as biomass and natural gas to be part of the energy system longer. Moreover, it can stimulate the desire for other renewable heating alternatives, such as individual heat pumps and individual boilers.

Trend 4: Increased Electricity Demand

DH networks are perceived as promising due to the potential of the DH network to use high-temperature sources, such as geothermal, high-temperature industrial waste heat and waste incineration. As these sources do not require a collective heat pump, they limit the electricity demand. If a high potential for geothermal and high-temperature waste heat is realized, less electricity will be required to fulfill the DH demand and vice versa. In addition to these high-temperature sources, low-temperature waste heat from datacenters identified as DH source. As the temperature of this source is still higher than that of ambient heat, less electricity is required to upgrade the heat. Collective heat pumps using ambient heat are also considered as a DH source. However, the higher temperature DH sources are preferred. DH competes to a certain extend with individual heat pumps. Individual heat pumps use ambient heat and therefore require more electricity compared to DH networks that use high-temperature sources or low-temperature industrial waste heat. Therefore, individual heat pumps put more pressure on the electricity grid.

Overall, it can be stated that it is expected that both the future heating sector in general and DH specifically will demand more electricity than in the current regional energy system. The heating sector is thus estimated to be electrified. In order to sufficiently supply the demanded electricity, the capacity of the electricity grid is required to increase. Therefore, the grid operators plan to adapt their investment plans in order to increase and maintain grid capacity in strategic areas. An advantage of DH is that the involved coupling elements provide options regarding the balancing of the electricity grid, as collective heat pumps and electric boilers can be combined with a heat buffer. This way, renewable heat can be stored. The potential of this flexibility mechanism depends on the thermal storage capacity of the buffers.

Trend 5: Decreased Electricity Supply

In the current system, the natural gas-fired CHP plant is the largest coupling element and contributor to both the DH and electricity supply. These plants are planned to be eliminated, resulting in an electricity supply gap. As the electricity demand is estimated to increase, the realization of sufficient electricity generation capacity is crucial.

6.9.3 Overall Conclusion

In the region North-Holland South, both governmental and non-governmental actors expect the most important heating alternatives to be DH and individual heat pumps. Therefore, the transition to a renewable heating system is estimated to result in an increased electricity demand. Electrification of the heating sector through especially individual heat pumps is expected. DH is viewed by all involved actors as a promising renewable heating alternative and there seems to be a 'DH hype'. DH networks are perceived as promising due to the many potential renewable DH sources. The use of high-temperature DH sources can limit electricity demand, while the use of low-temperature sources in combination with a collective heat pump can provide flexibility to the electricity grid. Therefore, DH could provide some relief for the electricity system.

However, research still is required to confirm the availability of DH sources, especially for geothermal. Therefore, different approaches of municipalities lead to different potential risks. Whenever municipalities assertively choose to implement DH networks connected to transition sources such as natural gas and biomass, there is a possibility that sources such as geothermal are not available. This can cause municipalities to be locked-in in a DH infrastructure without sufficient renewable DH sources. Moreover, whenever municipalities have a reluctant approach, this can result in a delay of policies leading to not meeting climate objectives. Lastly, different approaches may result in misaligned local initiatives.

7 NATIONAL VERSUS REGIONAL ENERGY SYSTEMS

In this chapter, the national and regional energy systems as explored in chapter 5 and 6 are compared in order to determine similarities and differences in their transition. The sixth sub-question *How do the transitions of the national and regional electricity and heating sector compare?* is answered. The methods as discussed in chapter 3 are applied.

7.1 CURRENT ENERGY SYSTEMS

The regional energy system of North-Holland South is part of the national Dutch energy system. In this section, the current energy systems of the areas are compared.

7.1.1 Area Properties

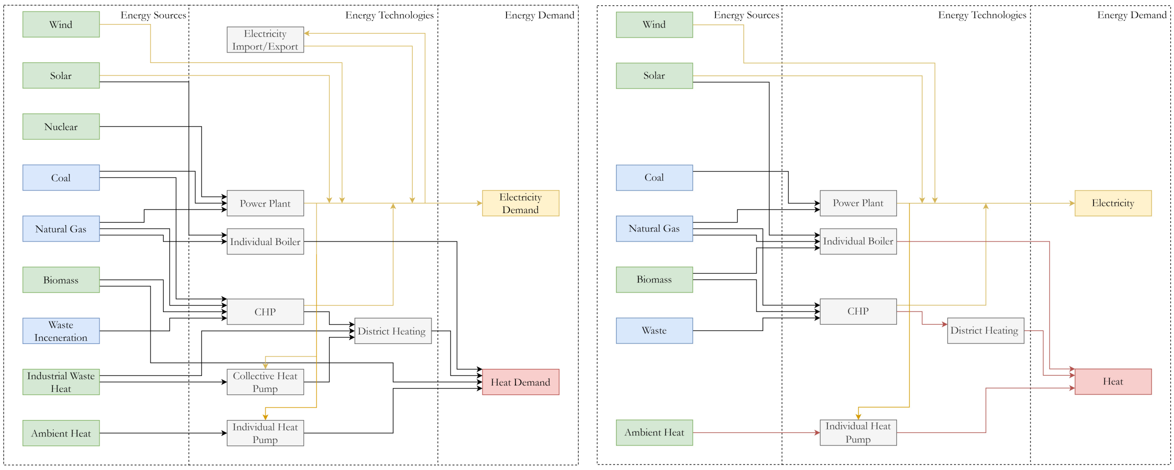
The region North-Holland South is characterized by a highly urbanized area around Amsterdam. The surrounding areas have a more rural character with agricultural activity. However, many residential areas can also be identified there. Table 7.1 shows the national and regional area properties for the built environment in 2019. Overall, the region has a much higher building density than the Netherlands [CBS, 2019c]. This property heavily impacts the manner in which the regional energy system is designed [Keirstead et al., 2012].

Property	National	Regional	Share [%]
Population [#]	17.282.163	2.181.670	13
Buildings [#]	7.814.912	978.902	13
Surface [ha]	4.154.303	162.665	4
Building Density [#/ha]	1,9	6,0	316

Table 7.1: National and regional area properties of the built environment in 2019. Data Sources: CBS [2019c,d, 2015a]

7.1.2 Current Energy Flows

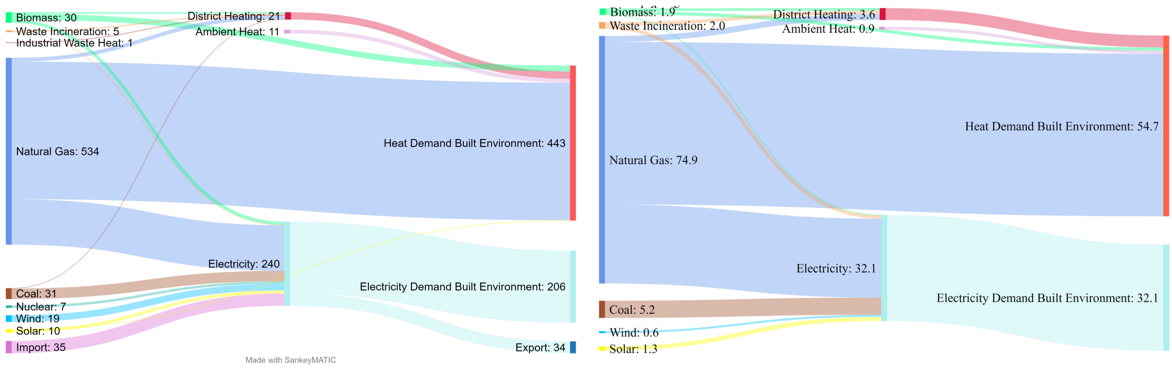
Figure 7.1 and figure 7.2 depict the comparison between the interconnections of the system components and the quantified energy flows of the current national and regional electricity and heating sector respectively.



(a) Current (2019) national

(b) Current (2019) regional

Figure 7.1: System diagrams of the interconnections between the system components of the regional and national electricity and heating sector for the built environment in 2019



(a) Current (2019) national

(b) Current (2019) regional

Figure 7.2: Sankey diagrams of the energy flows in PJ between the system components of the current national and regional electricity and heating sector for the built environment

It can be derived that the systems are quite similar, except for the contribution of nuclear power plants and import to the electricity supply and the contribution of industrial waste heat for DH supply. Both energy systems currently heavily rely on natural gas for electricity and heating supply. However, in the regional electricity sector, relatively more natural gas and coal are used to supply electricity, while relatively less wind and solar are contributing. The difference in wind energy is partly explained by the absence of offshore wind in the regional energy system. Furthermore, the contribution of waste incineration to the DH supply is relatively higher in the regional system. The availability of this DH source can be an explanation for the larger DH supply in the region North-Holland South. Moreover, the higher building density within the region can also stimulate the implementation of DH networks.

7.2 FUTURE ENERGY SYSTEMS

In this section, the future energy system of the region North-Holland South is compared to the energy systems of the national scenarios.

7.2.1 Driving Factors

When comparing the driving forces of the scenarios as discussed in section 5.4 with the regional energy plans of the case study, several observations can be done.

- A resemblance can be identified with regard to the regional scenario. In this scenario, the Dutch government outsources the governance of the energy transition largely to provinces and municipalities. Residents and companies are actively involved in projects initiated by local government bodies, such as solar PV, DH and home insulation. This approach is quite similar to the identified approach regarding the heat transition.

- A resemblance can be identified with regard to the national scenario. In this scenario, the national government takes the lead. This will lead to projects with high start-up costs, such as large-scale offshore wind and a national hydrogen infrastructure. This approach is quite similar to the identified approach regarding the transition of the electricity sector.

It could therefore be the case that the national scenario will have a similar electricity supply mix to the case study, while the regional scenario will have a similar heat supply mix.

7.2.2 Electricity Supply

Figure 7.3 depicts the comparison between the future electricity supply of region North-Holland South and the national scenarios. With regard to wind and solar, the composition of the regional electricity supply mix is similar to the regional and national scenario, as solar is clearly a bigger contributor than wind. These scenarios assume a large installation of decentralized solar panels by residents, as depicted in figure 7.4. This trend can also be identified in the case study. Moreover, no centralized electricity generation via solar is estimated in the region. This expectation fits the most with the regional scenario, as the share of centralized solar is the lowest.

With regard to import and the use of hydrogen, the regional supply mix compares to the international scenario. In the international scenario, the use of imported electricity and hydrogen was explained by the level of openness of the energy markets. Resulting from this, an advanced international infrastructure for the exchange of energy carriers (hydrogen, electricity) may be required. The use of imported electricity in the region can be explained by the fact that the region is part of the Netherlands. Therefore, the imported electricity does not necessarily originate from other countries, but from other regions as well, which is quite plausible. Moreover, the use of hydrogen in the region is explained by the conversion of the natural gas power plants into green hydrogen plants to provide flexibility. The used hydrogen is imported from other regions, such as hydrogen produced at the North-Sea.

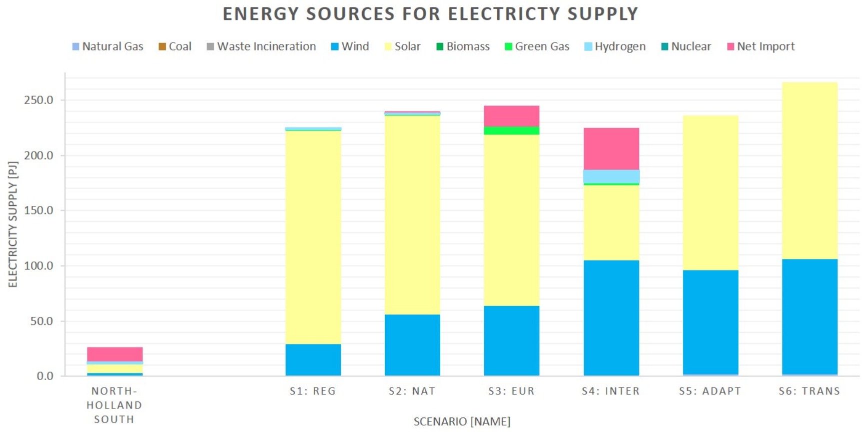


Figure 7.3: Final energy demand of the built environment in the case study (2050) and scenarios (2050)

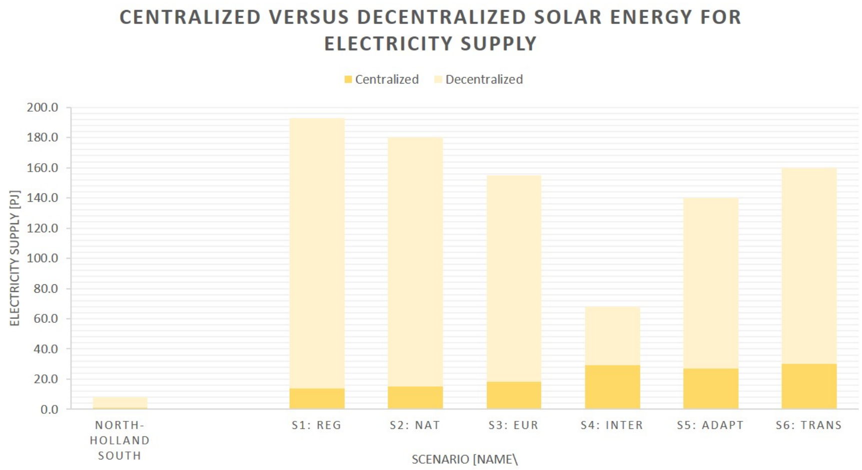


Figure 7.4: Final energy demand of the built environment in the case study (2050) and scenarios (2050)

7.2.3 Heat Supply

The comparison between the future heat supply of region North-Holland South and the national scenarios is depicted in figure 7.5. The three main heating alternatives are identified to be DH, individual heat pumps and individual boilers. DH and individual heat pumps are included in all of the scenarios. However, the use of green gas in individual boilers is not. The composition of the heat supply mix is quite similar to in the regional and national scenario. However, no individual solar boilers were assumed to be used. Biomass, hydrogen and natural gas for heat supply of the built environment were assumed not to be used according to the regional energy plans.

In the regional scenario, a political driver for DH is the local governance of the energy system, which causes DH networks to be realized. Therefore, the share of DH is higher than the share of individual heat pumps. In the national scenario, the national government takes the lead in the heat transition and therefore, solely large-scale DH networks are realized. This results in a lower share of DH. From the analysis of the regional energy plans, it became evident that indeed the implementation of DH networks on all scales is an attractive renewable heating alternative for municipalities. The impression was created within the TVHs that municipalities preferred the use of DH networks over individual heat pumps, due to lower social

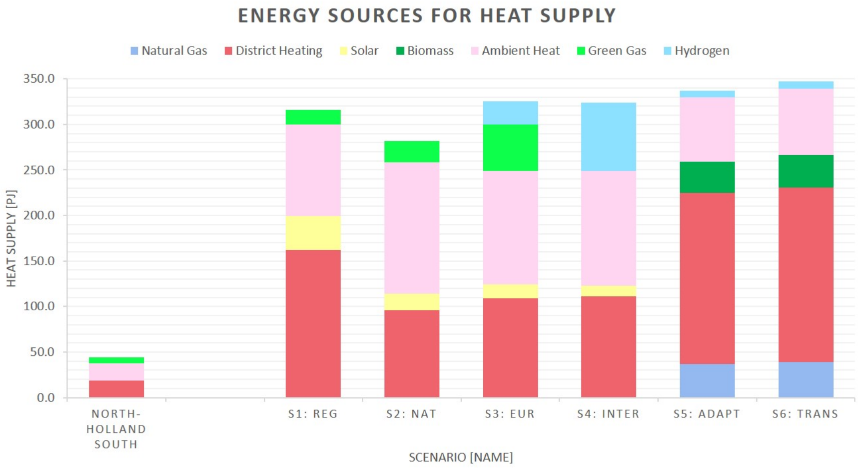


Figure 7.5: Final energy demand of the built environment in the case study (2050) and scenarios (2050)

costs and less electricity demand. Therefore, although the share of DH and individual heat pumps are equal in the regional energy system, it fits the regional energy scenario the most.

7.2.4 District Heating Supply

Figure 7.6 depicts the comparison between the future DH supply of region North-Holland South and the national scenarios. The DH sources identified were geothermal, ambient heat, industrial waste heat, waste incineration and an electric boiler. Except for the electric boiler, these DH sources were included in the scenarios. However, this exact composition of the DH supply mix is not similar to any of the scenarios. Biomass, hydrogen and green gas for DH supply of the built environment were assumed not to be used according to the regional energy plans.

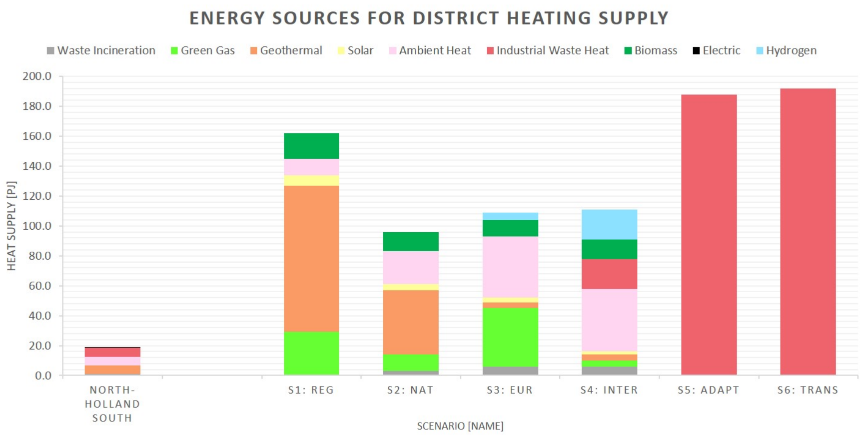


Figure 7.6: Final energy demand of the built environment in the case study (2050) and scenarios (2050)

With regard to geothermal, the regional and national scenario compare the most to the case study. It can be derived that in the regional scenario, the high share of geothermal as DH supply source in the regional scenarios is a result of municipal incentives. Municipalities are actively searching for geothermal sources to make heat available to their residents. Additionally, municipalities jointly realize larger-scale heat networks, in order for municipalities with less geothermal potential to have sufficient available heat. These larger-scale heat network also explain the high share of geothermal in the national scenario, in which the national government takes the lead. From the regional energy plans, it became evident that the geothermal is an attractive option for municipalities and DH operators. Municipalities really take the lead in the search for geothermal and desire to realize a large potential. Therefore, the regional energy system fits regional scenario the most with regard to geothermal.

Waste incineration emerges in the national, European and international scenario. These scenarios are not particularly driven by a high level of public environmental awareness. Therefore, it can be derived that there would be public support regarding waste incineration in combination with CCS. Moreover, it can be derived that in that case there will be waste to incinerate, as no fully circular economy is achieved. In the case study, the use of the AEB waste incineration plant for DH supply is also stimulated and not necessarily objected. As the share of waste incineration is the highest in the international scenario, the regional energy system resembles this scenario the most.

Lastly, there is much unclarity regarding the expectations for industrial waste heat and ambient heat. Industrial waste heat only emerges in the international, ADAPT and TRANSFORM scenario. With regards to share, the international scenario compares the most to the case study. From the driving forces of the international scenario, it is not clear why industrial waste heat is used as a DH source. Moreover, it is also not clear why the regional scenario does not expect industrial waste heat to play a role in their DH supply. From the regional energy plans it became evident that municipalities stimulate the use of industrial waste heat from high temperature sources and datacenters, as these are local DH sources.

7.2.5 Interconnections between Electricity and Heat

Figures 7.7, 7.8 and 7.9 compare the contributions of the coupling elements for the regional energy system and the scenarios to the heat supply, electricity demand and electricity supply respectively.

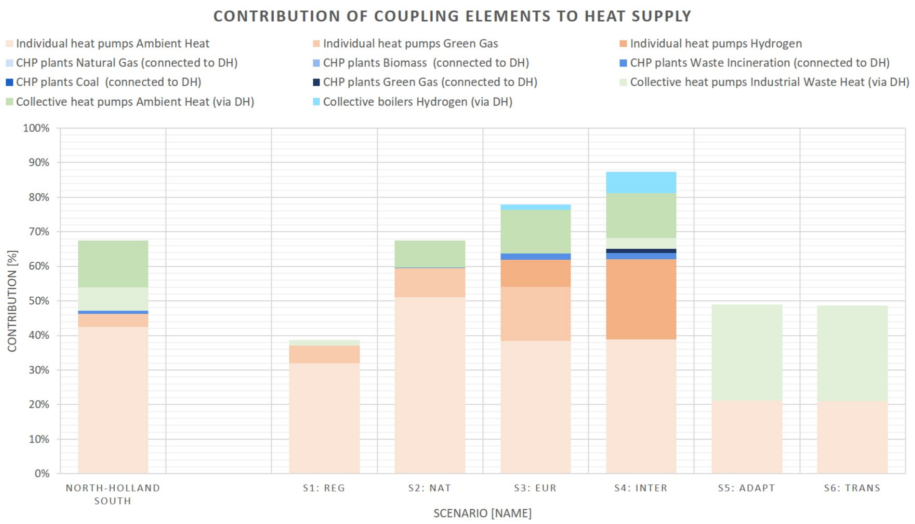


Figure 7.7: Contribution of coupling elements to the heat supply for the built environment in the case study (2050) and the scenarios (2050)

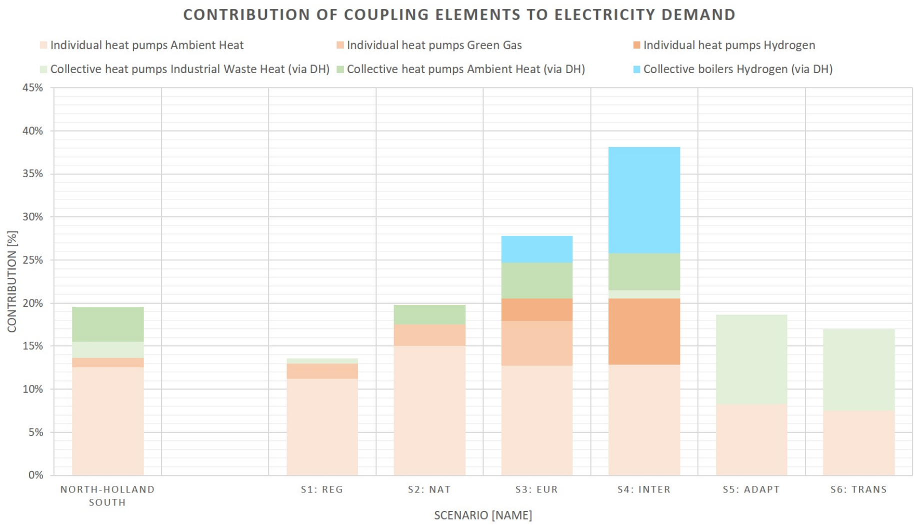


Figure 7.8: Contribution of coupling elements to the electricity demand for the built environment in the case study (2050) and the scenarios (2050)

Figure 5.10 and 5.11 show that the regional energy system compares most with the national scenario with regards to percentages. Both of these systems expect almost 70% of the heat supply technologies to be connected to the electricity sector. Mainly individual heat pumps (orange colours) and collective heat pumps (green colours) contribute to this, as they demand electricity in order to function. The use of collective hydrogen boilers and individual hydrogen heat pumps is not included in the regional energy system and therefore, the demanded electricity remains average.

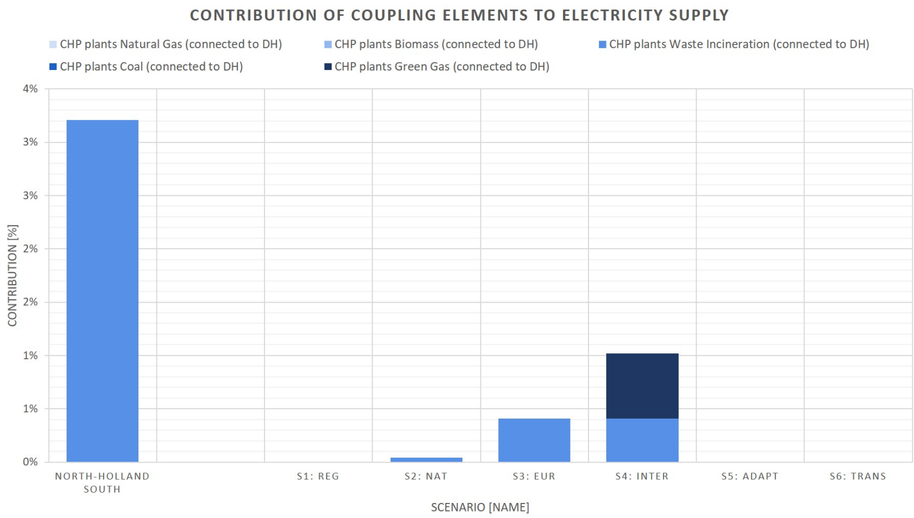


Figure 7.9: Contribution of coupling elements to the electricity supply for the built environment in the case study (2050) and the scenarios (2050)

From figure 5.12 it becomes evident that the regional energy system expects the contribution of the CHP plants to be approximately 3,5%. The European scenario compares most with this as the contribution is expected to be 1% and no green gas-fired CHP plants are included.

7.3 CONCLUSION

In this chapter, the sixth sub-question *How do the transitions of the national and regional electricity and heating sector compare?* is answered as follows:

Both the national and regional current energy systems have similar interconnections and are highly dependent on natural gas. The driving forces of the regional and national scenario strongly resemble the case study approach with regard to the heating and electricity sector respectively. However, it can be concluded that the future regional energy system of 2050 resembles a mix of mainly the regional, national and international scenarios.

This resemblance does not mean that the future national energy system of 2050 also will resemble a mix of the regional, national and international scenario. The results of merely one Dutch region can not be generalized with regard to the national energy system. This is strengthened by the differences in area properties between the region North-Holland South and the Netherlands. Moreover, the estimation of the future regional energy system was based on many assumptions with associated uncertainties.

8 DISCUSSION AND CONCLUSION

In this thesis, the impact of the transition from traditional to renewable DH on the Dutch electricity and heating sector is explored on both a national and regional level. In this chapter, the main findings are discussed and reflected upon. Lastly, a final conclusion is given.

8.1 MAIN FINDINGS

By combing the findings of the sub-questions answered throughout this thesis, the main research question *What is the impact of the transition from traditional to renewable district heating on the Dutch electricity and heating sector?* is answered.

The current Dutch energy system is experiencing an infrastructural natural gas lock-in, complicating the transition to a renewable energy system. In the national scenarios, there is much consent with regard to the energy mix for large-scale renewable electricity supply, while there is a great deviation in expected renewable heating alternatives. Moreover, the availability of renewable heating sources and especially DH sources is currently quite uncertain. The transition to renewable DH does not always seem to make sense alongside the strong expectations of a fully renewable electricity supply. This is mainly due to the elimination of the current main DH source, the natural gas-fired CHP plant. Overall, it is currently not clear how to exactly realize the national heat transition.

Regional energy plans provided more clarity to the implementation of DH in the region North-Holland South. The transition to a renewable DH system in the region is expected to have an impact on the electricity and heating sector.

- Electricity sector: I) the use of renewable high-temperature DH sources limits electricity demand, II) the use of renewable low-temperature sources in combination with a collective heat pump or E-boiler increases electricity demand, but can provide flexibility to the electricity grid through thermal storage.
- Heating sector: I) individual natural gas-fired boilers are substituted, II) current DH sources are substituted by uncertain renewable DH sources.

Both governmental and non-governmental actors expect renewable DH to be an important heating alternative in the region, despite the uncertainty regarding DH source availability. Regional future DH sources are estimated to be geothermal, industrial waste heat, ambient heat and waste incineration. However, there is a long and uncertain way to go before these DH sources are actually realized. Current research regarding source availability is not sufficient and there is potential for the lack of public support. This uncertainty causes risks to occur, as transition sources such as biomass and natural gas are stimulated to be part of the energy system for a longer period. The use of transition sources can cause delays in the implementation of long-term alternatives. Moreover, if DH systems are connected to transition sources while renewable DH sources will not become available, the energy system will be locked-in in a traditional DH infrastructure. Lastly, uncertainty may result in different approaches and misaligned local initiatives.

In order to fully understand the impact of the transition to renewable DH, it is important to understand the context in which this transition occurs. First, the regional energy system expects a significant electrification. This electrification needs to be supported by large volumes of renewable electricity. This can be challenging, as there must be a sufficient amount of regionally imported electricity, wind and solar energy and an enhanced electricity grid. Second, besides DH networks, planned renewable heating alternatives are mainly (hybrid green gas) individual heat pumps and a limited amount of green gas-fired individual boilers. Uncertainty regarding source availability is also applicable here, causing risks to occur. The use of individual heat pumps substantially increases the electricity demand. Moreover, the choice of municipalities for green gas can endanger the phasing-out of natural gas within the system and cause an infrastructural lock-in of the existing gas-infrastructure, if the availability of green gas eventually turns out to be low.

Considering this specific regional context, the impact of the transition to renewable DH can be beneficial. First, the implementation of DH in combination with both high- and low-temperature sources can provide some needed relief for the electricity sector. Secondly, there are uncertainties and risks related to source availability involved with all of the regionally planned renewable heating alternatives. These risks can be spread by implementing renewable DH, as there are many potential DH sources (even though uncertain). However, due to the involved uncertainties, risks and complex interactions between actors, technology and institutions, designing the future heat supply is challenging and decision-making is difficult. The heat transition is mainly managed on a municipal level without much collaboration with other levels of government. Municipalities have the final responsibility. Their identified lack of experience with regard to managing the local heat transition can increase the risks of misaligned local initiatives, policy delays and malfunctioning lock-ins.

8.2 SOCIETAL REFLECTION

The findings of this thesis have societal implications for policy and practice that result in several recommendations for policy-makers and project developers. This will bring the Netherlands closer to becoming natural gas free and achieve national climate objectives.

8.2.1 Societal Implications

The implementation of DH can be beneficial under specific local conditions. However, there are still uncertainties regarding the availability of energy sources. This is the case for DH sources specifically, but also with regard to green gas and renewable electricity required for other renewable heating alternatives. Due to the urgency of the heat transition, choices regarding renewable heating alternatives and synergies between electricity and heat must be made now. The better these choices are made, the more misaligned local initiatives, policy delays and malfunctioning infrastructural and heat source lock-ins can be prevented. Therefore, municipalities are strongly advised to collect new knowledge, expertise and competences regarding the facilitation of the heat transition. This can help with creating the legal and regulatory frameworks required to steer the transition pathway. Hereby, several factors are particularly important.

First, municipalities are advised to recognize the potential risk of delay and infrastructural and source related lock-ins within their decision-making. Hereby, an important factor is the careful use of transition sources. It is recommended to conduct risk assessment studies, include back-up sources for heat supply within the feasibility studies and determine the real potential of planned heat sources as soon as possible. This contributes to forming more certain, adaptive and concrete energy plans. It is advised to monitor and stimulate the development of planned heat sources, specifically geothermal, industrial waste heat and green gas. This can be done by collaborating with the national government, energy producers and grid operators and provide incentives. Simultaneously, municipalities are advised to monitor and increase the participation of citizens in the heat transition. It is advised to actively invite and thoroughly involve local residents to the decision-making process in an early stage, especially in order to create public support for geothermal and green gas as heat sources. Lastly, due to the expectation for a substantial electrification of the heating sector, it is important for municipalities to monitor the renewable electricity demanded by heat alternatives. Depending on the electrification of the heating sector and the need for flexibility, municipalities can stimulate thermal storage in combination with coupling elements within DH systems.

Besides the important role that municipalities need to play, provinces are advised to play a role in the collaboration between involved actors, as different approaches can lead to misaligned local initiatives. It is recommended to further monitor and facilitate the collaboration between different municipalities, energy producers and grid operators and act as a intermediary between municipalities and national government. It is important to stimulate supra-municipal collaborations, the sharing of developments and the evaluation and alignment of concrete plans. Moreover, energy producers and grid operators are advised to respond to the mentioned recommendations for municipalities. They are advised to pursue the exploration of the potential for geothermal heat, industrial waste heat and green gas and investigate the possibilities for thermal storage within the energy system. Electricity grid operators are recommended to address the need for flexibility and collaborate with DH grid operators and heat producers.

Moreover, the expectation for a substantial electrification of the heating sector also has implications for the national government. First, it is recommended to implement policies that enable electricity grid operators to pre-invest to increase grid capacity. As a large electrification of the heating sector is expected, electricity grids require to have a sufficient capacity in order to prevent congestion. Moreover, the national government is advised to keep monitoring the national expected increased electricity demand and associated required generated and imported electricity.

Following from this last point, all involved actors are advised to be highly aware of the increasing dependency on electricity. A fully renewable electricity supply is expected to be based on large shares of solar and wind energy and possibly imported electricity. This raises questions regarding the future import demand of Dutch regions and the Netherlands as a whole. The extent to which electricity import is possible, is dependent on how other countries design their future energy system and geopolitical conditions. A risk occurs when other countries are not able or willing to export electricity for a fair price (or not at all), while the Dutch electricity supply can not fulfill demand. As other European countries are also shifting from conventional sources to fluctuating RE sources, it is uncertain if a sufficient amount of electricity will be available to sustain Europe's security of supply. According to TenneT [2020] "an important risk of a greater decline in security of supply is a greater decline in available flexible production capacity in the European system". The dependency on imported electricity as a main energy carrier raises questions regarding the desirability of the expected strong electrification of the heating sector.

8.2.2 Recommendations for Policy-Makers and Project Developers

The recommendations for the involved regional actors following from the societal implications of the main findings are summarized in table 8.1.

Actor	Recommendation	Based on Main Finding
Municipalities	• Recognize the identified risks of delays and infrastructural and heat source lock-ins within energy plans • Monitor and stimulate the development of (district) heat sources, especially geothermal, industrial waste heat and green gas • Monitor and increase the participation of citizens in the heat transition, especially regarding large-scale geothermal and green gas applications • Monitor the renewable electricity demanded by heat alternatives • Stimulate thermal storage combined with coupling elements in DH systems • Actively take part in collaboration with other municipalities and involved actors	• (District) heat source uncertainty leads to risks of delays and infrastructural and heat source lock-ins • Large amounts of uncertain (district) heat sources are required, especially geothermal, industrial waste heat and green gas • The potential lack of public support can cause serious delays in the development of expected (district) heat sources, especially geothermal and green gas • A significant electrification of the heating sector is expected • DH systems can provide relief for the electricity sector through thermal storage • Different approaches can lead to misaligned local initiatives
Provinces	• Monitor, facilitate and stimulate the collaboration between different municipalities, energy producers and grid operators by extending the SPSE • Act as a intermediary between municipalities and national government	• Different approaches can lead to misaligned local initiatives • Different levels of government (municipalities, provinces and national government) do not cooperate sufficiently
Energy producers & Grid operators	• Explore the potential for geothermal heat, industrial waste heat and green gas • Investigate the possibilities for thermal storage combined with coupling elements • Collaboration between electricity grid operators, DH grid operators and heat producers	• Large amounts of uncertain (district) heat sources are required, especially geothermal, industrial waste heat and green gas • DH systems can provide relief for the electricity sector through thermal storage • Different approaches can lead to misaligned local initiatives
National government	• Implement policies that enable the electricity grid operators to pre-invest to increase grid capacity • Closely monitor the national expected increased electricity demand and associated required generated and imported electricity • Closely monitor progress of local heat transitions via provinces	• The expected electrification requires an enhanced electricity grid • The expected electrification needs to be supported by large volumes of renewable electricity • Municipalities lack experience with regard to managing the local heat transition

Table 8.1: Recommendations for involved regional actors

8.3 ACADEMIC REFLECTION

This thesis has implications within the academic field. In the academic reflection, the scientific contribution of this thesis is discussed. Moreover, the applicability of the CoSEM perspective is highlighted and limitations of the research are addressed.

8.3.1 Scientific Contribution

As mentioned in section 2.1, a particular subset of literature emphasizes the importance of DH within an IES [Lund et al., 2018b,a; Yu et al., 2018; Askeland et al., 2019; Li et al., 2020; Wang et al., 2021; Golmohamadi et al., 2022]. Accordingly, the present thesis shows that the Dutch electricity and heating sector are becoming increasingly integrated and an important role for DH is identified. However, Lund et al. [2018a] concluded that the primary current challenge is the understanding of the implementation of DH systems in an IES, in which an understanding of the local concrete conditions is required. Therefore, the present thesis contributes to existing scientific literature. It offers new and in-depth insights into the local concrete conditions involved with the transition to renewable DH by using an exploratory and mixed-methods case study approach.

The impact of the transition to renewable DH systems on the electricity and heating sector depends on the local context. The local context can vary and herewith the desirability of renewable DH systems. Hereby, it is important to consider the availability of renewable sources for not only DH, but also for the other expected heating alternatives. Different implications are caused by a different heat mix and source availability. It is noteworthy that this thesis discussed the implications of the use of transition sources in the energy system. The use of transition sources such as natural gas and biomass could potentially be problematic, as they can cause for delays in the implementation of 'sufficient' long-term alternatives. This observation is in line with Unruh [2000]; Erickson et al. [2015]; Safari et al. [2019]; Gürsan and de Gooyert [2021]. Gürsan and de Gooyert [2021] state that "taking advantage of a transition fuel comes also with challenges. Initial investments to a potential transition fuel such as natural gas could lock-out emerging renewable technologies for extended periods". Moreover, the use of transition sources can cause for infrastructural and heat source lock-ins. For example, the desire to maintain the existing natural gas-infrastructure to eventually provide green gas for individual boilers and hybrid heat pumps poses a risk, as the potential of green gas is very uncertain. This can result in a infrastructural natural gas lock-in.

Another important identified local factor is the management of the heat transition. Designing the future heat supply is a challenging endeavour, that is managed on a municipal level. According to Vringer et al. [2021] "the most relevant question in the public interest is whether Dutch municipalities have sufficient capacity to achieve the local CO2 emission reduction targets." In the present thesis it is concluded that municipalities sometimes struggle with the responsibility to implement the required legal and regulatory frameworks to steer the heat transition pathway, due to their lack of experience. This supports Rodhouse et al. [2021], stating " it has proven difficult [for municipalities] to get different groups of citizens actively engaged in planning and execution phases of the heat transition".

8.3.2 CoSEM Perspective

This thesis is performed in partial fulfillment of the requirements for the degree of the Master of Science (MSc) Complex Systems Engineering and Management (CoSEM) at Delft University of Technology. The MSc CoSEM explores innovations in complex socio-technical environments, such as energy system transitions. In this thesis, the DH technology and sources are considered within the context of the Dutch electricity and heating transition. The complex nature of the DH transition within an integrated and dynamic energy system is indicated by a diversity of perspectives. The DH system needs to remain technologically and economically viable. Moreover, the system should comply with existing policies and consider the interests of various involved actors, such as municipalities, heat producers, grid operators and end-users. Therefore, this thesis covers values originating from both the public and private domains. Simultaneously, these perspectives continuously change due to the transition of the energy system as a whole. In conclusion, this thesis is very suited as a CoSEM thesis, due to the high level of complexity and the technological, economic, policy and social components.

8.3.3 Limitations of the Research

This thesis is subject to several limitations due to the research scope and the research methodology.

Research Scope

This thesis considers the impact of the transition from current to future renewable DH on the electricity and heating sector of the built environment. Therefore other end-demand sectors were out of scope. However, the inclusion of other end-demand sectors such as industry, could have provided a more complete view on the transition of the integrated energy system. Moreover, this thesis included various involved actors in the regional analysis. A limitation is that certain actors were excluded, as at some point a line must be draw. The inclusion of more actors could have provided more perspectives on the regional energy transition and therefore a better basis for the regional assumptions.

Research Methodology

In this thesis, the single case study method was used in an exploratory manner. As the thesis is exploratory and not aimed at drawing a generalizing conclusion, the problem of case selection was smaller. However, not all of the municipalities within of the RES region North-Holland South have published their TVH reports. Therefore, another region could have been picked in which this was the case. This could have resulted in more complete results and a higher validity of the assumptions.

For data collection, a desk study was conducted regarding scenario reports for the Dutch national energy system of 2050. However, there were only two published reports that met the determined requirements: I) focus on long-term scenarios (2050), II) recently published, III) published by independent research groups. These two reports provided a total of six scenarios. However, by including reports that do not fulfill all the requirements, a broader perspective on future national trends could have been provided. Moreover, currently the use of nuclear power plants within the national Dutch energy system is a subject of discussion with the national government. This interesting development is not included within the national scenarios. Therefore, these scenarios do not reflect the latest developments. Furthermore, for data collection, semi-structured interviews were conducted with involved regional actors. A limitation here is the number of interviewees. Due to time constraints, a limited number of interviews was conducted, while the inclusion of more interviews could have provided more perspectives on the regional energy transition. This could have provided a better basis for the assumptions on which the regional energy system estimation was based. Therefore, more interviews could have been conducted with interviewees from the same or different actor-groups. Furthermore, end-users were not interviewed. To compensate for this, the view of a local municipality regarding end-user behaviour was derived. Moreover, it was difficult to capture the expectations of the involved actors. Sometimes, interviewees contradicted themselves or were not clear in formulating their answers. Moreover, the interview data could have been compromised by the interviewees or interviewer being biased. The interviewee data is thus of a subjective nature, which is a limitation of a qualitative exploratory case study based on interviews. However, additionally to the interviews, published data, such as the RES, TVHs and future strategy reports have been analyzed. This helped with confirming interview information and providing additional information regarding concrete plans and expectations.

Moreover, for data analysis, an energy flow analysis was conducted. Based on the interviews and the published data, assumptions were made in order to estimate the future regional energy system. In cases where a lot of uncertainty is involved, it was really difficult to convert qualitative information into quantitative assumptions. This was for example the case with regard to the use of green gas for heat supply and the availability of geothermal and industrial waste heat. Therefore, some assumptions are very uncertain. Furthermore, a scenario analysis was conducted for data analysis. Hereby, there are limitations associated with the modelling of the scenarios by Berenschot & Kalavasta [2020]; TNO [2020b]. The scenarios are limited by assumptions with regard to future developments, which may not be completely substantiated. Moreover, models are always simplifications of reality and this can obscure the representation of the analyzed energy system. Therefore, scenarios are limited in terms of technological, economic, policy and social details. Furthermore, for data analysis, a stakeholder analysis was conducted. A limitation is the omission of certain stakeholders, as at some point a line must be drawn. This point is also addressed in the research scope limitations. In the stakeholder analysis, organizations that are involved with or responsible over the energy flows within the regional electricity and heating sector are included. The inclusion of more stakeholders, such as environmental associations and housing associations, could have provided more perspectives on the regional energy transition and therefore a better basis for the regional assumptions.

8.4 SUGGESTIONS FOR FUTURE RESEARCH

Several promising areas for further research are identified. First, a focus for future research can be whether the conclusions of this thesis can be generalised for the Netherlands. Therefore, it is suggested to conduct more case studies and explore the energy plans of the other 29 energy regions within the Netherlands. It is of interest to estimate the future energy systems of these regions and to explore how involved actors approach the regional energy transition. Subsequently, the regions can be compared with each other and a cumulative future energy system can be determined. This cumulative future energy system can be compared with the national energy scenarios in order to determine similarities between them. This can help with validating or excluding certain scenario trends to a certain extent. When conducting other case studies, it is suggested to broaden the perspective of the research and include other end-demand sectors, such as industry and transport. Therefore, the interconnections and synergies between these end-demand sectors can be investigated. Moreover, in order to broaden the perspective and keep up with the latest developments, it is suggested to include recent national scenario reports, resulting in more scenarios which reflect more recent developments, such as the implementation of nuclear power plants. Moreover, within the case studies, certain suggestions can be implemented to improve the basis for the regional assumptions. It is suggested to include more TVHs of municipalities when these are published and available. Moreover, it is suggested to include more stakeholders in the case study and conduct more interviews. These interviews can be held with interviewees from the same or a different actor group (i.e. heat producers).

Furthermore, it is suggested for further research to focus on the smart use of DH within an integrated energy system. DH systems are perceived as promising as they offer possibilities for increase electricity flexibility. Therefore, research regarding the smart operation of collective heat pumps or E-boilers in combination with thermal storage within a local integrated energy system is of interest. This can also be applied to the flexibility options that individual heat pumps have to offer. Therefore, the interconnections and synergies between electricity and heating can be investigated on a deeper level, taking heat and electricity demand curves and storage capacity into account. This can for example be achieved by modelling regional energy systems. Other aspects, such as costs can then also be included.

Moreover, it is suggested to conduct research regarding the governance capacity of municipalities for realizing the heat transition. Involved regional actors require legal and regulatory frameworks to steer the transition pathway. It is of interest to determine if these frameworks are currently realized and how to speed up this process. For example, currently sufficient legal and regulatory frameworks are in place for regulating the gas and electricity sector. However, these frameworks can be required in the future for regulating DH systems.

8.5 conclusion

This thesis explored the impact of the transition from a traditional to a renewable DH system on the Dutch electricity and heating sector. On a national level, it is currently not clear how to exactly realize the heat transition. However, from the case study of the region North-Holland South, it became evident that renewable DH is expected to be one of the main heating alternatives. The transition to renewable DH can partly substitute the current natural gas-based heat supply and provide some relief for the electricity sector, when renewable high- and/or low-temperature DH sources are available. These impacts are promising considering the regional context: the system is currently experiencing a natural gas lock-in and is expecting a significant electrification. However, local renewable DH sources are still uncertain.

This uncertainty causes risks to occur, such as misaligned local initiatives, policy delays and malfunctioning infrastructural and heat source lock-ins. However, in the region North-Holland South, all of the expected renewable heat sources (DH sources, renewable electricity and green gas) bring along uncertainties and similar risks. Therefore, the implementation of a range of renewable heating alternatives contributes to spreading the risks. Renewable DH is particularly helpful, as there are many theoretically potential DH sources and DH can provide some relief for the electricity sector. However, spreading the risks does not remove these risks. An ultimate shortage of a large part of the planned heat sources or major delays in realizing them, would be problematic. Whenever this is the case in more Dutch energy regions, the achievement of the national climate goals will be endangered.

The way in which the risks and the local (district) heat transition are managed depends on the decision-making by involved actors, especially municipalities. In the region North-Holland South, choices regarding renewable heating sources and synergies between electricity and heat must be made and effective legal and regulatory frameworks are urgently required. Due to their final responsibility and current lack of experience, municipalities are strongly advised to collect new knowledge, expertise and competences. Hereby, important factors to consider are I) the potential risk of delays and infrastructural and source related lock-ins, II) the development of the potential for different (district) heat sources, III) the participation of citizens in the heat transition and IV) the possibilities for thermal storage in combination with coupling elements (such as heat pumps or E-boilers) within DH systems. Moreover, provinces, energy producers and grid operators can support municipalities in doing this, especially with regard to exploring the potential of heat sources and thermal storage. Lastly, involved actors are advised to be highly aware of the risks involved with the increasing dependency on electricity in the heating sector in their decision-making.

Urgent and significant changes in the Dutch energy system are required. The mentioned recommendations can be implemented within the region North-Holland South and possibly within other energy regions, depending on their heat transition development. For achieving national climate goals, it is important to take an integrated approach, make future-proof choices and act now!

BIBLIOGRAPHY

AEB (2019). AEB Jaarverslag 2019. Technical report.

Agrell, P. J. and Bogetoft, P. (2005). Economic and environmental efficiencey of district heating plants. *Energy Policy*, 33(10).

Alcamo, J. and Henrichs, T. (2008). Chapter Two Towards Guidelines for Environmental Scenario Analysis.

Algemene Rekenkamer (2012). A gas hub: benefits, need and risks. Technical report.

Arthur, W. B. (1994). to Increasing Returns and Path Dependence in the Economy, W. Brian Arthur, University of Michigan Press, 1994. *Mathematical Social Sciences*.

Asim, M., Saleem, S., Imran, M., Leung, M. K., Hussain, S. A., Miró, L. S., and Rodríguez, I. (2020). Thermo-economic and environmental analysis of integrating renewable energy sources in a district heating and cooling network. *Energy Efficiency*, 13(1).

Askeland, K., Bozhkova, K. N., and Sorknæs, P. (2019). Balancing Europe: Can district heating affect the flexibility potential of Norwegian hydropower resources? *Renewable Energy*, 141.

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

Averfalk, H., Ingvarsson, P., Persson, U., Gong, M., and Werner, S. (2017). Large heat pumps in Swedish district heating systems.

Averfalk, H. and Werner, S. (2017). Essential improvements in future district heating systems. In *Energy Procedia*, volume 116.

Barnett, J., Evans, L. S., Gross, C., Kiem, A. S., Kingsford, R. T., Palutikof, J. P., Pickering, C. M., and Smithers, S. G. (2015). From barriers to limits to climate change adaptation: Path dependency and the speed of change. *Ecology and Society*, 20(3).

Bekkering, J., Hengeveld, E. J., van Gemert, W. J., and Broekhuis, A. A. (2015). Will implementation of green gas into the gas supply be feasible in the future? *Applied Energy*, 140.

Benonysson, A., Bøhm, B., and Ravn, H. F. (1995). Operational optimization in a district heating system. *Energy Conversion and Management*, 36(5).

Berenschot & Kalavasta (2020). Klimaatneutrale energiescenario's 2050. Technical report.

Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M., and Eom, J. (2015). Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting and Social Change*, 90(PA).

Bojic, M. and Trifunovic, N. (2000). Linear programming optimization of heat distribution in a district-heating system by valve adjustments and substation retrofit. *Building and Environment*, 35(2).

Bolderston, A. (2012). Conducting a research interview. *Journal of Medical Imaging and Radiation Sciences*, 43(1).

Brauers, H., Braunger, I., and Jewell, J. (2021). Liquefied natural gas expansion plans in Germany: The risk of gas lock-in under energy transitions. *Energy Research and Social Science*, 76.

CBS (2015a). Bodemgebruik; uitgebreide gebruiksvorm, per gemeente.

CBS (2015b). Elektriciteit in Nederland. Technical report.

CBS (2019a). Cijfers - Energie.

CBS (2019b). Hernieuwbare Energie 2019.

CBS (2019c). Inwoners per gemeente.

CBS (2019d). Voorraad woningen.

CE Delft (2019). Rapportage Systeemstudie Energie-infrastructuur Noord-Holland. Technical report, CE Delft, Delft.

Chen, S. and Chen, B. (2015). Urban energy consumption: Different insights from energy flow analysis, input-output analysis and ecological network analysis. *Applied Energy*, 138.

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., and Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research and Social Science*, 37.

Collins, S., Deane, J. P., Poncelet, K., Panos, E., Pietzcker, R. C., Delarue, E., and Ó Gallachóir, B. P. (2017). Integrating short term variations of the power system into integrated energy system models: A methodological review.

Connolly, D., Lund, H., and Mathiesen, B. V. (2016). Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union.

Consonni, S., Lombardi, L., and Viganò, F. (2017). Municipal Solid Waste to Energy Technology. In *Encyclopedia of Sustainable Technologies*.

Creswell, J. W. (2003). Research design Qualitative quantitative and mixed methods approaches. *Research design Qualitative quantitative and mixed methods approaches*.

Curti, V., Favrat, D., and von Spakovsky, M. R. (2000). An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part II: Application. *International Journal of Thermal Sciences*, 39(7).

Devabhaktuni, V., Alam, M., Shekara Sreenadh Reddy Depuru, S., Green, R. C., Nims, D., and Near, C. (2013). Solar energy: Trends and enabling technologies.

Difs, K., Bennstam, M., Trygg, L., and Nordenstam, L. (2010). Energy conservation measures in buildings heated by district heating - A local energy system perspective. *Energy*, 35(8).

Dincer, I. and Rosen, M. A. (2021). Exergy analyses of refrigeration and heat pump systems. *Exergy*, pages 125–141.

Duinker, P. N. and Greig, L. A. (2007). Scenario analysis in environmental impact assessment: Improving explorations of the future.

Ebrahimigharehbaghi, S., Qian, Q. K., Meijer, F. M., and Visscher, H. J. (2019). Unravelling Dutch homeowners' behaviour towards energy efficiency renovations: What drives and hinders their decision-making? *Energy Policy*, 129.

EC (2018). COMMUNICATION FROM THE COMMISSION A Clean Planet for all.

Edmonds, W. A. and Kennedy, T. D. (2020). *An Applied Guide to Research Designs: Quantitative, Qualitative, and Mixed Methods*.

Eneco (2020). Eneco Bestuursverslag 2020. Technical report.

Erickson, P., Kartha, S., Lazarus, M., and Tempest, K. (2015). Assessing carbon lock-in. *Environmental Research Letters*, 10(8).

Ericsson, K. and Werner, S. (2016). The introduction and expansion of biomass use in Swedish district heating systems. *Biomass and Bioenergy*, 94.

Escribano Francés, G., Marín-Quemada, J. M., and San Martín González, E. (2013). RES and risk: Renewable energy's contribution to energy security. A portfolio-based approach.

Eurostat (2019). Database Eurostat.

Fang, H., Xia, J., Zhu, K., Su, Y., and Jiang, Y. (2013). Industrial waste heat utilization for low temperature district heating. *Energy Policy*, 62.

Fawcett, T., Eyre, N., and Layberry, R. (2015). Heat pumps and global residential heating. *Eceee 2015*, (June).

Fischer, D. and Madani, H. (2017). On heat pumps in smart grids: A review.

Gasparotto, J. and Da Boit Martinello, K. (2021). Coal as an energy source and its impacts on human health. *Energy Geoscience*, 2(2).

Gasunie (2020). Gasunie Report 2020. Technical report, Groningen.

Gasunie (2022). Interview Hans Coenen.

Gasunie and TenneT (2019). Infrastructure Outlook 2050 - Phase II. Technical report.

Gemeente Amstelveen (2021). Transitievisie Warmte Amstelveen. Technical report.

Gemeente Amsterdam (2019). Het Amsterdamse Bronnenboek. Technical report.

Gemeente Amsterdam (2020). Transitievisie Warmte Amterdam. Technical report.

Gemeente Amsterdam (2022). Interview Milan van Schendel.

Gemeente Diemen (2018). Biomassacentrale.

Gemeente Diemen (2021). Transitievisie Warmte Diemen. Technical report.

Gemeente Haarlem (2021). Transitievisie Warmte Haarlem. Technical report.

Gemeente Heemskerk (2021). Transitievisie Warmte Heemskerk. Technical report.

Gemeente Heemstede (2021). Transitievisie Warmte Heemstede. Technical report.

Gemeente Hilversum (2021). Transitievisie Warmte Hilversum. Technical report.

Gemeente Landsmeer (2021). Transitievisie Warmte Landsmeer. Technical report.

Gemeente Laren (2021). Transitievisie Warmte Laren. Technical report.

Gemeente Oostzaan (2021). Transitievisie Warmte Oostzaan. Technical report.

Gemeente Uithoorn (2021). Transitievisie Warmte Uithoorn. Technical report.

Gemeente Waterland (2021). Transitievisie Warmte Waterland. Technical report.

Gemeente Weesp (2021). Transitievisie Warmte Weesp.

Gemeente Wormerland (2021). Transitievisie Warmte Wormerland. Technical report.

Gemeente Zaanstad (2021). Transitievisie Warmte Zaanstad. Technical report.

Golmohamadi, H., Larsen, K. G., Jensen, P. G., and Hasrat, I. R. (2022). Integration of flexibility potentials of district heating systems into electricity markets: A review. *Renewable and Sustainable Energy Reviews*, 159.

González-Gómez, F., García-Rubio, M. A., and González-Martínez, J. (2014). Beyond the public-private controversy in urban water management in Spain. *Utilities Policy*, 31:1–9.

Greening, B. and Azapagic, A. (2014). Domestic solar thermal water heating: A sustainable option for theUK? *Renewable Energy*, 63.

Guelpa, E. and Verda, V. (2019). Thermal energy storage in district heating and cooling systems: A review.

Gürsan, C. and de Gooyert, V. (2021). The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition?

Hedegaard, K. and Münster, M. (2013). Influence of individual heat pumps on wind power integration - Energy system investments and operation. *Energy Conversion and Management*, 75.

Hepbasli, A. (2018). 4.4 Heat Pumps. *Comprehensive Energy Systems*, 4-5:98–124.

IEA (2021). Hydrogen - Tracking Report. Technical report.

IRENA (2017). Renewable Energy in District Heating and Cooling, A sector roadmap for REmap. Technical Report March.

Jimenez-Navarro, J. P., Kavvadias, K., Filippidou, F., Pavičević, M., and Quoilin, S. (2020). Coupling the heating and power sectors: The role of centralised combined heat and power plants and district heat in a European decarbonised power system. *Applied Energy*, 270.

Johnson, N., Krey, V., McCollum, D. L., Rao, S., Riahi, K., and Rogelj, J. (2015). Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, 90(PA).

Keirstead, J., Jennings, M., and Sivakumar, A. (2012). A review of urban energy system models: Approaches, challenges and opportunities.

Kiviluoma, J. and Meibom, P. (2010). Flexibility from district heating to decrease wind power integration costs. In *12th International Symposium on District Heating and Cooling*.

Köfinger, M., Schmidt, R. R., Basciotti, D., Terreros, O., Baldvinsson, I., Mayrhofer, J., Moser, S., Tichler, R., and Pauli, H. (2018). Simulation based evaluation of large scale waste heat utilization in urban district heating networks: Optimized integration and operation of a seasonal storage. *Energy*, 159.

Kohl, W. L. (2004). National Security and Energy. In *Encyclopedia of Energy*.

Kotilainen, K., Aalto, P., Valta, J., Rautiainen, A., Kojo, M., and Sovacool, B. K. (2019). From path dependence to policy mixes for Nordic electric mobility: Lessons for accelerating future transport transitions. *Policy Sciences*, 52(4).

Ladenburg, J., Hevia-Koch, P., Petrović, S., and Knapp, L. (2020). The offshore-onshore conundrum: Preferences for wind energy considering spatial data in Denmark. *Renewable and Sustainable Energy Reviews*, 121.

Lake, A., Rezaie, B., and Beyerlein, S. (2017). Review of district heating and cooling systems for a sustainable future.

Leurent, M., Da Costa, P., Rämä, M., Persson, U., and Jasserand, F. (2018). Cost-benefit analysis of district heating systems using heat from nuclear plants in seven European countries. *Energy*, 149.

Li, H. and Nord, N. (2018). Transition to the 4th generation district heating - Possibilities, bottlenecks, and challenges. In *Energy Procedia*, volume 149.

Li, X., Li, W., Zhang, R., Jiang, T., Chen, H., and Li, G. (2020). Collaborative scheduling and flexibility assessment of integrated electricity and district heating systems utilizing thermal inertia of district heating network and aggregated buildings. *Applied Energy*, 258.

Liander (2020). Liander Jaarbericht 2020.

Liander (2022). Interview Hans van der Geest.

Liu, W., Best, F., and Crijns-Graus, W. (2021). Exploring the pathways towards a sustainable heating system – A case study of Utrecht in the Netherlands. *Journal of Cleaner Production*, 280.

Liu, X., Wu, J., Jenkins, N., and Bagdanavicius, A. (2016). Combined analysis of electricity and heat networks. *Applied Energy*, 162.

Luc, K. M., Li, R., Xu, L., Nielsen, T. R., and Hensen, J. L. (2020). Energy flexibility potential of a small district connected to a district heating system. *Energy and Buildings*, 225:110074.

Lund, H., Duic, N., Østergaard, P. A., and Mathiesen, B. V. (2018a). Future district heating systems and technologies: On the role of smart energy systems and 4th generation district heating. *Energy*, 165.

Lund, H., Möller, B., Mathiesen, B. V., and Dyrelund, A. (2010). The role of district heating in future renewable energy systems. *Energy*, 35(3).

Lund, H., Østergaard, P. A., Chang, M., Werner, S., Svendsen, S., Sorknæs, P., Thorsen, J. E., Hvelplund, F., Mortensen, B. O. G., Mathiesen, B. V., Bojesen, C., Duic, N., Zhang, X., and Möller, B. (2018b). The status of 4th generation district heating: Research and results.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., and Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems.

Lund, R. and Persson, U. (2016). Mapping of potential heat sources for heat pumps for district heating in Denmark. *Energy*, 110.

Lupton, R. C. and Allwood, J. M. (2017). Hybrid Sankey diagrams: Visual analysis of multidimensional data for understanding resource use. *Resources, Conservation and Recycling*, 124.

Mac Kinnon, M. A., Brouwer, J., and Samuelsen, S. (2018). The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration.

MacKay, D. J. (2013). Solar energy in the context of energy use, energy transportation and energy storage.

Marchand, M., Proost, S., and Wilberz, E. (1983). A model of district heating using a CHP plant. *Energy Economics*, 5(4).

Mathers, N. and Nick Fox, A. H. (1998). Trent Focus for Research and Development in Primary Health Care. *Institute of General Practice Northern General Hospital Sheffield*, 26(11).

Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Ostergaard, P. A., Möller, B., Nielsen, S., Ridjan, I., KarnOe, P., Sperling, K., and Hvelplund, F. K. (2015). Smart Energy Systems for coherent 100% renewable energy and transport solutions.

Mazhar, A. R., Liu, S., and Shukla, A. (2018). A state of art review on the district heating systems.

McLellan, E., MaCqueen, K. M., and Neidig, J. L. (2003). Beyond the Qualitative Interview: Data Preparation and Transcription. *Field Methods*, 15(1).

Microsoft (2010a). Microsoft Excel.

Microsoft (2010b). Microsoft Word.

Microsoft (2019). Microsoft Visio.

Miedema, J. H., Van Der Windt, H. J., and Moll, H. C. (2018). Opportunities and Barriers for Biomass Gasification for Green Gas in the Dutch Residential Sector. *Energies*, 11(11).

Milieucentraal (2020). Warmtenet zonder aardgas.

Mitridati, L. and Pinson, P. (2016). Optimal coupling of heat and electricity systems: A stochastic hierarchical approach. In *2016 International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2016 - Proceedings*.

Netbeheer Nederland (2019). Netcapaciteit.

Niaz, S., Manzoor, T., and Pandith, A. H. (2015). Hydrogen storage: Materials, methods and perspectives.

Nielsen, S., Hansen, K., Lund, R., and Moreno, D. (2020). Unconventional excess heat sources for district heating in a national energy system context. *Energies*, 13(19).

NOS (2022). Oplopende gasprijzen, wat zijn de gevolgen?

Obregón, L., Orozco, C., Camargo, J., Duarte, J., and Valencia, G. (2019). Research trend on nuclear energy from 2008 to 2018: A bibliometric analysis. *International Journal of Energy Economics and Policy*, 9(6).

Oil & Gas Engineering Ltd. (2019). Thermal Power Plants and District Heating Solutions.

Østergaard, P. A., Johannsen, R. M., Lund, H., and Mathiesen, B. V. (2021). Latest developments in 4th generation district heating and smart energy systems. *International Journal of Sustainable Energy Planning and Management*, 31.

Pan, Z., Guo, Q., and Sun, H. (2016). Interactions of district electricity and heating systems considering time-scale characteristics based on quasi-steady multi-energy flow. *Applied Energy*, 167.

Papadis, E. and Tsatsaronis, G. (2020). Challenges in the decarbonization of the energy sector.

Pareek, A., Dom, R., Gupta, J., Chandran, J., Adepu, V., and Borse, P. H. (2020). Insights into renewable hydrogen energy: Recent advances and prospects. *Materials Science for Energy Technologies*, 3.

Pärssinen, M., Wahlroos, M., Manner, J., and Syri, S. (2019). Waste heat from data centers: An investment analysis. *Sustainable Cities and Society*, 44.

PBL (2020a). Availability and applications of sustainable biomass. Report on a search for shared facts and views. . Technical report, Den Haag.

PBL (2020b). Klimaat- en Energieverkenning 2020. Technical report, Den Haag.

Postma, T. J. and Liebl, F. (2005). How to improve scenario analysis as a strategic management tool? *Technological Forecasting and Social Change*, 72(2).

Potts, C. G. and Draaijer, L. M. (1985). Developments in rigid polyurethane foams for the insulation of district heating pipelines. *Journal of Cellular Plastics*, 21(1).

Prăvălie, R. and Bandoc, G. (2018). Nuclear energy: Between global electricity demand, worldwide decarbonisation imperativeness, and planetary environmental implications.

Provincie Noord-Holland (2022). Interview Pim van Herk.

Quintel (2019). Energy Transition Model.

Rayaprolu, K. (2009). *Boilers for Power and Process*.

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C. H., and Stringer, L. C. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, 90(5).

RES Noord-Holland Zuid (2021). Regionale Energiestrategie Noord-Holland Zuid 1.0. Technical report.

Rijksoverheid (2019). Klimaatakkoord — Rapport —.

Rijksoverheid (2020). Wetsvoorstel afbouw salderingsregeling naar de Kamer.

Rijksoverheid (2022). Coalitieakkoord 'Omzien naar elkaar, vooruitkijken naar de toekomst'. Technical report.

Rodhouse, T. S., Pesch, U., Cuppen, E. H., and Correljé, A. F. (2021). Public agency and responsibility in energy governance: A Q study on diverse imagined publics in the Dutch heat transition. *Energy Research and Social Science*, 77.

RSW (2022). Duurzame Energie.

Rudig, W. (1986). Combined heat and power for district heating. *Physics in Technology*, 17(3).

Rudra, S. and Tesfagaber, Y. K. (2019). Future district heating plant integrated with municipal solid waste (MSW) gasification for hydrogen production. *Energy*, 180.

RVO (2020). Monitor Wind op Land 2019. Technical report.

Safari, A., Das, N., Langhelle, O., Roy, J., and Assadi, M. (2019). Natural gas: A transition fuel for sustainable energy system transformation? *Energy Science and Engineering*, 7(4).

Sanaei, S. M. and Nakata, T. (2012). Optimum design of district heating: Application of a novel methodology for improved design of community scale integrated energy systems. *Energy*, 38(1).

SankeyMatic (2020). SankeyMatic .

Sarat Raju, G. and Karunya, G. (2018). Power Plant Engineering. Technical report, INSTITUTE OF AERONAUTICAL ENGINEERING.

Sayegh, M. A., Danielewicz, J., Nannou, T., Miniewicz, M., Jadwiszczak, P., Piekarska, K., and Jouhara, H. (2017). Trends of European research and development in district heating technologies.

Seawright, J. and Gerring, J. (2008). Case Selection Techniques in Case Study Research. *Political Research Quarterly*, 61(2).

SER (2013). Energieakkoord voor Duurzame Groei. Technical report.

Shahzad Baig K and Yousaf M (2017). Coal Fired Power Plants: Emission Problems and Controlling Techniques. *Journal of Earth Science & Climatic Change*, 08(07).

Shao, C., Ding, Y., Wang, J., and Song, Y. (2018). Modeling and integration of flexible demand in heat and electricity integrated energy system. *IEEE Transactions on Sustainable Energy*, 9(1).

Soundararajan, K., Ho, H. K., and Su, B. (2014). Sankey diagram framework for energy and exergy flows. *Applied Energy*, 136.

Steg, L., Shwom, R., and Dietz, T. (2018). What drives energy consumers?: Engaging people in a sustainable energy transition. *IEEE Power and Energy Magazine*, 16(1).

Subramanyam, V., Paramshivan, D., Kumar, A., and Mondal, M. A. H. (2015). Using Sankey diagrams to map energy flow from primary fuel to end use. *Energy Conversion and Management*, 91.

Tanrisever, F., Derinkuyu, K., and Jongen, G. (2015). Organization and functioning of liberalized electricity markets: An overview of the Dutch market.

TenneT (2020). Rapport Monitoring Leveringszekerheid . Technical report.

Tereshchenko, T. and Nord, N. (2018). Future Trends in District Heating Development.

Thelen, K. (1999). Historical institutionalism in comparative politics.

Timpe, C. and Scheeper, M. (2003). A look into the future: scenarios for distributed generation in Europe. *ECN-C-04-012*, (December).

TNO (2020a). Review of energy transition scenario studies of the Netherlands up to 2050.

TNO (2020b). Scenario's voor een Klimaatneutraal Energisysteem. Technical report.

TNO (2020c). Warmtemonitor 2019. Technical report, TNO & CBS.

UNFCC (2015). UNFCC Paris Agreement. *UNFCC*, 45(4).

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, 28(12).

Vadén, T., Majava, A., Toivanen, T., Järvensivu, P., Hakala, E., and Eronen, J. T. (2019). To continue to burn something? Technological, economic and political path dependencies in district heating in Helsinki, Finland. *Energy Research and Social Science*, 58.

Vattenfall (2020). Annual and Sustainability Report 2020. Technical report.

Vattenfall (2021a). E-boiler.

Vattenfall (2021b). Over Vattenfall.

Vattenfall (2022a). Interview Bart de Hue.

Vattenfall (2022b). Interview Floor de Kleijn.

Vattenfall (2022c). Interview Frank de Vries.

Vattenfall (2022d). Interview Richard van den Broek.

Volkova, A., Mašatin, V., and Siirde, A. (2018). Methodology for evaluating the transition process dynamics towards 4th generation district heating networks. *Energy*, 150.

Vringer, K., de Vries, R., and Visser, H. (2021). Measuring governing capacity for the energy transition of Dutch municipalities. *Energy Policy*, 149.

Vuillecard, C., Hubert, C. E., Contreau, R., mazzenga, A., Stabat, P., and Adnot, J. (2011). Small scale impact of gas technologies on electric load management - μCHP & hybrid heat pump. *Energy*, 36(5).

Wang, C. N., Hsueh, M. H., and Lin, D. F. (2019). Hydrogen power plant site selection under fuzzy multicriteria decision-making (FMCDM) environment conditions. *Symmetry*, 11(4).

Wang, X., Bie, Z., Liu, F., and Kou, Y. (2021). Co-optimization planning of integrated electricity and district heating systems based on improved quadratic convex relaxation. *Applied Energy*, 285.

Werner, S. (2017). District heating and cooling in Sweden.

Werner, S. and Frederiksen, S. (2013). District Heating and Cooling. In *Lund Studentlitteratur*.

Westpoort Warmte (2022). Interview Martin Buijk.

Winterscheid, C., Dalenbäck, J. O., and Holler, S. (2017). Integration of solar thermal systems in existing district heating systems. *Energy*, 137.

Yin, R. K. (2009). *Case Study Research: Design and Methods*. 4th edition edition.

Yu, J., Guo, L., Ma, M., Kamel, S., Li, W., and Song, X. (2018). Risk assessment of integrated electrical, natural gas and district heating systems considering solar thermal CHP plants and electric boilers. *International Journal of Electrical Power and Energy Systems*, 103.

Zhang, S., Gu, W., Qiu, H., Yao, S., Pan, G., and Chen, X. (2021). State estimation models of district heating networks for integrated energy system considering incomplete measurements. *Applied Energy*, 282.

Ziemele, J., Gravelsins, A., Blumberga, A., and Blumberga, D. (2016). The Effect of Energy Efficiency Improvements on the Development of 4th Generation District Heating. In *Energy Procedia*, volume 95.

A APPENDIX A: ENERGY SYSTEMS OF THE SCENARIOS

The driving forces of the scenarios addressed in section 5.4 shape the structure of the scenario's energy system. In the following sections, the energy systems of the scenarios are presented in terms of the interconnection of system components and quantified energy flows. The scope of the scenarios from the reports includes the total energy demand of the Dutch energy system. Therefore, subsectors included are the built environment, transport and industry. As this thesis focuses specifically on the built environment and the electricity and heating sector (see section 3.1.1), the scope of the scenario analysis considers the heat and electricity demand of the built environment in 2050.

A.0.1 Regional Scenario

The regional scenario by Berenschot & Kalavasta [2020] is depicted in a system diagram in figure A.1.

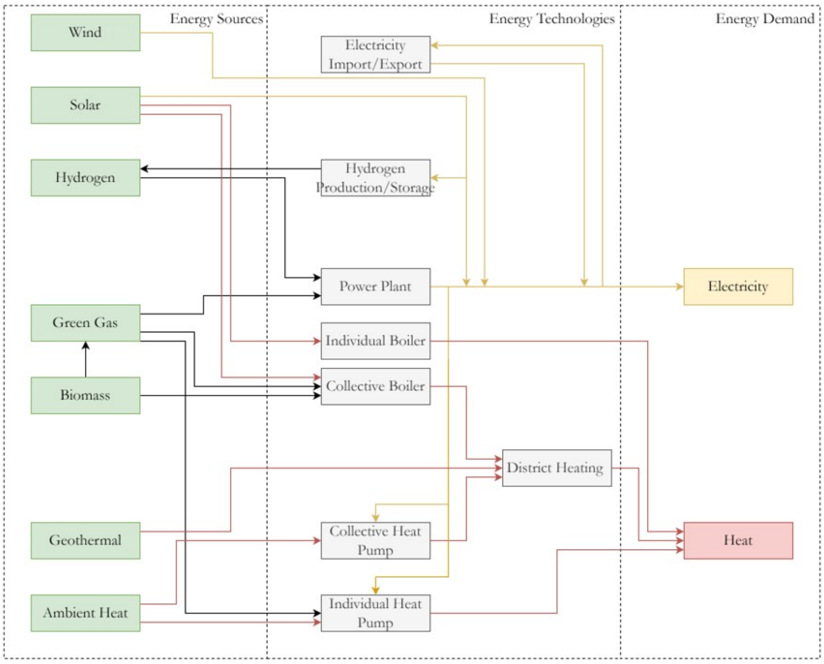


Figure A.1: System diagram of the interconnections between the system components of the Dutch electricity and heating sector for the built environment in the regional scenario for 2050. Data sources: Berenschot & Kalavasta [2020]

The quantified energy flows of the regional scenario by Berenschot & Kalavasta [2020] are depicted in figure A.2.

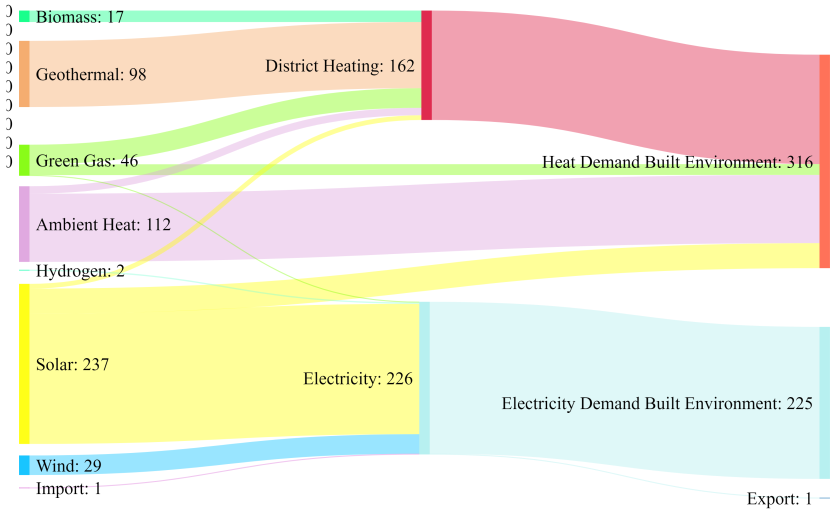


Figure A.2: Sankey diagram of the energy flows in PJ between the system components of the Dutch electricity and heating sector for the built environment in the regional scenario for 2050. Left side represents supply, right side represents demand. Data sources: Berenschot & Kalavasta [2020]

A.0.2 National Scenario

The national scenario by Berenschot & Kalavasta [2020] is depicted in a system diagram in figure A.3.

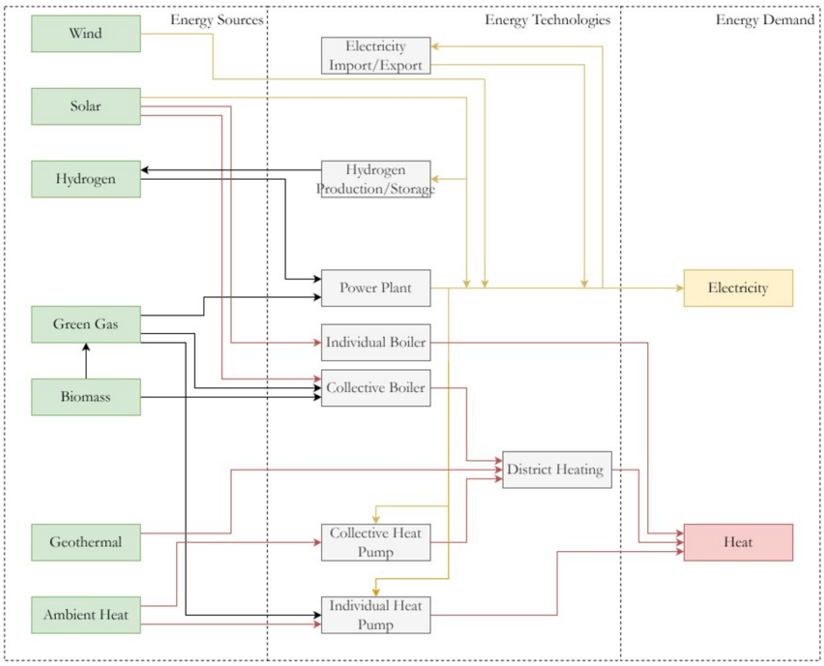


Figure A.3: System diagram of the interconnections between the system components of the Dutch electricity and heating sector for the built environment in the national scenario for 2050. Data sources: Berenschot & Kalavasta [2020]

The quantified energy flows of the national scenario by Berenschot & Kalavasta [2020] are depicted in figure A.4.

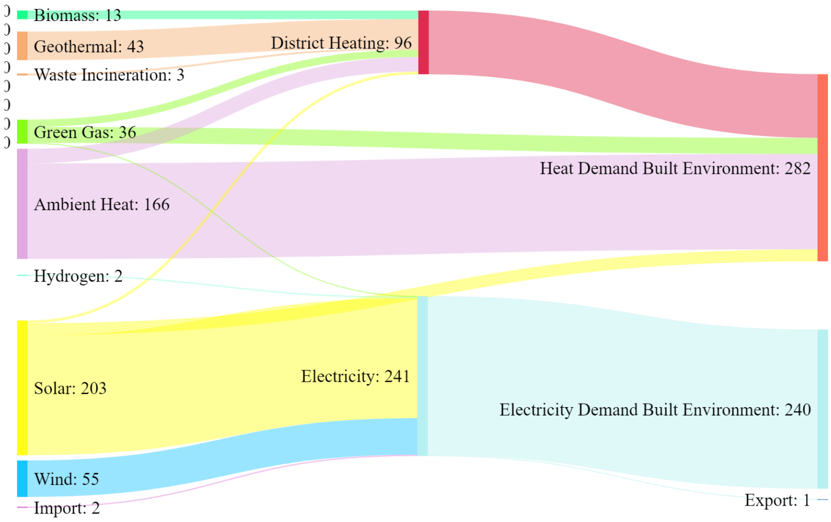


Figure A.4: Sankey diagram of the energy flows in PJ between the system components of the Dutch electricity and heating sector for the built environment in the national scenario for 2050. Left side represents supply, right side represents demand. Data sources: Berenschot & Kalavasta [2020]

A.0.3 European Scenario

The European scenario by Berenschot & Kalavasta [2020] is depicted in a system diagram in figure A.5.

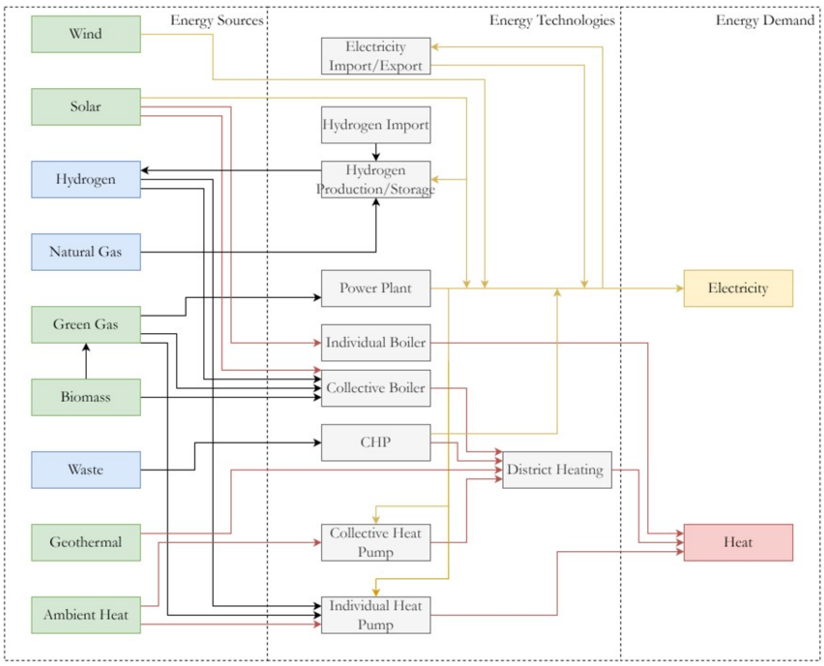


Figure A.5: System diagram of the interconnections between the system components of the Dutch electricity and heating sector for the built environment in the European scenario for 2050. Data sources: Berenschot & Kalavasta [2020]. Software: Microsoft Visio

The quantified energy flows of the European scenario by Berenschot & Kalavasta [2020] are depicted in figure A.6.

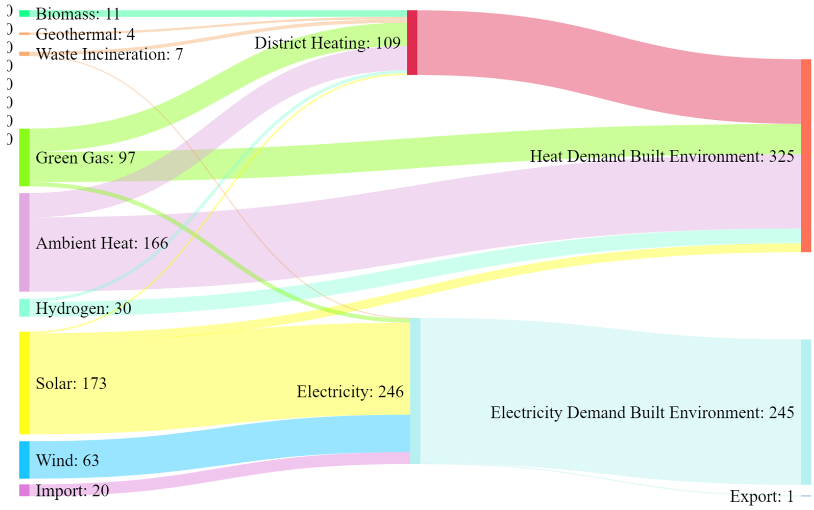


Figure A.6: Sankey diagram of the energy flows in PJ between the system components of the Dutch electricity and heating sector for the built environment in the European scenario for 2050. Left side represents supply, right side represents demand. Data sources: Berenschot & Kalavasta [2020]

A.0.4 International Scenario

The international scenario by Berenschot & Kalavasta [2020] is depicted in a system diagram in figure A.7.

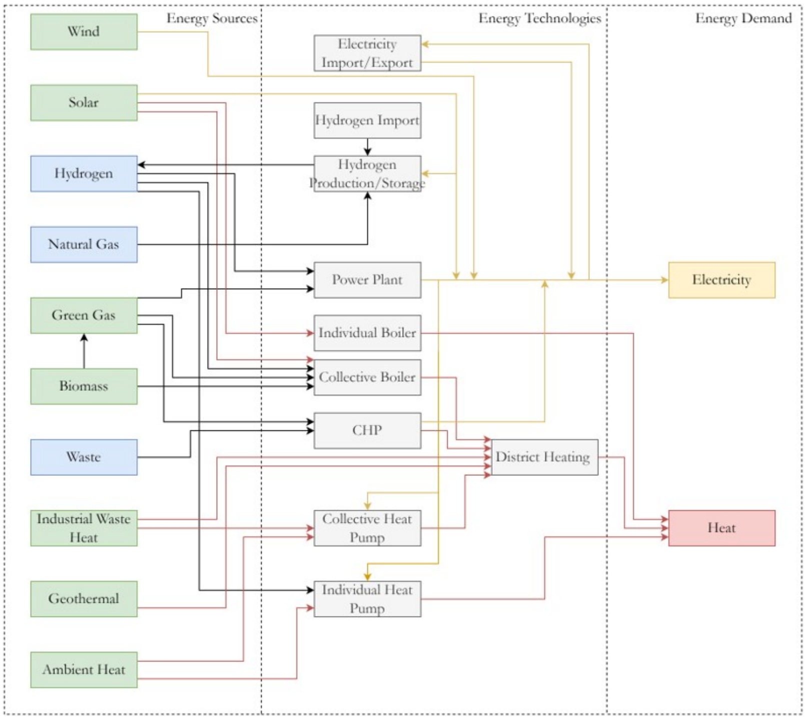


Figure A.7: System diagram of the interconnections between the system components of the Dutch electricity and heating sector for the built environment in the international scenario for 2050. Data sources: Berenschot & Kalavasta [2020]

The quantified energy flows of the international scenario by Berenschot & Kalavasta [2020] are depicted in figure A.6.

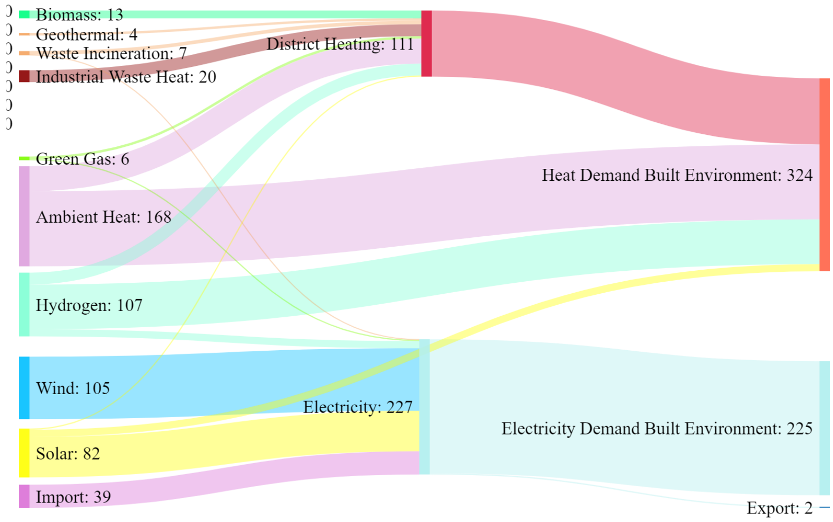


Figure A.8: Sankey diagram of the energy flows in PJ between the system components of the Dutch electricity and heating sector for the built environment in the international scenario for 2050. Left side represents supply, right side represents demand. Data sources: Berenschot & Kalavasta [2020]

A.0.5 ADAPT Scenario

The ADAPT scenario by TNO [2020b] is depicted in a system diagram in figure A.9.

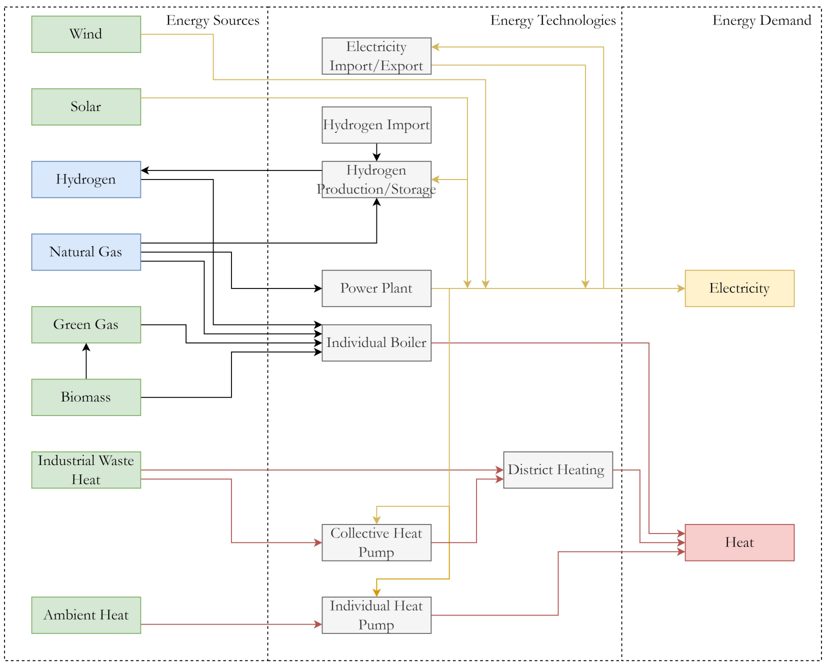


Figure A.9: System diagram of the interconnections between the system components of the Dutch electricity and heating sector for the built environment in the ADAPT scenario for 2050. Data sources: TNO [2020b]

The quantified energy flows of the ADAPT scenario by TNO [2020b] are depicted in figure A.10.

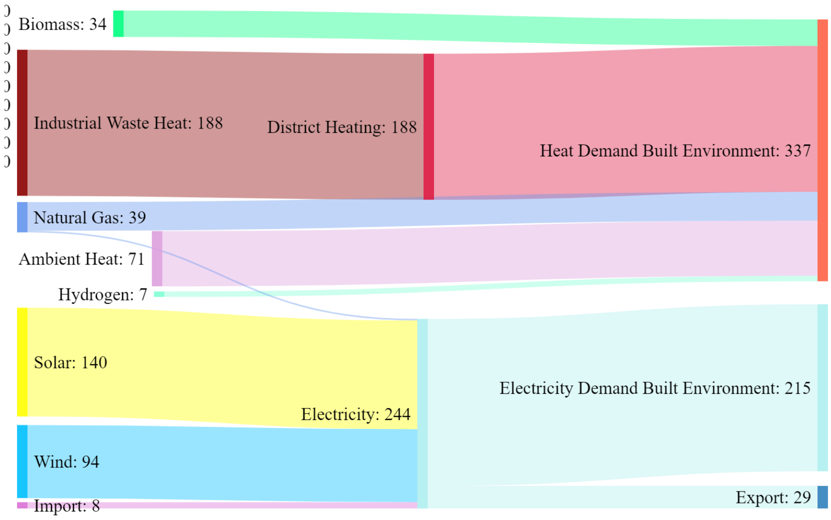


Figure A.10: Sankey diagram of the energy flows in PJ between the system components of the Dutch electricity and heating sector for the built environment in the ADAPT scenario for 2050. Left side represents supply, right side represents demand. Data sources: TNO [2020b]

A.0.6 TRANSFORM Scenario

The TRANSFORM scenario by TNO [2020b] is depicted in a system diagram in figure A.11 and is quite similar to the ADAPT scenario depicted in figure A.9.

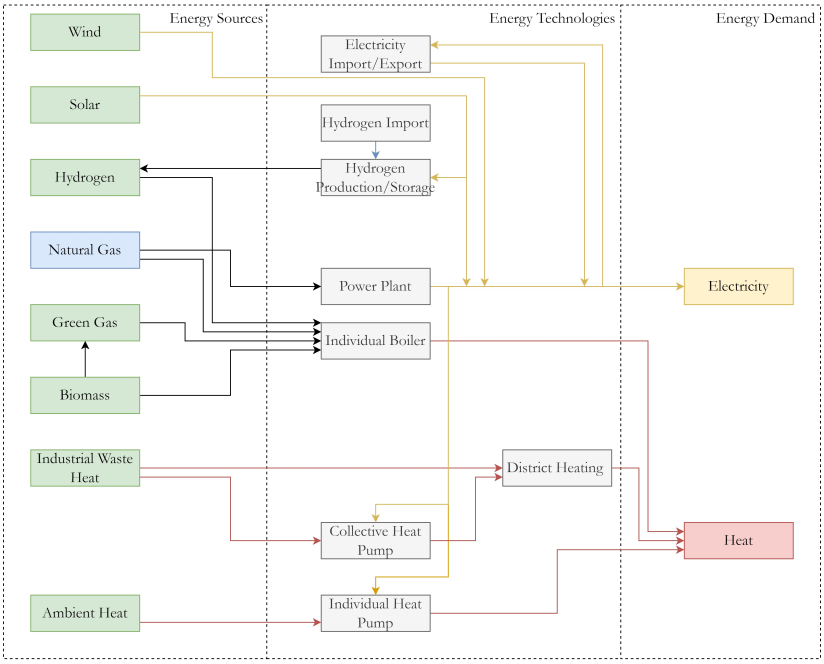


Figure A.11: System diagram of the interconnections between the system components of the Dutch electricity and heating sector for the built environment in the TRANSFORM scenario for 2050. Data sources: TNO [2020b]

The quantified energy flows of the TRANSFORM scenario by TNO [2020b] are depicted in figure A.12 and are nearly similar to the energy flows of the ADAPT scenario depicted in figure A.10.

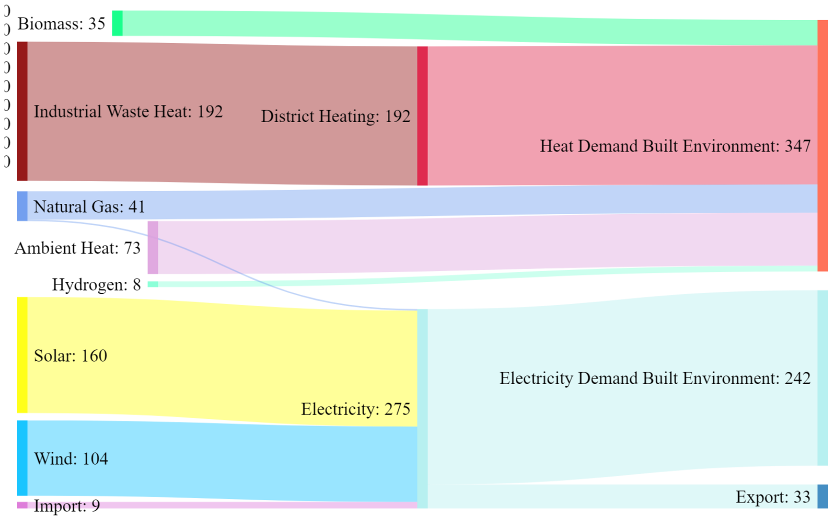


Figure A.12: Sankey diagram of the energy flows in PJ between the system components of the Dutch electricity and heating sector for the built environment in the TRANSFORM scenario for 2050. Left side represents supply, right side represents demand. Data sources: TNO [2020b]

B APPENDIX B: RENEWABLE HEATING SOURCES OF MUNICIPALITIES

The Transition Vision for Heat (TVH) of the various municipalities of the region North-Holland include concrete plans for the heat transition, as discussed in section 6.4.2. Table B.1 shows the municipalities and their planned renewable heat sources and DH sources.

Municipality	Renewable Heat Sources	DH Sources	Reference
Amstelveen	DH network, (hybrid) individual heat pumps	Industrial waste heat, aquathermal, geothermal	Gemeente Amstelveen [2021]
Amsterdam	DH network, (hybrid) individual heat pumps, individual green gas boiler	Industrial waste heat, aquathermal, geothermal, TES, biomass, solar, waste incineration	Gemeente Amsterdam [2020]
Diemen	DH network, (hybrid) individual heat pumps	Industrial waste heat, aquathermal	Gemeente Diemen [2021]
Haarlem	DH network, (hybrid) individual heat pumps, individual green gas boiler	Industrial waste heat, geothermal, solar	Gemeente Haarlem [2021]
Heemskerk	DH network, (hybrid) individual heat pumps, individual green gas boiler	Aquathermal, geothermal	Gemeente Heemskerk [2021]
Heemstede	DH network, (hybrid) individual heat pumps, individual green gas boiler	Not specified	Gemeente Heemstede [2021]
Hilversum	DH network, (hybrid) individual heat pumps, individual green gas boiler	Industrial waste heat, aquathermal, geothermal	Gemeente Hilversum [2021]
Landsmeer	DH network, individual heat pumps	Not specified	Gemeente Landsmeer [2021]
Laren	(Hybrid) individual heat pumps, individual green gas	Not applicable	Gemeente Laren [2021]
Oostzaan	DH network, (hybrid) individual heat pumps	Aquathermal	Gemeente Oostzaan [2021]
Uithoorn	DH network, (hybrid) individual heat pumps	Aquathermal	Gemeente Uithoorn [2021]
Waterland	DH network, (hybrid) individual heat pumps	Not specified	Gemeente Waterland [2021]
Weesp	DH network, (hybrid) individual heat pumps, individual green gas boiler	Industrial waste heat, aquathermal	Gemeente Weesp [2021]
Wormerland	DH network, (hybrid) individual heat pumps, individual green gas boiler	Industrial waste heat, aquathermal	Gemeente Wormerland [2021]
Zaanstad	DH network, (hybrid) individual heat pumps, individual green gas boiler	Aquathermal geothermal	Gemeente Zaanstad [2021]

Table B.1: Municipalities of the region North-Holland South and their planned renewable heating sources according to their TVHs

C APPENDIX C: INTERVIEW PROTOCOL

C.1 INTERVIEW PROTOCOL

Introduction
This thesis explores the impact of the transition from traditional to renewable district heating systems on the Dutch electricity and heat sector. Specifically, the impact of this transition on the supply and demand balances of various heat and electricity sources is analyzed. The purpose of this interview is to collect knowledge about the expectations and plans regarding the energy transition in the region North-Holland South up until 2050. With this knowledge, better insight can be gained into the future energy system of the region and the process towards this system. By participating in this interview you contribute to case-specific data collection. The interview is expected to last 60 minutes. This interview consists of the following parts: heat transition, electricity transition & cooperation.

Part A: Heat transition

1. What do you think will be the future role of district heating networks in the region North-Holland South in 2050?
2. What do you think will be the most important sources for district heating networks in this region in 2050?
3. What makes you expect these specific heat sources?
4. Are there concrete plans within your organization regarding the development of these specific heat sources?
5. What problems do you see with regard to the development of these specific heat sources up to 2050?
6. What solutions are necessary to solve these problems according to you?
7. In addition to district heating networks, what do you think are important sources of heat in the region North-Holland South in 2050?
8. What makes you expect these specific heat sources?
9. Are there concrete plans within your organization regarding the development of these specific heat sources?
10. What problems do you see with regard to the development of these specific heat sources up to 2050?
11. What solutions are necessary to solve these problems according to you?

Part B: Electricity Transition

1. What do you think will be the most important sources of electricity in the region North-Holland South in 2050?
2. What makes you expect these specific resources?

3. Are there concrete plans within your organization regarding the development of these specific sources?
4. What problems do you see regarding the development of these specific sources up to 2050?
5. What solutions are necessary to solve these problems according to you?

Part C: Collaboration

1. Who do you think are the most important actors involved in the energy transition of the region North-Holland South?
2. What is the role of your organization within this process?
3. How are the concrete plans of the involved actors coordinated?
4. Is a certain actor playing a leading role in making concrete plans? If yes, which actor?
5. To what extent are the RES/TVHs of the region North-Holland South taken into account when making concrete plans for the future energy system?
6. Do you think the developments in the heat and electricity sector are well aligned?

These were the questions. Thank you very much for your attention and time! If you have any questions, you can always contact Simone de Bruin.

D APPENDIX D: ASSUMPTIONS REGIONAL FUTURE ENERGY SYSTEM

Table D.1 and D.2 show numerical assumptions on which the estimated future electricity and heating sector of region North-Holland South are based, as discussed in section 6.7.

End-Demand	Contribution [PJ]	Assumption Base
Electricity	37,4	RES
Heat	44,3	RES
Electricity Supply	**Contribution [PJ]**	**Assumption Base**
Solar	8,3	RES, Vattenfall
Wind	2,5	RES, Vattenfall
Hydrogen	2,0	Vattenfall, TenneT, Gasunie, Liander
Waste Incineration	0,6	RES, AEB, Westpoort Warmte, Vattenfall
Import	24,0	RES, Vattenfall, TenneT, Liander
Heat Supply	**Contribution [PJ]**	**Assumption Base**
District Heating	18,8	RES, TVHs, Vattenfall, Westpoort Warmte
Ambient Heat	18,8	RES, TVHs, Vattenfall
Green Gas	6,7	RES, TVHs, Gasunie, Liander, Vattenfall
District Heating Supply	**Contribution [PJ]**	**Assumption Base**
Geothermal	5,9	RES, TVHs, Vattenfall, Westpoort Warmte
Industrial Waste Heat (HT)	2,8	RES, TVHs, Vattenfall, Westpoort Warmte
Industrial Waste Heat (LT)	3,1	RES, TVHs, Vattenfall, Westpoort Warmte
Ambient Heat	5,9	RES, TVHs, Vattenfall, Westpoort Warmte
Waste Incineration	0,8	RES, TVHs, Vattenfall, Westpoort Warmte, AEB
Solar	0,01	TVHs
Electric	0,24	Vattenfall

Table D.1: Assumptions for the energy flows of the electricity and heating sector of the regional future energy system (2050)

Producer	Plant	Location	Energy Source	Capacity [MW]
Vattenfall	Hemweg-8	Amsterdam	Coal	Closed
Vattenfall	Hemweg-9	Amsterdam	Hydrogen	435
Vattenfall	Diemen-33	Diemen	Hydrogen	Closed
Vattenfall	Diemen-34	Diemen	Hydrogen	435*
Vattenfall	Ijmond-1	Cluster Velsen	Natural Gas	Closed
Vattenfall	Velsen-24	Cluster Velsen	Natural Gas	Closed
Vattenfall	Velsen-25	Cluster Velsen	Natural Gas	Closed
AEB	AEC	Amsterdam	Waste	Closed
AEB	HRC	Amsterdam	Waste	60*
AEB	Biomass Plant	Amsterdam	Biomass	Closed
Orgaworld	Greenmills	Amsterdam	Biomass	Closed
SVP	de Purmer	Purmerend	Biomass	Closed

Table D.2: Assumed power (and heat) plants in region North-Holland South in 2050

COLOPHON

This MSc thesis: Decarbonizing the Dutch Energy System: The Impact of Renewable District Heating on the Electricity and Heating Sector was typeset in LaTeX, using the arsclassica package by Lorenzo Pantieri. Cover figure: Oil & Gas Engineering Ltd. [2019].