Decarbonising the heating sector in the Netherlands by 2050

Looking towards a carbon-neutral future

Master Thesis

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Summary

Actions on climate change are becoming more urgent. Governments all over the world are being pushed to act against CO_2 emissions and to transit to low-carbon energy system. However, some countries are facing major challenges in the energy transition towards carbon neutrality. This happens to be the case in the Netherlands where the country is falling behind in achieving the European targets for 2020. The reason was found on a national energy system based on a robust natural gas infrastructure creating a carbon lock-in in gas technologies and infrastructures. The carbon lock-in is preventing the energy transition towards clean energy to occur more rapidly making it a complex challenge to overcome.

In 2016, 93% of the energy produced for space heating was obtained through natural gas technologies such as natural gas boilers. This technology is, by far, the most used in Dutch households. Therefore, space heating in the built environment is responsible for a major share of CO_2 emissions in the Netherlands. It is the aim of this thesis to present decarbonised alternatives to the heating sector in the Netherlands.

Using a theoretical framework to identify and overcome carbon lock-in situations, three alternative scenarios are presented following three different strategies: end-of-pipe, continuity and discontinuity. The alternatives were designed using an energy system analysis software – EnergyPLAN. Further, Smart Energy Systems concept was used to highlight possible synergies between the sub-sectors of the Dutch energy system, specifically between the electricity sector and the heating sector.

Power-to-gas and power-to-heat approaches were considered to design the alternatives focusing on integrating fluctuating energy from renewable energy sources in the most effective way. The decarbonisation on power-to-gas strategy was found by substituting natural gas for green gas. The production of green gas was simulated based on hydrogenation processes where the hydrogen was obtained through electrolysers powered by intermittent renewable energies. On the other hand, the decarbonisation following power-to-heat strategy was reached by expanding the district heating network and incorporating large-scale heat pumps, geothermal heat pumps and excess heat sources. The heat pumps are working as conversion units to integrate intermittent energy from renewable energy sources such as wind, solar and excess heat, in the district heating grid.

The results show that it is possible to reduce the emissions on the Dutch heating sector up to 30% of the 2015 levels. Besides CO_2 emissions, the results were further analysed based on efficiency and costs. Solutions based on thermal grids prove to be more efficient and cost effective in reducing the CO_2 emissions than gas grids solutions.

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1. Problem Analysis

Introduction

As the consequences of climate change are becoming more evident, finding ways for reducing carbon emissions is becoming an urgent matter for governments and policy-makers all over the world. In 2015, at the annual Conference of Parties (COP21) an unprecedented agreement was signed - the Paris Agreement - where 196 countries pledge to make a joint effort to limit global average temperature below 2°C above pre-industrial levels by 2100 with an ideal target of limit global temperature to increase above 1.5°C of the pre-industrial levels. (United Nations, 2016; (UNFCCC, 2015) A clear signal was given to all stakeholders, investors, companies, civil society, and policy-makers that the global transition to clean energy is unavoidable and that it is necessary to stop investing resources on fossil fuels. The agreement reinforces the importance of collaboration and cooperation between nations stressing the need for quick actions, investments, transparency, and education to achieve a sustainable low carbon future for the world. (Ec.europa.eu, 2019; UNFCCC, 2015; UNFCCC.int, n.a.; European Commission, 2016)

In the aftermath of the Paris Agreement, the European Commission (2016) (European Commission, 2016) stressed that *“The transition to a low carbon, resource-efficient economy demands a fundamental shift in technology, energy, economics, finance and ultimately society as a whole”* (European Commission, 2016) and this can be seen as an opportunity for economic transformation, creation of jobs and economic growth. The Paris Agreement came as a confirmation of the path already taken by the European Union (EU) towards decarbonising its economy, a path that started long before the Paris Agreement. By 2016 greenhouse gas (GHG) emissions in the European Union were already down by 22.4% compared with 1990 levels, which is already above the 20% reduction target for 2020 for the union (ibid).

By taking a closer look at the carbon emissions in the European Union in 2016, the energy sector together with the transport sector generates almost 80% of all the EU emissions. The energy sector alone is responsible for more than 55% of the total emissions making it the main responsible for GHG in the EU (see figure 1). This led to an increase in renewable energy-related research policies. Besides the positive impacts on the global climate, renewable energy technologies can also reduce the dependence of national (and regionals) energy systems on foreign energy sources such as fossil fuels. (Negro, Alkemade and Hekkert, 2012) It is, therefore, crucial to radically change the current energy system by increasing the share of renewable energies and low-carbon technologies, and reducing the use of fossil fuel technologies.

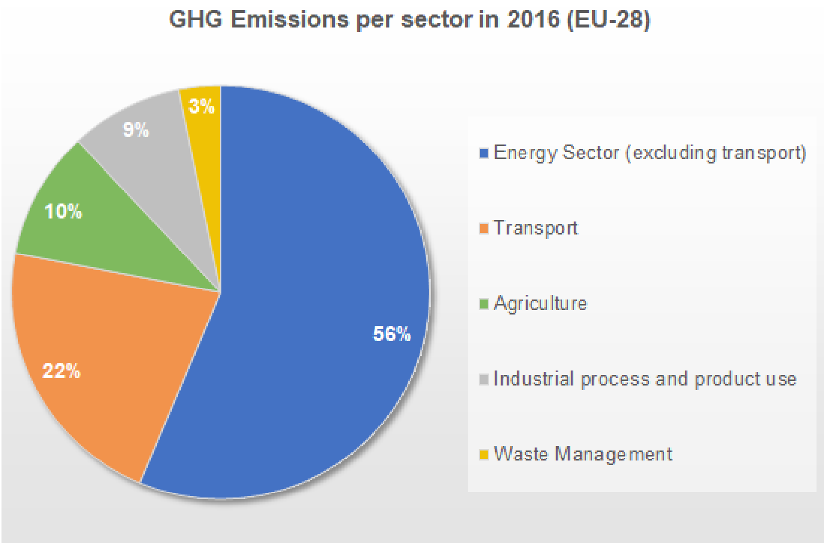

Figure 1 - Greenhouse gas emissions per sector in the European Union (EU-28) in 2016 (Data Source: Eurostat)

Inspired by the success of the implemented policies in the time-frame 2005-2016, the European Commission agreed on a new regulatory framework including more ambitious bindings for increasing the share of energy from renewables, improvements in energy efficiency, and a greater cut in GHG for the EU for 2030 and 2050 (European Commission, n.d.; (European Commission, 2018b)

The EU set targets for its final energy consumption for 2020, 2030 and 2050 can be seen in the following table:

	2020	2030	2050
Cut in greenhouse gas emissions (from 1990 levels)	20%	45%	80% - 100%
EU energy from renewables	20%	at least 32%	> 80%
Improvement in energy efficiency	20%	32.5%	-

Table 1 - Main energy-related targets for the European Union in the short and long-term.

Even though the overall results are optimistic, this, however, is not the reality for all Member States in the EU. Some countries are struggling to achieve the targets they ratified. One reason can be found in the way the energy systems are designed. Some countries have their entire infrastructure 'locked-in' on fossil fuels and a radical change is not an easy task to implement.

This is the case of the Netherlands, where its energy system is based on a robust natural gas infrastructure with an equally strong economy and business involved in the production, commercialisation and consumption. In 2015 the country's emissions were 8% lower than the levels of 1990 (European Commission, 2017) and reached 13% lower in 2017, still far from the country's goal needed for 2020 (Schoots, Hekkenberg and Hammingh, 2017; Vuuren et al., 2017), placing the Netherlands among the most polluting countries in the EU. (Berg and Meijer, 2018) In fact, according to Hölsgens (2016), the Netherlands is ranked 20th in terms of the world countries with the biggest contribution to climate change in absolute terms and, considering the amount per capita, it even ranks 6th. These numbers show that even though the Dutch economy is a medium-sized one, it holds a considerable share of the responsibility for global climate change. (Hölsgens, 2016)

When it comes to the share of energy from renewable energy sources, the Netherlands is also expected to fail the target of share energy from renewable energy sources. (Schoots, Hekkenberg and Hammingh, 2017; Fleming, 2019; Vuuren et al., 2017; European Environment Agency, 2018) Despite the share of energy from renewable energy sources have been added to the Dutch energy mix since the '70s, their uptake has been fairly slow. (Hölsgens, 2016)

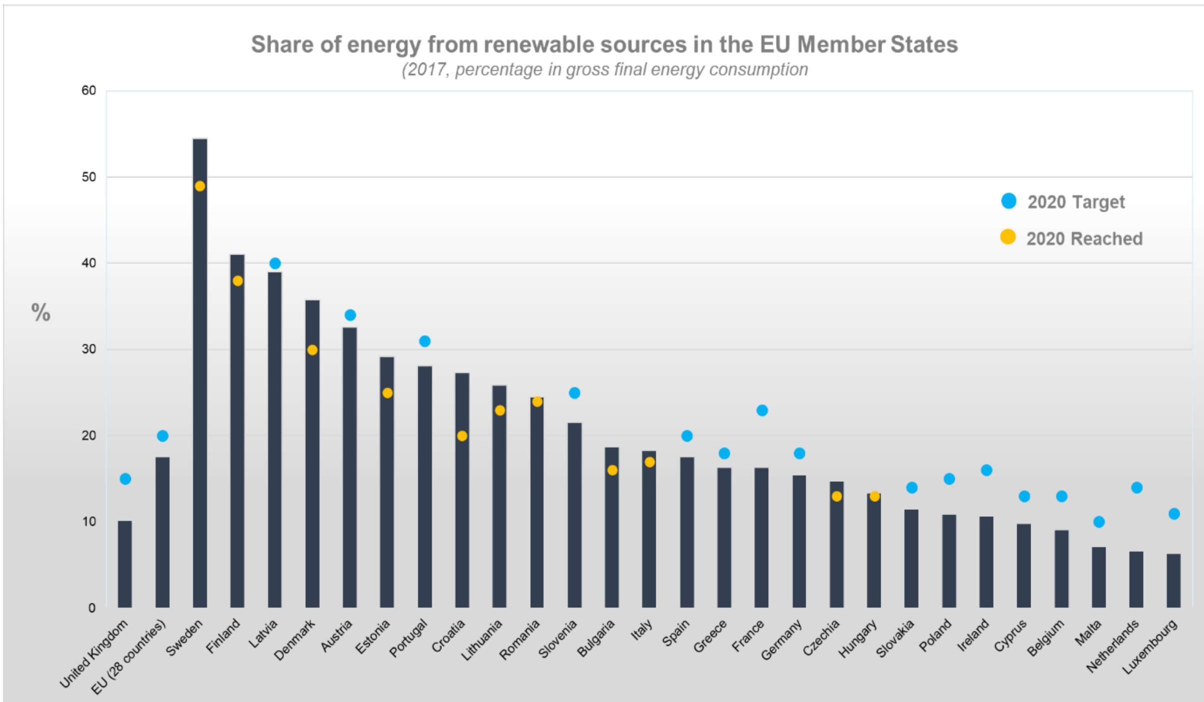

Figure 2 - Share of energy from renewable sources in final energy consumption by the EU Member States in 2017. (Data Source: Eurostat)

As presented in figure 2, in 2017 the Netherlands ranked 27th out of 28 EU member countries for energy consumption from renewable energy sources. In the same year, the country was the Member State furthest away from its 2020 target of 14% share (7.4% behind its 2020 goal). (Fleming, 2019)

Nonetheless, the Netherlands is on track to meet the 2020 energy efficiency savings target by reducing final energy consumption by an average of 1.5% on an annual basis. (European Commission, 2017; Government of the Netherlands, 2018)

Additional effort for achieving the country's agreed goals are urgently needed. Acknowledging this, the debate around the energy transition has increased and policies for the reduction of emissions are being discussed. (Vuuren et al., 2017) As an attempt to prevent the failure in achieving the Paris Agreement and the EU targets with the current policy, last year, the Second Chamber of the Dutch Parliament passed a bill defining more ambitious targets for reducing emissions on 49% reduction by 2030 and 95% by 2050 compared to the 1990 levels. (Government.nl, 2018; (Roberts, 2018; Hofhuis and Schaik, 2019) The law also includes that the electricity supply has to become 100% carbon neutral by 2050. In addition, the current government is committed to completely phase out coal by 2030. (Roberts, 2018; Berg and Meijer, 2018) Therefore, it is expected that actual and relevant reductions enforced by these public policies will happen in the (near) future.

This reveals that there is a strong political will in reducing emissions, yet, these are not easy goals to attain. The Netherlands is a heavily industrialized country and companies fear to be less competitive if changes are implemented faster than other European countries. (Berg and Meijer, 2018) Nevertheless, the Dutch Government sees the energy transition as an economic opportunity for the country. (Ministry of Economic Affairs, 2017)

Due to the Dutch tradition of using natural gas as its main energy source for the heating sector, several studies have been conducted in the direction of 'power-to-gas' approach keeping the gas infrastructure and changing the nature of the distributed fuel into a 'greener' gas. (Vlap, H. *et al.*, 2015; Leeuwen, C. and Mulder, M. 2018; Winkler-Goldstein, R. and Rastetter, A., 2013) The results show, however, that these technical solutions are still far from being realistic in terms of technology, efficiency, production, and the economy needed. Recently, the Dutch government expressed its openness to explore other solutions through its Energy Agenda (Ministry of Economic Affairs, 2017) and Energy Report (Ministry of Economic Affairs, 2016). At the same, considering a 'power-to-heat' approach, alternatives to gas infrastructure have been presented for the Netherlands by the project Heat Roadmap Europe. (Paardekooper et al., 2018) The aim of the project is to present low-carbon strategies for the energy sector, specifically for the heating and cooling sector, in 14 European countries, including the Netherlands. The methods used in all the 14 Heat Roadmap projects were aligned within the Smart Energy Systems concept covering aspects as excess heat sources, decentralized energy production, and energy efficiency measures both on the demand and the supply.

This thesis explores both approaches - power-to-gas and power-to-heat - for the Dutch heating sector and the implications of these two strategies will be further explained in Chapter 5 (Designing the Scenarios).

First, it is relevant to understand the Dutch energy system and the importance of natural gas in the heating sector. This will be addressed in the following chapter.

The Dutch energy system

The energy sector has a significant role in the overall functioning of the Dutch economy. Data from Energy Union Factsheet report from 2015 shows that it represented more than 6% of the total added value for the country and 0.35% of the total employment could be found in the energy sector alone. (European Commission, 2017)

In the same year, the energy mix in the Netherlands had a higher share of natural gas usage compared to the average energy mix of the EU - 38% and 22% respectively. The Dutch share of oil is higher than the EU average as well and it represents 40.6% and 34.4% respectively. The remaining of the energy mix includes 14.2% of solid fuels, 4.7% of renewables, 1% of waste, and 1.4% of nuclear provided by a single nuclear power plant which is planned to close in 2033. (European Commission, 2017) These are numbers considering the Dutch in gross inland consumption of primary products. Considering in gross final energy consumption, the share of renewables was 5.84% in 2015 (European Commission, 2017) and 7.4% in 2017 as previously stated in Chapter 1 (Problem Analysis).

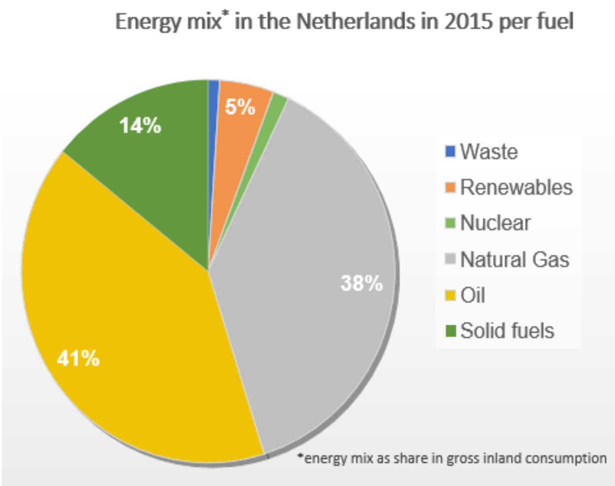

Figure 3 – Dutch energy mix, 2015 data. (Data source: [15](European Commission, 2017)

As mentioned before, the share of energy from renewable energy sources have been added to the Dutch energy mix at a rather slow pace. According to Hölsgens (2016), from an economic point of view renewables can only deliver electricity which can still be acquired through cheap sources like coal and natural gas (Hölsgens, 2016) and, institutionally, the existing energy system has developed in a way to support a stable flow of energy with a high degree of certainty. (Boer et al., 2018) These two arguments added to the overall challenge of renewable energy intermittency can explain much of the inertia seen in the Dutch energy system. Significant investments are required and imply a structural shift in economic activities. Energy-related investments and jobs need to transfer from traditional fossil fuels activities towards low-carbon and clean energies technologies. (European Commission, 2017; Ministry of Economic Affairs, 2017) Different policies favouring renewable energies and low-carbon technologies over fossil fuels together with a better integration of those renewable energies and efficient energy storage technologies (e.g. power-to-gas and/or power-to-heat technologies) are a possible path to haste the energy transition.

One other challenge has to do with the large energy-intensive industrial sector in the Netherlands. The industrial sector faces a tough transition as it requires to change past practices. It is expected that the sector will rise its CO_2 emissions rather than reducing in the coming years. (Ministry of Economic Affairs, 2017)

The low temperature heating sector

The heating (and cooling) demand represent 50% of all final energy demand in the Netherlands from which, almost half is needed for the built environment. (Paardekooper et al., 2018) In 2016, the contribution from renewable energy sources was only 5.5% (European Commission, 2018a) meaning that the built environment presents major challenges for reducing emissions, especially in space heating. The cooling sector has a total weight of less than 5% of the heating and cooling demand which is why the focus of thesis is the heating sector.

Low temperature heat, as opposed to industrial heat, is mainly used for heating homes, offices and buildings. In 2016, the Netherlands used 219 TWh of primary energy to produce low-temperature heat, where natural gas portrays 93%. (Ministry of Economic Affairs, 2016) The final energy demand for space heating in the Netherlands is 139 TWh (Paardekooper et al., 2018) and looking to the Dutch households, around 97-98% are heated with natural gas. (Hölsgens, 2016; Green Gas Grids, 2014)

Data from Heat Road Map Europe shows that in 2015 the share of district heating in the country was 13% and individual heating technologies accounted for 87% of the heating demand (see figure 4), being the last one mainly supplied through individual natural gas boilers. (Heat Road Map Europe, 2017)

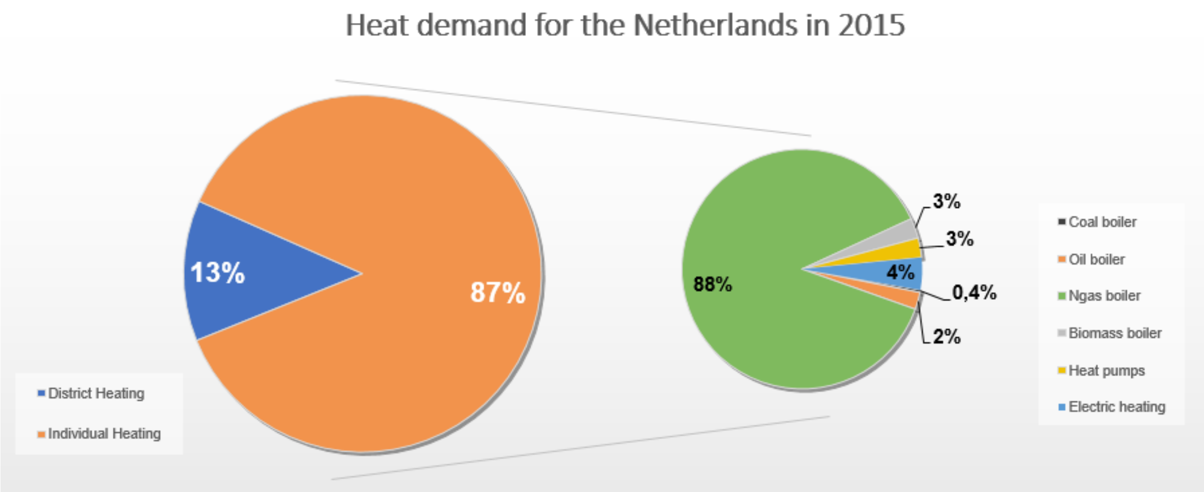

Figure 4 – Heat demand in the Netherlands in 2015. (Data available at www.heatroadmap.eu)

According to the Energy Report "Transition to sustainable energy" (2017), in 2012 space heating represented 45 million of tonnes of CO_2 emissions. It is obvious that the sector is highly dependent on natural gas which developed into locking-in the infrastructures and technologies that go with it. Ambitious energy savings measures and reducing the use of natural gas as much as possible by incorporating low-carbon technologies in the heating sector will be vital for fulfilling the targets. (Ministry of Economic Affairs, 2017; Ministry of Economic Affairs, 2016).

It is the Dutch Government concern to reduce the use of natural gas as much as possible while increasing heat savings, the use of excess heat sources, biofuels and heat and electricity from renewable sources. This has direct implications at the local and regional level as effective heat alternative sources need to be found, optimized and adjusted to the local context. A good understanding about the costs for the consumers and the infrastructure is needed, as well as the effects on the existing systems. Further, after evaluating the costs and benefits of the locally available alternatives to natural gas, local and regional heat plans can be designed as part of the energy transition providing local and regional government authorities with the important role of deciding what is the best solution for their case. (Ministry of Economic Affairs, 2016)

In 2015, several stakeholders including provinces, municipalities, energy organisations and heat producers presented a joint initiative focusing in the expansion of the district heating grid. The initiative included delivering heat at a lower price than gas, thermal grid infrastructure investments and local decision-making based on cost-benefit analysis for achieving the carbon-neutral goals. (Ministry of Economic Affairs, 2016) This suggestion of increasing the district heating grid will be addressed in the modelled scenarios. The transition from a heating sector based on a gas grid towards alternatives with more relevant thermal grid will be explored. Following this, the aim of this thesis is to combine ambitious goals for energy savings together with the incorporation of low-carbon technologies in the low temperature heating sector in the most effective way. Further, it is relevant to understand how and why natural gas became the main energy source for space heating in the Netherlands. This is explained in the following section.

Locking-in on natural gas - how did it happen?

Since the 1970s natural gas has accounted for roughly half of all the energy consumed in the Netherlands. (Correljé, Van Der Linde and Westerwoudt, 2003; Hölsgens, 2016) It is important to bear in mind that many decades of domestic natural gas exploitation guaranteed a substantial amount of wealth for the Netherlands. (Hölsgens, 2016)

The history of natural gas use in the Netherlands goes back to the middle of the 20th century. Back in 1948, the first source of natural gas was found in the Netherlands and in 1959 the biggest natural gas field of the country, and one of the biggest in the world at the time, was discovered - the Groningen field. Since then, this energy source gained momentum in the country and has been used to power and heat Dutch industry, business and homes. For decades the country had access to this reliable and 'cleaner' source of energy at a relatively low-cost allowing the Netherlands to reduce its dependence on fuels like coal and oil earlier than other European countries. This caused a change in the energy system regime in the Netherlands from an oil and coal system to a gas-based system. The reduction of fuel import and the increase in gas export (especially for other European countries) contributed to a positive trade balance for the country and enabled the expansion of the European gas market. (Correljé, Van Der Linde and Westerwoudt, 2003)

The natural gas was already used for process heat and power generation by the industrial sector, but it was the decision to create a national distribution gas grid and to connect it to the already existing local distribution city-gas grid that was the turning point in the Dutch energy supply. City-gas was already used by domestic users for cooking and hot water, but the connection to a national distribution gas grid allowed the create a demand for space heating by households, smaller business and the commercial and public sectors. (Hölsgens, 2016; Correljé, Van Der Linde and Westerwoudt, 2003) Once these smaller users have converted all their appliances to natural gas they would be locked-in into the gas market. This contributed to the expansion of the gas market which facilitated and justified the necessary investments for construction and conversion of the existing infrastructure.

During the oils crisis in the '70s, the lack of diversity in the energy supply showed the vulnerability of the energy systems around Europe. (Hölsgens, 2016) Natural gas became even more relevant as a domestic energy supply putting it in a prominent position in the Dutch political and economic agendas. State and private income rapidly increase due to the exploitation of this resource and several interests - economic, financial and political - were, and still are, involved in the production, commercialisation and consumption of natural gas. One can conclude that the locking-in into natural gas is not just technological, it goes deep into the very fabric in which the Netherlands developed as the country it is today.

One thing that is important to point out is the very nature of the gas produced in the Netherlands. The Dutch natural gas is peculiar because of its low-calorific value. Its composition is 82% of methane, 14% of nitrogen, 3% of heavier and wetter hydrocarbons, and 1% of carbon dioxide. (Correljé, Van Der Linde and Westerwoudt, 2003) As a result, Dutch appliances, particularly in households, had to be adjusted for low-calorific gas and will not function properly with high-calorific natural gas. This means that changing to another type of gas is rather complicated. The solution to deal with imported gas has been to add nitrogen to lower its calorific value. The need for adjusting or substituting appliances is a challenge that should not be overlooked as it will probably have high costs. (Hölsgens, 2016)

Regardless of its success, the production of natural gas is set to decline in the coming years. (Hafner and Tagliapietra, 2017) Rising concerns due to recurrent earthquakes connected to natural gas extraction have increased protests in the province of Groningen. The public pressure forced the Dutch government to take action and in 2015 the government decided to limit the production of natural gas to the minimum required in cold winters (Hölsgens, 2016; European Commission, 2017) and to phase out Groningen gas field by 2030. It is expected that the country will become a net importer of natural gas by 2025. (European Commission, 2017) Other sources are more optimistic about this date and go as further to 2030 - 2040. (Hölsgens, 2016)

In the meantime, investments are still needed to keep the current gas production. The Dutch economy and consumers are largely locked-in natural gas and a full-scale change in consumption patterns in the Netherlands is needed if the country does not want to become dependent on gas imports. Several stakeholders agree that the diversification of gas supply and substituting it with biogas and green gas is needed. The Netherlands has already knowledge in upgrading biogas to natural gas quality and has been injecting it into the gas grid as earlier as 1987, and the approach to produce green gas started in 2006. (Green Gas Grids, 2014) According to Hafner and Tagliapietra (2017) "*Energy experts agree almost unanimously that to fully remove natural gas from the energy equation in the Netherlands in the next 10 years is almost impossible*." (Hafner and Tagliapietra, 2017) The same source also mentions that proper actions are needed for the industrial sector as well to convert gas systems.

Nevertheless, an energy transition is unavoidable (Hölsgens, 2016) and the consumption of natural gas must decline.

2. Problem Formulation

Up until now, the domestic reserves of natural gas have slowed down the energy transition in the Netherlands, but domestic alternatives energy sources need to be found. The heating sector is a major contributor for the CO_2 emissions and low-carbon solutions need to be implemented to achieve European (and national) targets. The country can follow one of three paths: 1) keep with end-of-pipe solutions with minor changes to the overall system by keeping the existing infrastructure with add-on technologies; 2) alternative solutions which embrace infrastructure change to some extend allowing more technologies into the system 3) radical change the energy system through the replacement of the current system.

This leads to the Problem Formulation and the research questions of this thesis:

How can the Netherlands achieve the decarbonisation of the heating sector by 2050?

1. Which approaches can be taken to decarbonise the Dutch heating sector?
2. How does a decarbonised heating sector look like?

To answer to these questions, firstly, a deeper understanding of the Dutch current energy system needs to be analysed. In order to model alternatives that fit the Dutch context, the current conditions, barriers and opportunities need to be understood in order to adjust the solutions to what 'makes sense' for the Netherlands. Secondly, following the previous analysis, different scenarios will be designed using an energy system analysis tool – EnergyPLAN – to simulate the decarbonisation of the energy heating sector for 2050. Several alternatives are presented allowing to compare different solutions for the same (decarbonised) goal. Lastly, the alternatives will be analysed from a socio-technical and institutional point of view to answer the problem formulation.

To do this, a deeper understanding of which barriers and opportunities need to take place. In Chapter 1 (Problem Analysis), the Dutch energy system is analysed as a whole and not individually in order to embrace the possible synergies inside the system. Identifying the major barriers for decarbonisation and possible ways to overcome them will be further explained in Chapter 3 (Theoretical Approach). The aim of this thesis is to reach carbon neutrality for the heating sector of the Netherlands by 2050. Going deep into understanding what is preventing this goal to be achieved by identifying 'lock-ins' in the energy system and possible ways to 'unlock-it' is taking into account. Afterwards, the Smart Energy System concept is used to get a deeper insight into the design of alternatives using a system's perspective. Having the perspective of the whole energy system allows for identify the synergies within the system making it easier to integrate them. The technological solutions are analysed as part of an energy system and the socio-technical aspects of radical change are unveiled.

At this point, the design of decarbonised alternatives for the Netherlands can be modelled and the assumptions settled considering the Dutch context. For this, the data from Heat Roadmap Netherlands is crucial. The ‘business as usual’ 2050 scenario (BAU 2050) developed in the project will be the starting point for designing the alternatives. The alternatives include 1) moderate change, 2) relevant change and, 3) radical change to the Dutch infrastructure considering both gas grids (power-to-gas) and thermal grids (power-to-heat). This allows for a deeper comparison of the alternatives considering the degree of ambition towards change. In Chapter 5 (Designing the Scenarios) can be found a thorough description of how the scenarios are modelled. The following step is to analyse the results using the theoretical framework of ‘lock-in’ concepts. This is made in Chapter 6 (Results Analysis). Lastly, a critical discussion about the results together with the methods and theoretical approach takes place in Chapters 7 (Discussion). Finally, the answer to the Problem formulation is presented in Chapter 8 (Conclusion).

Some delimitations were made for scoping this thesis. One reason lies in the very topic of this thesis being limited to the Dutch heating sector. Industry, transport and cooling sectors are not part of the analysis. Those sectors are still part of the energy system but the possible synergies between them are not explored. This means that, from a Smart Energy System concept, the synergies found are limited to the electricity and heating sectors. Secondly, the Dutch energy system was analysed as an independent and isolated system. In other words, the system was not considered as being part of the European energy system meaning the impacts of imports and exports of energy such as electricity were disregarded.

Secondly, the analysis is based on the specific time-frame of 2050 not addressing the path towards that year. In other words, it shows how the system may look in 2050 but not the (political) planning strategies to reach that energy system. Acknowledgements of future policies and strategic planning touch upon but only scratching the surface of the topic. Additionally, an analysis on the costs and investments was made to understand the impact of the choices. A thorough socio-economic analysis including cost-benefits analysis and strategic planning is lacking and this is where further research can focus.

3. Theoretical Approach

As presented above, the energy transition towards a decarbonised one needs shifting at many levels. Social-technical and institutional changes are crucial for this transition to happen. At this point, it becomes clear that the relationship between economic, political, social, and technical aspects made the Dutch energy system an extremely complex issue.

Notwithstanding, it is known that an energy transition towards carbon neutrality is necessary and inevitable. Several low-carbon technologies and practices already exist, have been tested and are mature. If this is the case, then why are not these technologies and practices being introduced faster in the Dutch energy system?

The answer to this question is manifold. As presented in the previous chapter timing, political strategies, historic reasons and economic circumstances created barriers to change. Several scholars suggest that this inertia is due to technological path dependence which leads to a possibility of carbon lock-in situation (Schmidt and Marschinski, 2009; Unruh, 2000; Unruh, 2002; Arthur, 1989; Lehmann et al., 2012) favouring the continuity of dominating 'dirty' technologies even though cleaner and low carbon alternatives are available. In other words, when a particular technology becomes dominant it becomes harder for alternatives to gain momentum and find their place in the regime even though they are considered better solutions. The extent of this market failure is closely influenced by policies and institutions, which, in their turn, can be influenced by infrastructures and user's practices. (Mattauch, Creutzig and Edenhofer, 2015)

In this chapter, theories of 'carbon lock-in' are used to highlight barriers preventing energy transitions and perpetuate fossil fuel-based systems. Once the barriers are identified then possible solutions about how to overcome them are brought to light. Further, the implications for social-technical and institutional aspects are unveiled when different levels of change are taken into consideration.

Carbon lock-in theory

Carbon lock-in can be defined as "*(...) the result of a specific path dependence favouring fossil-fuel technologies over low-carbon alternatives.* (Lehmann et al., 2012, p325) The authors argue that these path dependencies are fostered by infrastructure provision (e.g. gas grid, gas pipelines) and economic return (e.g. a cheaper source of fuel) (Lehmann et al., 2012) The technological lock-in is subjected by institutional, policy and market failures (Mattauch, Creutzig and Edenhofer, 2015;

Unruh, 2000) meaning that regulations and institutions play a key role in defining these path dependencies.

According to Unruh (2000), "*carbon lock-in arises from systemic interactions among technologies and institutions.*" (Unruh, 2000, p818) He bases his statement in the notion of a Techno-Institutional Complex (TIC). The TIC concept implies that large technological systems, e.g. a national energy system, must be seen as complex systems of technologies together with public and private institutions surround the dominating technology, this is known as a techno-institutional regime. Once a TIC is established it tends to perpetuate itself through the creation of knowledge and capital mechanisms securing its path-dependent techno-institutional evolution. This way it prevents technological change that threatens the existing regime and alternatives are kept lock-out. (Schmidt and Marschinski, 2009) The Multi-Level Perspective (MLP) theory also describes the dynamics between social-technical aspects, institutions and technology's path dependence into the existing regime. The theory argues that technological transition is not a mere change in technology but a change in a heterogeneous network of elements such as user practices, industry structure, infrastructure, market and regulation. The overall coordination and orientation between these elements allow for small incremental innovations preventing radical changes to occur as they try to secure the stability of the regime configuration, their power and dominant position. (Geels, 2002)

The concepts of regimes and path dependency are used throughout this chapter to explain the relationships, interconnections and power structures between institutions and organisations inside energy regimes although these theories (MLP and TIC) will not be further developed in this thesis.

In his theory '*Escaping carbon lock-in*', Unruh (2002) identifies five sources of lock-in in carbon-based solutions:

4. Technological, which is directly related to the technologies, the dominance of some designs and architecture of systems, its standards and compatibilities;
5. Organisational, where routines and compartmentalization lead to silo thinking and influence customer-supplier relations;
6. Industrial, where industry standards and interdependency of technologies play a role in locking-in processes and systems;
7. Societal, which are related to users' preferences, behaviours and expectations towards how a system should fulfil the users' needs;
8. Institutional, through policies, laws and rules which have a direct influence in techno-institutional regimes.

(Unruh, 2002)

Usually, when there is a system's lock-in several (if not all) sources are present through a tight relationship between the actors involved. Technologies and technological infrastructures are closely connected to the organisations and (public and private) institutions who create, run and employ them. (Unruh, 2000; Unruh, 2002; Arthur, 1989). According to Lund (2014) "*(...) these organizations will not by themselves create and promote alternatives required to implement change.*" (Lund 2014, p22) Other solutions are perceived as a threat and are kept out of the existing framework who lock-out alternatives even when these alternatives present improvements to the overall system.

As mentioned by Hölsgens (2016) the "*Reduction of emissions is not only a purely technological effort. (...) social drivers play an important role."* (Hölsgens, 2016, p127) Over time these systems evolve to standardization through routines and interdependency and become fully embedded in society preferences, behaviours and expectations contributing to the continuity of the system dominance (Unruh, 2000; Unruh, 2002). Once the system reaches stability, there is no apparent reason for it to spontaneously change. In other words, without an external 'push', the current regime will not change by itself and the energy transition can be postponed. A market failure related to path-dependence and technological lock-in happens, which leads to societal loss. (Schmidt and Marschinski, 2009) Another aspect that should not be underestimated for low-carbon alternatives to arise is the societal aspect. It is expected that users change their behaviour and expectations towards the regime and this can be a rather hard thing to achieve due to inertia and lack of information.

Analysing these concepts together with the Dutch energy system it becomes easier to understand the slow penetration of renewable energy in a system which was designed to work based on natural gas technologies. Decades ago, the political decision to create a national distribution gas grid nurtured the infrastructure, industry, technologies, and appliances related to natural gas. The availability of cheap, secure and reliable heat encouraged more customers to connect to the natural gas grid increasing the demand. On the other hand, as more capacity was needed to supply the demand the government decided to expand the gas grid solidifying the technological and institutional lock-in. The government intervention and the regulatory institutions played a fundamental role in creating the path dependency towards the carbon lock-in we witness today. The gas-related technologies have been dominant in the Dutch energy regime due to (small) incremental innovation to the existing infrastructure through the years. Institutional and organisational decisions allowed for this dominance protecting the market and favouring natural gas technologies. As pointed out in Chapter 1 (Problem Analysis), the choice of expanding the natural gas market to include smaller users and households having them converting all their appliances to natural gas they would be locked into the gas market. This choice was a major contributor to the overall lock-in of the energy system in the Netherlands.

It is, therefore, necessary to address these forces if changes are to be implemented. Social-technical and institutional aspects are crucial for moving the development of energy use and production in the right direction. Without relevant institutional change, development and innovation of technologies and, economic changes the so needed energy transition will probably not going to happen. (Correljé, Van Der Linde and Westerwoudt, 2003; (Mattauch, Creutzig and Edenhofer, 2015)

Unlocking the carbon lock-in

Nevertheless, is important to bear in mind that carbon lock-in is not a permanent condition. Changes in the landscape force systems' regimes to change as, for example, the current pressures for decarbonising the energy systems set by the European Union and the Paris Agreement. These pressures are pushing the (energy) regimes to change towards carbon neutrality path dependency and this has implications in many levels. The same way new technologies need new inputs, new customers for its outputs, and new institutions to exploit them, institutional changes are also needed in the forms of new policies, new organisational forms, and new rules. (Correljé, Van Der Linde and Westerwoudt, 2003)

Usually, the first approach to deal with the pressures on techno-institutional regimes is to make add-ons to the existing infrastructure and minimizing changes in the system. These are called ***end-of-pipe*** approaches which have the least impact in the existing infrastructure. These approaches usually deal with the issue downstream on the output side of the system. (Unruh, 2002) maintaining a similar (if not the same) path dependency. One example could be changing the fuel burned on CHP's changing from fossil fuel to biomass by making small adjustments to the plant but not changing the surrounding infrastructure like the electrical grid. Considering the Dutch heating sector, keeping the gas infrastructure and the gas-related appliances in place but changing the nature of the gas from natural gas to 'green gas' can be seen as an end-of-pipe solution. Of course, this alternative may create several other issues that can compromise its implementation such as technological and economic feasibility and resource availability for the production of 'green gas' which may result in another lock-in.

If end-of-pipe solutions are not enough to solve the issue, the next step is to find alternatives that can overcome the challenges through incremental innovation on the system. These are what Unruh (2002) calls ***continuity*** approaches due to the fact that the new system design will be as similar as possible to the previous one. Technologies with less representativeness in the existing regime can gain a bigger share but the architecture of the regime itself and the stakeholders will stay similar. For the Dutch heating sector, this could mean that other heating technologies (e.g. district heating technologies and/or heat pumps), which have a small share of the heating sector, can rise and compete with natural gas technologies. Besides representing greater changes than end-of-pipe alternatives it also faces different challenges as new appliances and infrastructure are needed.

Lastly, approaches that completely replace the existing system are called ***discontinuity*** approaches. According to Unruh (2002), these are considered the most radical changes as "*(...) they seek a discontinuous transition to a different, hopefully superior, system.*" (Unruh, 2002, p319) This will break with the existing path dependency completely reshaping the techno-institutional regime. Changing from gas-based technologies to district heating technologies would represent a radical change for the Dutch heating sector as it will change the entire regime. The implications will occur on all levels of the regime with the implementation of new technologies, institutions, infrastructure, market, regulation and end-users.

These three approaches - end-of-pipe, continuity and discontinuity - are modelled for this thesis and their design is thoroughly explained in Chapter 5 (Designing the Scenarios). For now, it is important to state that the aim of this thesis is not to decide which one is best, but to present different alternatives considering the same final goal of reducing carbon emissions in the Dutch heating sector. The importance of designing several (coherent) choices will be explored in the next chapter.

The importance of alternatives

By now it has been shown that a techno-institutional lock-in settles due path dependence choices. The technologies that best fit into the existing regime of the dominant stakeholders will be preferred solidifying the lock-in and perpetuating the regime in the same path. So, how can change happen?

For (radical) change to happen more than one dimension in the energy system's regime needs to happen. Lund (2014) argues that for a radical change to happen more than one dimension are changed. The more dimensions changed the more radical the change is. This is particularly important in carbon lock-in situations due to the several elements part of the techno-institutional regime (technological, organisational, industrial, societal and institutional). The availability of several (realistic, coherent and transparent) alternatives break with the old path dependency and choose one for the carbon neutrality goal. The existing organisations around a particular technology will have the best interest in keeping the regime as it is as they do not want to lose their dominance. Lund states that "*The organizations linked to the existing technologies are consolidated from an economic as well as a political point of view.*" (Lund, 2014, p21) The threat of new technologies can lead them to use their power to influence and affect the decision-making process by presenting alternatives that serve their interest and fit their framework, keeping other alternatives out of the process. If this happens the lock-in situation will most likely continue, which is why both institutional and technical changes should be part of the decision-making process. (Lund, 2014)

As described in Chapter 1 (Problem Analysis), the previous Dutch energy transitions had a clear benefit for producers, suppliers and consumers (e.g. lower cost). In a transition towards a low-carbon economy, these benefits are less obvious. Investments in the energy sector are large and have a lifetime of 20-40 year (Lund, 2014). Timing is, therefore, a fundamental element of the decision-making. In this sense, a decision made today will shape the future of the energy system for many years. This thesis focus is on the heating sector for 2050 which means that the decision on which path to follow needs to be made rather soon. That having been said, how should the alternatives be designed?

In his book Renewable Energy Systems, Henrik Lund (2014) presents guidelines for designing alternative scenarios for current energy systems. He identifies three conditions:

1. alternatives should be designed with equally comparable parameters (e.g. energy production and capacity);
2. savings on the demand, efficiency improvements and renewable energy sources should be involved in the design;
3. the direct costs should correspond to the ones on the main proposal.

(Lund, 2014)

In this way, the alternatives are comparable in several aspects such as technological innovation, environment and local jobs creation, just to mention a few. There is a vast consensus that a broad diversification of energy sources means increasing security and liability of the supply and increases the flexibility of the entire energy system. Synergies can be found inside the system to make it more efficient, this is the Smart Energy Systems concept and it will be briefly described after.

The role of the government

The decision behind which alternative or approach to choose is a political one. It is up to governments to create the political and institutional frameworks for alternatives to compete with the old technologies and conquer their place in the (new) techno-institutional regime. The Dutch government will have to decide which solution is more sustainable for heating the built environment, when and how should the infrastructure be phased out considering the benefits for society as a whole and for business and economic growth. It is a complex decision.

Unruh (2002) states that "*(...) decisions are frequently made with limited foresight and discounting of potential future risks or disutilities (...)*" (Unruh, 2002, p318) When forecasting the future, policymakers tend to prefer end-of-pipe and continuity approaches than discontinuity ones even though some experts argue that in order to greatly reduce CO_2 emissions and to pursue the decarbonisation of an energy system requires more than end-of-pipe solutions. The reason lies in the fact that the first two approaches can, most likely, reduce short-term costs and overcome the inertia towards change. The downside is that short-term solutions may be lacking vision for the long term. As claimed by Lund (2014) radical alternatives to the existing regime cannot be found in the organisations who are part of the techno-institutional regime. The alternatives should incorporate technical alternatives, socioeconomic feasibility studies and identify institutional barriers.

Notwithstanding, some solutions may not be possible to implement due to policy constraints which secure the lock-in and are needed to be overcome first. As mentioned before, there is no apparent reason for a stable system to spontaneously change. Techno-institutional regimes tend to create and perpetuate their own stability and secure their dominance and this leaves small room for alternatives. Without powerful external factors to the regime, radical change is most likely not to occur. One of these factors has been mentioned before - the external pressures towards States for decarbonising their economy. Another powerful change agent is the energy market itself where increasing returns for suppliers and consumers can boost the transition towards new technologies re-shaping the techno-institutional regime. Lastly, the governments have the authority to cause change towards low-carbon technologies, but challenges related to short and weak mandates represent a major barrier. Usually, social change sets the pressure for institutional priorities to change in democratic societies. (Unruh, 2000; Unruh, 2002).

In the Netherlands, the government played a crucial role in the part with the exploitation of natural gas and it still is involved in setting the extraction rate of this resource. On the other hand, the Dutch State is also in charge of setting subsidies for renewable energies and providing license for their implementations. (Hölsgens, 2016) It is reasonable to declare that for the transition towards a carbon-neutral energy system the government will play a major role. Governments design rules, laws, standards, subsidies and taxation which can influence the future path dependency of the Dutch energy regime. The infrastructure is nor easy nor cheap to change and represents substantial investments cost to change it on a national level. Providing stakeholders with the right information so they can make well-grounded decisions. It is the government responsibility to ensure the transition to a carbon-neutral built environment and the Dutch government has pledged to support stakeholders and local decision-making by providing the necessary frameworks in terms of policies and market regulations to facilitate the space heating energy transition. (Ministry of Economic Affairs, 2016)

4. Methodology

To help decisionmakers in formulating future strategies and policies for a carbon-neutral energy system looking forward to 2050, alternatives must be modelled. In this chapter, first the structure of the thesis is presented. Secondly, the methods used to answer the Problem Formulation are unveiled.

Figure 5 illustrates the research design for this thesis. The boxes in the middle correspond to the main chapters in this report and the boxes on the sides represent where specific knowledge is used in the report.

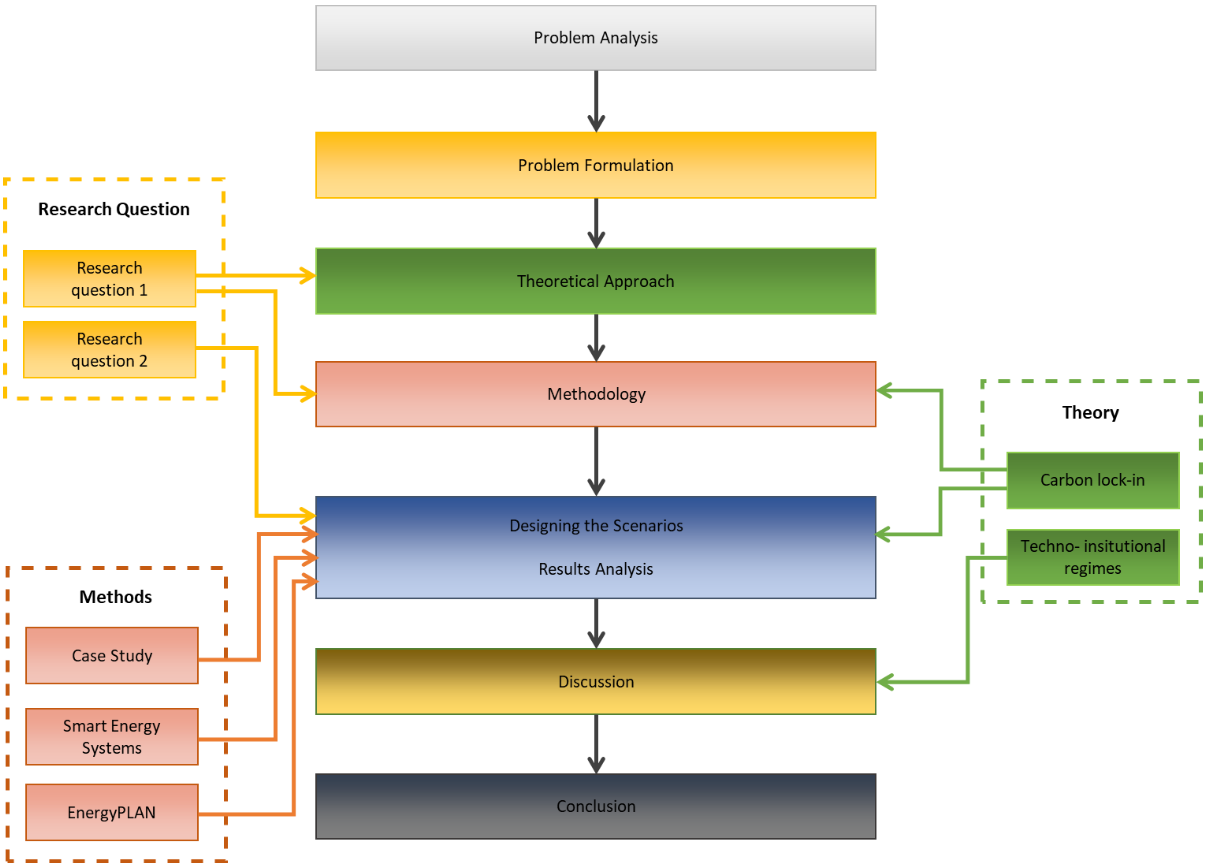

Figure 5 – Thesis design.

The inputs from the Problem Analysis led to the Problem Formulation and to the Theoretical Approach chosen which defined the strategy to answer the first research question by setting the foundations for modelling the alternatives. The answer for the second research question is found in Designing the Scenarios and Results Analysis. The findings are further discussed in relation to the assumptions, methods and strategies selected for this thesis. Lastly, a precise answer to the Problem Formulation is presented in the Conclusion.

To handle the complexity of this thesis, a choice of multiple methods was key for a thorough analysis. This thesis is based on a case study of the Dutch heating sector and quantitative methods were used to handle the empirical data using an energy systems simulation software. Additionally, two time-horizons were used: 1) longitudinal time horizon to understand how the Dutch heating sector and the carbon lock-in came to be as it is today, and 2) cross-sectional time horizon by comparing the alternatives in the year 2050.

Literature review

To better understand the problem area, an extensive review over the literature on the topic was conducted with the focus on the scientific quality and credibility of the sources. The research was focused in reports from the European Commission, scientific research papers and reports in the field of energy transition to low carbon technologies with the focus on the heating sector. Relevant data was examined to build a clear idea of the *state-of-the-art* followed by the development of the theoretical approach and the empirical data for the analysis. Some sources were found following the bibliography of the selected literature as a mean to get deeper knowledge about the subject. Governmental energy reports and national plans were studied as well to understand the Dutch case study context. Finding literature related to the legislation, policies and specific data related to the Dutch heating sector turned out to be a major challenge, most likely due to language constrains. This kind of information is usually available in the country's mother tongue and only a few aspects are translated to English.

Case Study

In this thesis, the selection of the case was not made randomly. While analysing the problem area of transition towards low-carbon technologies for the energy systems, the Netherlands appear far behind the targets set by the European Union being the second last in all 28 Member States in share of energy supplied by renewables. (see figure 2). The reason why the choice fell in the Netherlands and not in the last one (Luxembourg) was because the country has a high weight in the European CO_2 emissions, as explained in Chapter 1 (Problem Analysis).

The case study is influenced by the local context and its national energy system. In this sense, it can be hard to generalise to other places. For instance, in the Netherlands, the regime for the heating sector is based on gas but in other places, the regime is based in district heating (e.g. in Denmark) or electric heating. Flyvbjerg (2006) argues that a case study produces knowledge dependent on the context. The decarbonisation goal for the Dutch case, therefore, may not be achieved the same way somewhere else. Despite this, it can at least serve as an example (Flyvbjerg, B. 2006) and it is the goal of this thesis to present examples of alternative decarbonised solutions for the Dutch heating sector.

Smart Energy Systems

The concept of Smart Energy Systems is used in this thesis for better integration of sub-sectors in an energy system while modelling the different scenarios. But first, what is the Smart Energy Systems concept about?

The definition of 'system' is connected to the interaction of elements which influence one another directly or indirectly and where the whole is often greater than the sum of individual parts. (BusinessDictionary.com, n.d.) When it comes to 'energy systems' the elements are connected to an energy network or infrastructure including physical, technological, institutional and social elements. A 'smart energy system' arose from a paradigm shift from single-sector thinking into holistic thinking for designing future energy systems. (Lund et al., 2017) Although there are several definitions according to which author is considered, the concept used in this thesis can be found in Henrik Lund's book *Renewable Energy Systems* which explores and describes the concept extensively through several case studies examples, and is as follow:

"*A Smart Energy System is defined as an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system* " (Lund, 2014; Connolly et. al. 2013; Lund et al., 2017)

In other words, it uses a cross-sectoral approach to make the energy system more flexible, robust and resilient using synergies between the various energy sub-sectors. As energy systems are context specific and 'one solution cannot serve them all', several synergies can be found depending on which energy system is being analysed. For instance, considering the conversion of biomass into green gas there is the need for steam that can be supplied by CHP plants. The low-temperature heat that is produced as a by-product of the conversion can be used in district heating grids as a source of excess heat. This way both the by-product of CHP's (steam) and conversion technologies of biomass (low-temperature heat) can be used instead of being wasted. (Lund et al., 2017) Due to the fluctuation nature of renewable energies, using excess electricity produced this way can be stored in the form of gas (power-to-gas) or heat (power-to-heat) which is much cheaper than electricity storage. These are just a few examples of the possibilities that Smart Energy Systems can provide.

The following figure illustrates the Smart Energy Systems concept focusing on renewable energies sources.

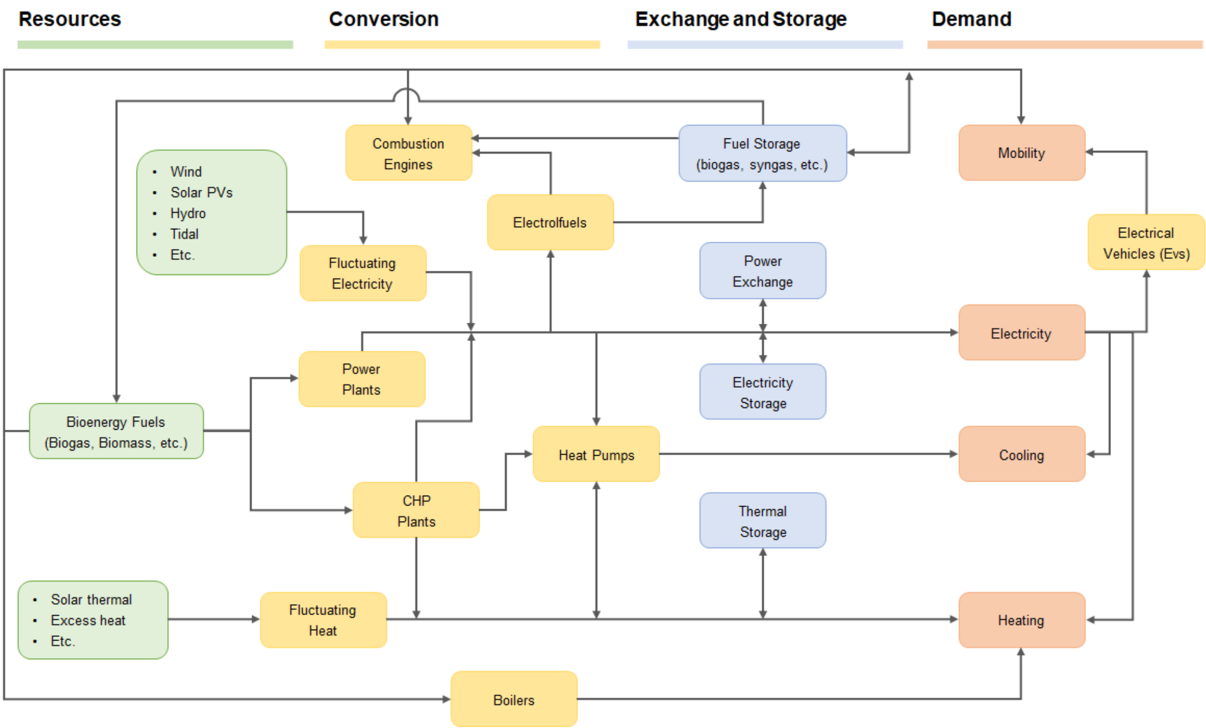

Figure 6 - Illustration of a (100% renewable) Smart Energy System displaying renewable energies as resources, points of conversion and conversion technologies, storage options and final demands. (Adapted from IDA's Energy Vision 2050, [42](Mathiesen, et al., 2015))

An important remark for Smart Energy Systems is that it acknowledges the essence of the different elements of techno-institutional regimes: technological, organisational, industrial, societal and institutional. Integrating renewable energies allows for local development (including jobs, business, etc.) related to the construction, operation and maintenance of these and satellite technologies. Renewables can play a greater role than just decarbonising the sector. (Mathiesen, et al., 2015) Techno-institutional regimes are different considering which case is being analysed, consequently, its elements are influenced by the local conditions. This is backed up by the case study method used in this thesis.

Using the Smart Energy Systems concept, the main goal is to integrate renewable energies as much as possible in the Dutch energy system together with energy storage making the whole system more flexible and efficient. This way it is possible to find the best (and smartest) solution for the entire system as well as for each individual element. (Lund et al., 2017; (Mathiesen, et al., 2015)

The Smart Energy System concept embraces three main grid infrastructures:

- Smart Electricity Grids to connect fluctuating renewables (e.g. wind and solar PV) to the flexible electricity demands (e.g heat pumps, electrolysers, and EVs)
- Smart Thermal Grids (i.e. District Heating and Cooling) to integrate the electricity from renewables into the heating sector through power-to-heat technologies (e.g heat pumps) enabling thermal storage and the use of excess heat.
- Smart Gas Grids to connect the electricity, heating, and transport sectors through power-to-gas technologies (e.g electrolysers) enabling gas storage.

(Lund et al., 2017; (Mathiesen, et al., 2015)

In this thesis, the three main infrastructures are used to increase flexibility and optimise the system. The electricity grid is used to integrate renewable energies that can be utilised for the heating sector and, as mentioned both power-to-gas and power-to-heat technologies were used for designing the scenarios. The differences between the two approaches are explained in the next section.

Power-to-gas and power-to-heat technologies

A rough definition for power-to-gas is that it uses electricity to produce green gas that can be stored or injected in a gas grid. To develop the definition further using the Smart Energy Systems concept is to maximize renewable energy to produce ‘green gas’, thus bypassing the fluctuation nature of renewables by producing the gas when the electricity production is higher than the demand. (Lund et al., 2017) For example, on a windy night when the demand is low, the electricity produced by wind turbines can be ‘stored’ in the form of gas (hydrogen) by using power-to-gas technologies such as electrolysers. This way the wind energy that would be wasted other way can be ‘stored’ and utilised later in several sectors. This technology is often considered as a solution for the transport sector (Lund et al., 2017) while overlooking other sectors such as the heating sector. In this thesis, this approach is used for the heating sector disregarding the transport and industry sector.

In power-to-heat technologies, the same principle as power-to-gas is used. The difference is that instead of storing the electricity in the form of gas, it does it in the form of hot water. Using the previous example of a windy night, the electricity produced by wind turbines can be ‘stored’ in the form of heat by using power-to-heat technologies such as heat pumps. In the morning this heat can then be used when people wake up and start heating their homes or showering.

EnergyPLAN

To analyse possible alternatives for decarbonising the heating sector for the Netherlands by 2050, these alternatives need to be modelled. The tool used in this thesis for modelling was EnergyPLAN. This tool was developed by the Sustainable Energy Planning Research Group at Aalborg University and is available online for download as '*freeware*'. (EnergyPLAN, n.d.)

EnergyPLAN was designed to simulate energy systems using the Smart Energy Systems concept through the integration of its sub-sectors (e.g. electricity, heating, cooling, transport and industry) including technical aspects, costs and investments. This is a very important feature as it allows to produce data for feasibility studies. (EnergyPLAN, n.d.) As a tool to simulate energy strategies, it is possible to include different technologies and the (known or unknown future) availability of resources such as biomass, electrofuels and biogas. EnergyPlan has been used in an extended number of scientific research (Østergaard, 2015) and several projects such as Heat Road Map Europe and IDA's Energy Vision 2050. It is, therefore, a well-proven tool for energy systems simulation.

The software simulates the annual energy demand and production through an hourly based calculation (ibid) making easier to understand the behaviour of (intermittent) renewable energy sources, which is especially important considering the seasonal availability of resources for some technologies. For example, considering solar energy, it can only be produced during the day when the sun is shining and there are more hours of sun during the Summer than during the Winter meaning that an hour-by-hour model will consider these aspects.

The very essence of EnergyPLAN is that it provides quantitative data that can be further analysed based on the assumptions made for the inputs. The data used in the simulations was provided by Heat Road Map Netherlands. The Baseline Scenario for 2015 (BL 2015), the Business-as-Usual Scenario for 2050 (BAU 2050) and respective distribution files are all available at the project's website. These files proved to be crucial for designing the scenarios as they are representative for today's energy system (BL 2015) and future energy system (BAU 2050) following the same path dependency. Additional data related to technologies, fuel and infrastructure costs were acquired at Danish Energy Agency (DEA) all available at: www.ens.dk/en/our-services/projections-and-models/technology-data (Danish Energy Agency, 2016; Danish Energy Agency, 2017; Danish Energy Agency, 2019)

Initially, the data was handling using Microsoft Office Tool - Excel. Common specifications such as percentage of heating savings, district heating and individual heating share, and green gas production were prepared and calculated for each alternative. This data was then used as input for the simulations. The remaining inputs (such as RES capacity, heat pump capacity, etc.) were found using an iterative approach. Rounds of analysis were repeated and evaluated using different conditions until the most effective solution was found.

EnergyPLAN has many advantages for simulating present and future energy systems, but due to its complexity it was challenging to work with. Much effort was spent in studying and understanding how the software works and which data to use in EnergyPLAN. The major challenge was found upstream on how data should be treated beforehand for input, what it represents, and how it affects the output.

5. Designing the scenarios

In this chapter, an explanation of how the alternative scenarios were designed and which assumptions were considered is made. For modelling the scenarios, the approach followed is the one described in Chapter 3 (Theoretical Approach) - end-of-pipe, continuity and discontinuity. The '*business-as-usual"* (BAU 2050) scenario for 2050 from the Heat Road Map Netherlands was the foundation for modelling all scenarios. Besides this, the concept of Smart Energy Systems is used for better integration of the different sectors in an energy system.

The Heat Roadmap Netherlands report, states that the heating and cooling count for 284 TWh/year of the final energy demand in the Netherlands (2015 values) and 49% of this total is for space heating alone. Even though the values are from 2015, there has not been many changes in the Dutch heating sector since then meaning these numbers are up to date. The report presents a radical change to the existing energy system for 2050 by considering technologies alternative to gas - mainly district heating and large-scale heat pumps - and investments for new infrastructure such as a thermal grid. The report finds that an additional 15% on heat savings and a share of district heating between 47% and 76% are the optimal point for the investments to be economically attractive. (Paardekooper et al., 2018) The report also reflects aspects as energy efficiency measures, both on the demand and supply side, leading to energy savings and reducing the overall cost of the energy system. The model displays deep decarbonisation considering technical feasibility and economic viability. The BAU 2050 scenario was presented as a comparison point and to put the results into perspective.

In the BAU 2050 scenario was assumed a 20% reduction in the space heat demand through heat saving measures representing a total heat demand of 105 TWh/year. As figure 7 shows, the share of district heating represents 22% of the heating demand and individual heating accounts for 78% where 68% is for natural gas boilers alone. (Paardekooper et al., 2018)

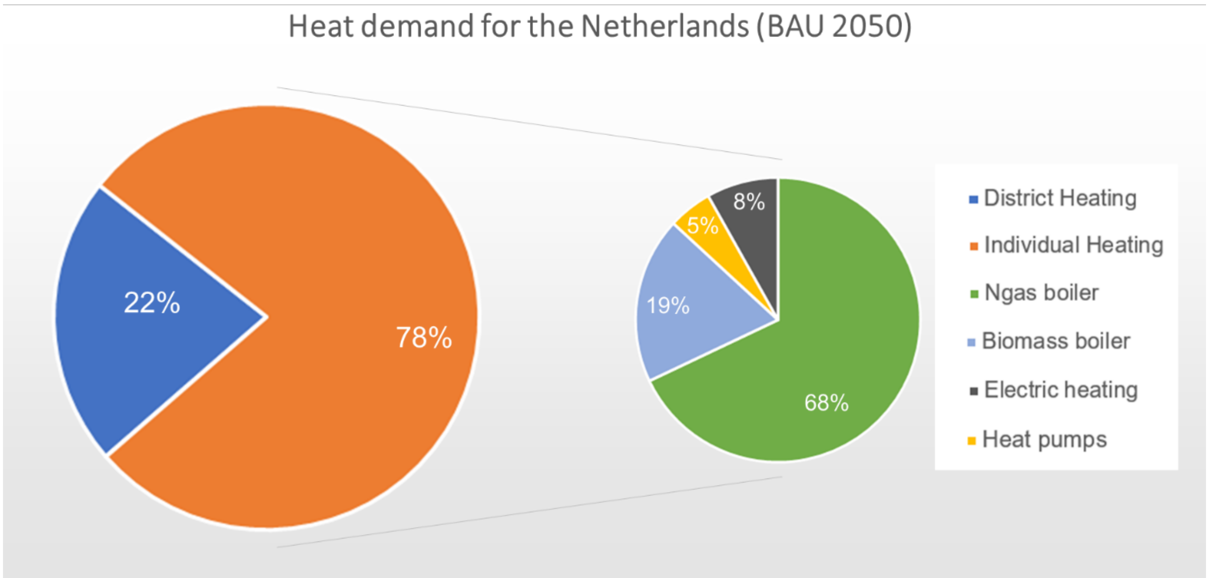

Figure 7 - Heat demand in 2050 for the Netherlands. (Adapted from Heat Road Map Netherlands available at www.heatroadmap.eu)

The BAU 2050 scenario shows the evolution of the Dutch energy system if it stays in the same path dependence. It is based on the techno-institutional regime of today with ‘frozen policies’ projections looking forward to 2050. This means that this scenario does not embrace the carbon-neutral goals making it a great underlying base for comparison new path dependency alternatives as to the ones presented in the decarbonised scenarios.

In this thesis, three alternative scenarios are presented for decarbonising the heating sector in the Netherlands by 2050. The approach for designing these three scenarios was based on the theory for unlocking carbon lock-in infrastructures, as described in Chapter 3 (Theoretical Approach), and using the Smart Energy Systems concept for integrating renewable energy sources as much as possible. The first scenario has a starting point of 22% share of district heating which is the same for BAU 2050. In alternative scenarios 2 and 3, the share of district heating used is 50% and 75% respectively, staying in the frame for district heating feasibility recommended by Heat Road Map Netherlands. In this way, the modelling starts with an end-of-pipe solution based on green gas, and gradually it changes in Scenario 2 by balancing the gas infrastructure with the district heating infrastructure, ending in a radical change in Scenario 3 by phasing out the gas infrastructure completely from the heating sector.

The Dutch Government expressed the will for investing in space heating saving measures and the EU set the target 32.5% for improvements in energy efficiency by 2030. Ministry of Economic Affairs, 2017) In this thesis, an additional 15% reduction was considered due to heat saving measures in all alternatives. Considering the 20% already accounted in BAU 2050, this portrays a very ambitious goal for energy savings. As mentioned in Heat Road Map Netherlands (2018), “*To achieve over 30% of reduction, both renovation rates and renovation depths have to be increased* *and the efficacy of the existing policies constantly monitored and reviewed.*" (Paardekooper et al., 2018, p16) In the end, an additional 15% reduction means almost 16 TWh/year savings compared to BAU 2050 totalizing 90 TWh/year in the heat demand.

Decarbonising the heating sector was the target in all scenarios even though the strategies followed are different as it is presented further in this chapter. To restrain the CO_2 emissions to migrate from the heating sector into the electricity sector, one-third of the coal-fired CHPs were converted into biomass preventing the rise of carbon emissions in the electricity sector. The integration of renewable energy sources was optimised prioritising offshore wind and solar PV keeping the critical excess electricity production (CEEP) under 10%.

The reasons behind favouring solar PV over onshore wind were mainly because of spatial issues and land management challenges. Onshore wind installations will use land that can be used for something else, (e.g. crops) and the feeling of "*not in my backyard*" towards wind turbines has grown in the past years. Solar PV can use the space available in the rooftops of existing buildings overcoming these challenges.

The reason to favour offshore wind over onshore has to do with the wind potential showed in figure 8. It is obvious that the potential is much higher in offshore installations. Considering the "*not in my backyard*" challenge, it is expected that offshore wind will face less resistance than onshore installations as well. In all scenarios, the onshore wind capacity was kept constant at 3400 MW which was the capacity of onshore wind installed in the Netherlands by 2018. (Komusanac, Fraile and Brindley, 2018)

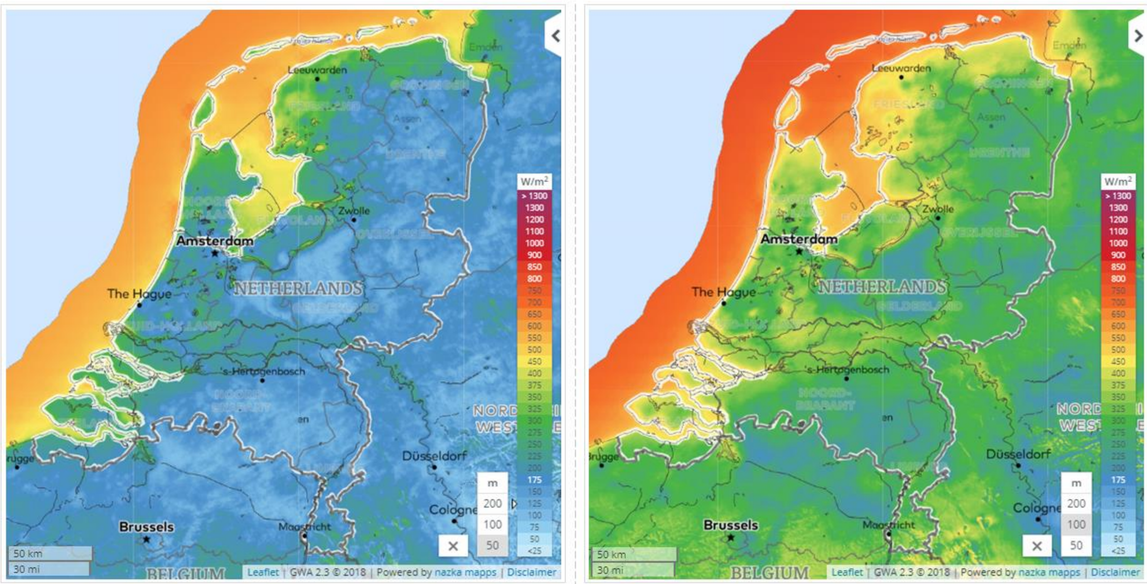

Figure 8 - Wind power potential in the Netherlands considering different heights - 50m high on the left and 100m high on the right. (Maps obtained from Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: HTTPS://GLOBALWINDATLAS.INFO. Accessed May 2019.)

All three alternative scenarios plus the BAU 2050 are explained further in the following sections. For an easy guidance, the main assumptions and inputs made for designing the alternative scenarios were gathered and are presented in Table 2.

	Scenario 1	Scenario 2	Scenario 3
Heat demand (TWh/year)			
District Heating	20.04	44.77	67.16
Individual Heating	69.51	44.77	22.39
Ind. Ngas boiler	43.29	18.56	0
Ind. Biomass boiler	15.47	15.47	0
Ind. Heat pumps	4.08	4.08	15.72
Ind. Electric heating	6.67	6.67	6.67
Total heat demand	**89.55**	**89.55**	**89.55**

	Scenario 1	Scenario 2	Scenario 3
Heat-only production inputs			
Heat pumps (MWe)	0	800	2000
Geothermal (TWh/year)	0	0	4
Excess heat sources (TWh/year)	0	5.6	11.3

	Scenario 1	Scenario 2	Scenario 3
Other assumptions			
CEEP	10%	10%	10%
Additional savings on the heat demand	15%	15%	15%
District heating grid losses	12%	13%	14%
Interest rate	3%	3%	3%

Table 2 – Data overview of the main inputs for three alternative scenarios.

Scenario 1: end-of-pipe solution

As explained in Chapter 3 (Theoretical Approach), end-of-pipe solutions have the least impact in the existing infrastructure keeping a similar path dependency. In this sense, all the existing infrastructure is maintained, and it is the nature of the fuel that switches from natural gas to green gas. There are no changes in the techno-institutional regime. For instance, the end-users do not need to change their appliances or behaviour as the end product will still be gas. The utility companies and the gas grid operators are the same as the green gas will represent the same share in the heating sector as previously the natural gas did.

In this scenario, the individual heating demand and district heating demand are the same as in BAU 2050 comprising 22% of district heating and 78% of individual heating, and the share of technologies in the heating demand is also the same (see figure 7). The purpose was to create a minimal impact on the infrastructure in accordance with the specifications of the end-of-pipe solution expressed in the theory. To decarbonise the heating sector this way, all the natural gas used for the natural gas boilers was converted into green gas.

The following picture shows a simplified scheme of the approach used in Scenario 1. It is important to stress that, even though there is 22% of district heating in this scenario, none alterations were made to the district heating. In this sense, there is no power-to-heat technology in district heating production as the production is ensured by CHP plants and boilers keeping it the same way as in BAU 2050.

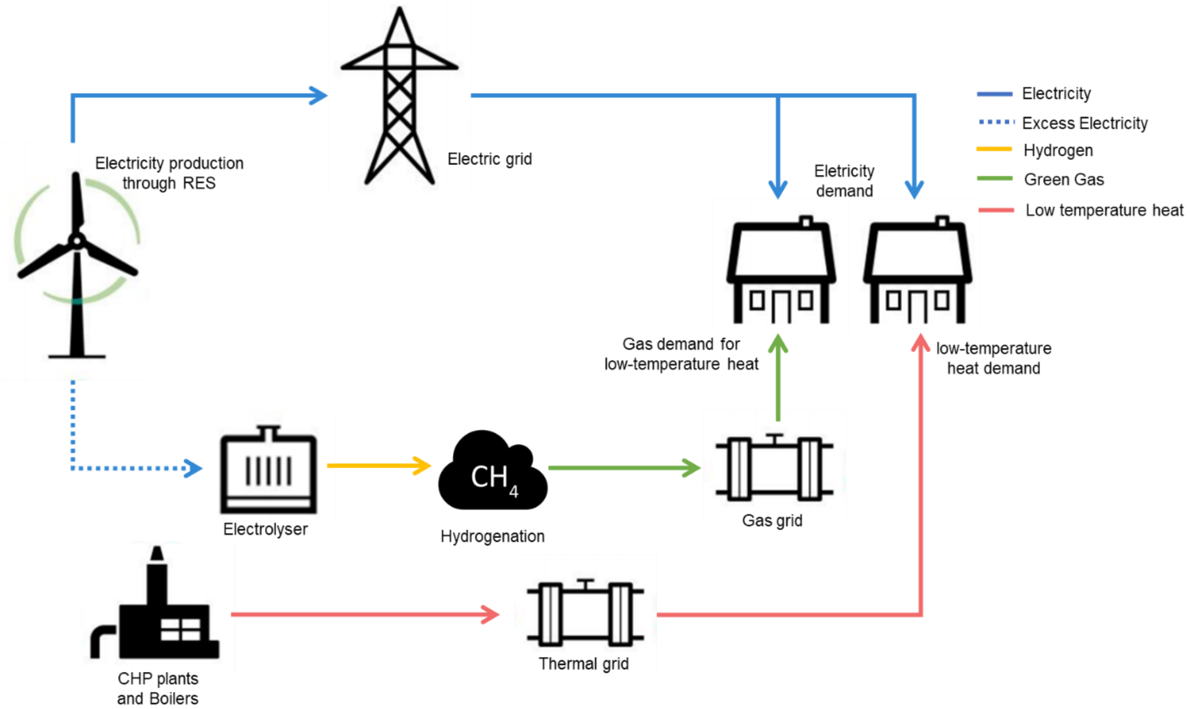

Figure 9 – Power-to-gas scheme used in Scenario 1.

This green gas has, of course, to be produced and the amount is dependent on the natural gas demand for the individual natural gas boilers which is 46.88 TWh/year. The biomass potential for the Netherlands was considered to produce the green gas. A study from 2009 shows that the biomass potential for the Netherlands is expected to be between 53 to 94 PJ (14.7 to 26.1 TWh) in 2020. (Koppejan et al., 2009) Although it is not possible to accurately predict the biomass potential for 2050, it was assumed that it will still be the same amount as in 2020. Therefore, the 26.1 TWh/year were considered for biogas hydrogenation process and the remaining 20.77 TWh/year, which need to be imported, were considered in the biomass hydrogenation process. The capacity for the electrolysers for producing the needed hydrogen was adjusted considering a 30% buffer. The available excess electricity produced by renewable energies is availed by the electrolysers and 1 GWh of storage for the hydrogen was considered to increase the overall efficiency of the system.

Scenario 2: continuity solution

For the second scenario, the continuity solution, the district heating is raised from 25% to 50% and, consequently, the green gas technologies are downscaled having a lower share in the heating sector. This provokes changes in the techno-institutional regime as new end-users for district heating emerge and new appliances must be installed. The gas infrastructure is still used, and the gas-related companies and utilities are still in place, but new investments are made for the thermal grids and, of course, new thermal grid operators arise. In this scenario, the techno-institutional regime changes, balancing the two infrastructures, but it cannot be considered a radical change since the gas infrastructure is still used. Power-to-heat and power-to-gas technologies coexist, and both use excess electricity from renewable energy sources to decarbonise the heating sector.

The following picture shows a simplified scheme of the approach used in this scenario. It becomes clear that the techno-institutional regime changes by having more households connected to the thermal grid. In this scenario, the excess electricity produced by renewable energies is used for both power-to-gas and power-to-heat technologies.

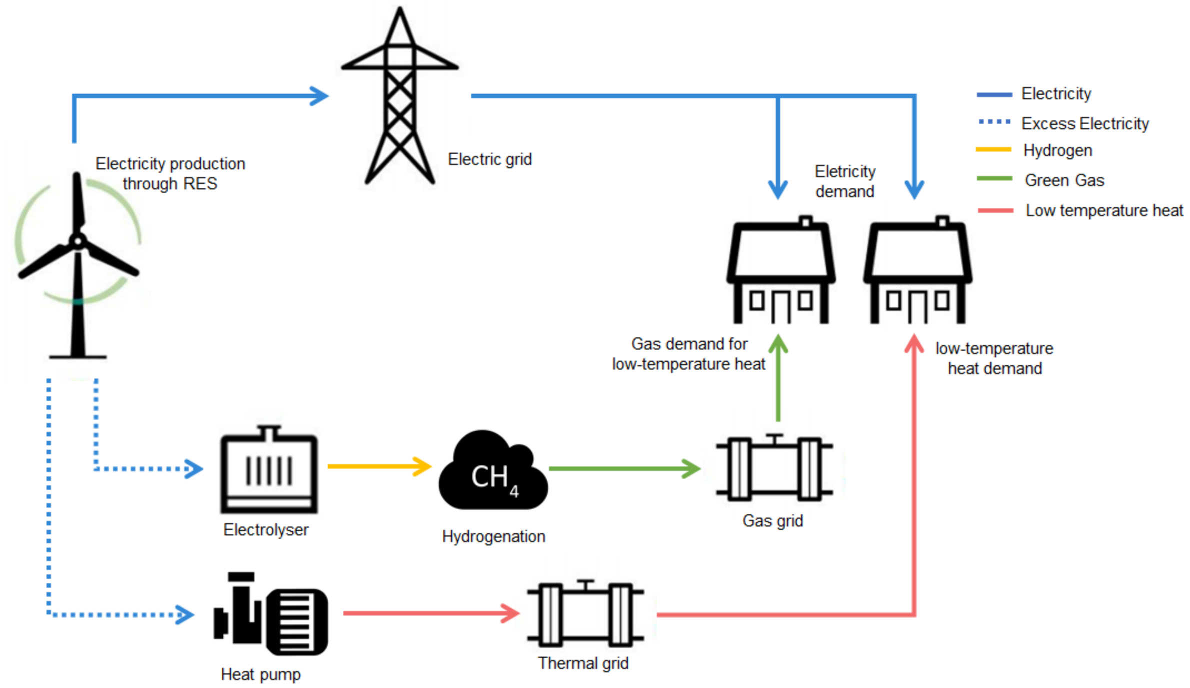

Figure 10 - Power-to-gas and power-to-heat scheme used in Scenario 2.

District heating and individual heating represent 46.5 TWh/year each of the total heating demand. In its turn, natural gas boilers represent 41% (see figure 11) of the individual heating portraying 20 TWh/year that needs to be supplied with green gas. In this case, biogas hydrogenation process covered all green gas production for the individual gas boilers as the demand could be supplied by the available potential biomass. The capacity for the electrolysers was adjusted in the same way as in Scenario 1.

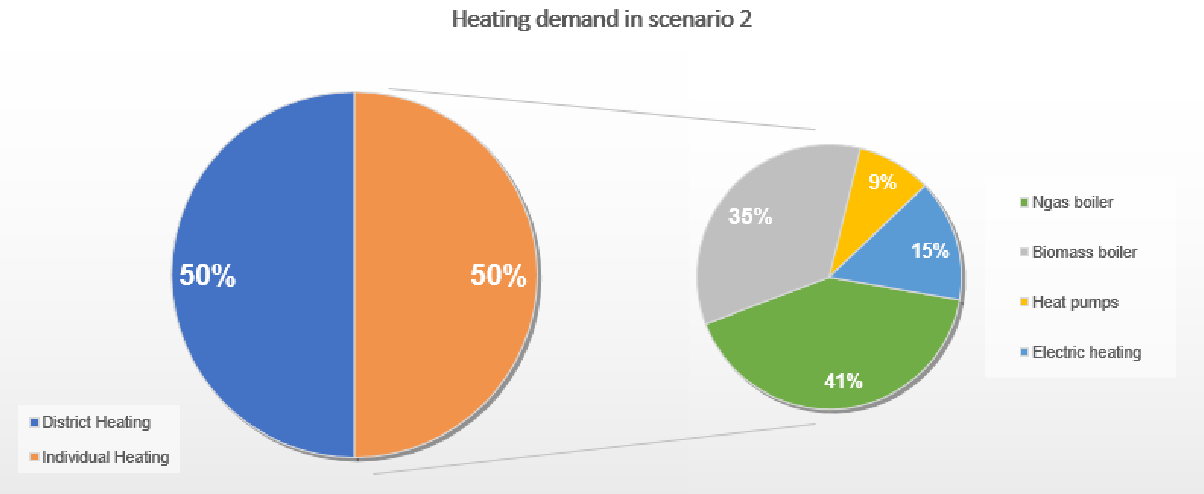

Figure 11 - Share of district heating and individual heating in Scenario 2 are presented on the left. The share of technologies for individual heating are presented on the right.

As the share of district heating increases, new technologies were added to the system to supply the heat. A total of 800 MWe of compressed heat pumps with a coefficient of production (COP) 3 were installed in group 3 to supply the heat. As a consequence of spreading the district heating infrastructure, losses in the grid increase so an additional 13% district heating grid losses were considered due to the heat has to travel further distances. On the other hand, having a district heating grid covering bigger areas allows for excess heat, e.g. produced from industrial processes, to be injected into the grid adding heat that would be wasted otherwise. Large-scale compression heat pumps, such as the ones introduced in this scenario, can use this heat source and adjust its temperature into district heating temperature. (David et al., 2017) According to the STRATEGO project. the excess heat potential in the Netherlands is of 583 PJ - 162 TWh/year - which is much more than the heat demand for the Netherlands. (Persson, 2015) Although, this does not mean that all the excess heat can be recovered. Considering the example of industrial excess heat, industrial areas are often withdrawn from the city centres where the heat demand is higher. (Mathiesen, et al., 2015) The distance between the excess heat source and the demand site should be as close as possible in order to have excess heat with the right quality injected into the grid. Nevertheless, even if only a small part of the excess heat can be recovered, this contributes to the efficiency of the district heating system. Additionally, it uses an inexpensive heat source increasing the sustainability and flexibility of the supply. (David et al., 2017) Accordingly to this reasoning, 3.5% of the total excess heat potential was considered which represents 5.6 TWh/year. This may be seen as a conservative amount, but it is in the same line as in Heat Road Map Europe Netherlands where 5.3 TWh/year were considered for 56% share of district heating. (Paardekooper et al., 2018) Heat storage was increased to 51.5 GWh allowing the system to become more efficient.

Scenario 3: discontinuity solution

The last scenario describes a radical change in the Dutch heating sector. The purpose with the discontinuity solution is to create a completely new techno-institutional regime in all its elements - technological, organisational, industrial, societal and institutional - meaning a radical change in the heating sector has to occur by 'breaking' with gas technologies. By increasing the share of district heating up to 75%, the need for natural gas boilers disappears as the graphic 12 shows. The remaining biomass boilers – 11.6 TWh/year - were converted to individual heat pumps to increase the efficiency of the system and decrease the biomass consumption in the heating sector.

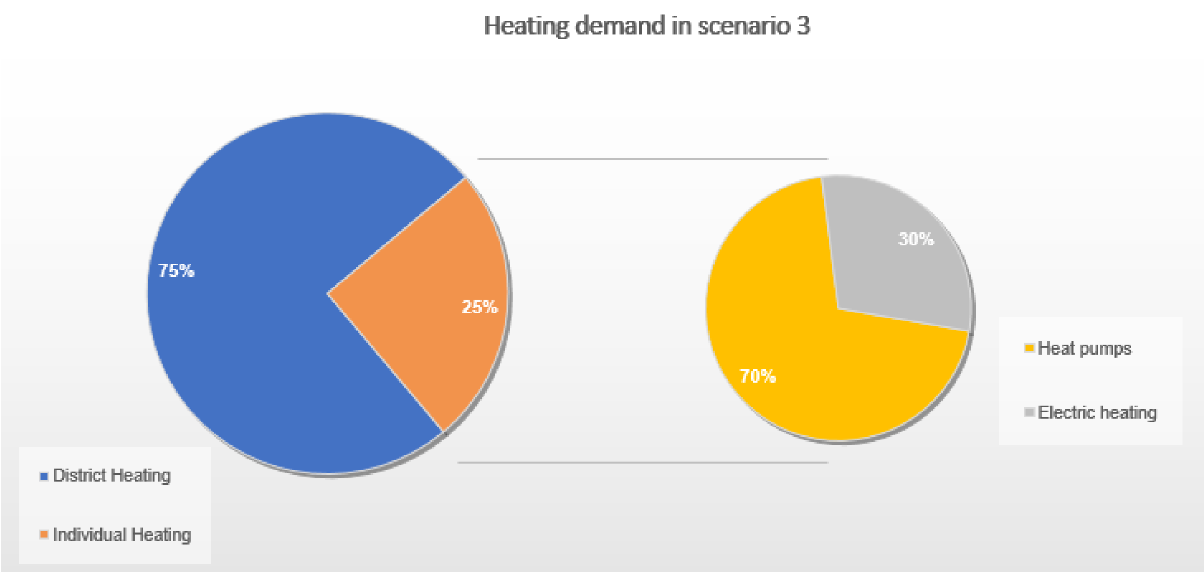

Figure 12 - Share of district heating and individual heating in Scenario 3 are presented on the left. The share of technologies for individual heating are presented on the right.

The following picture shows a simplified scheme of the approach used in this scenario. It represents a disruption with gas supply and the 'old' infrastructure leading to a discontinuity on the path dependency. Power-to-heat is the only technology used to incorporate excess electricity production from renewable energy sources into the heating sector.

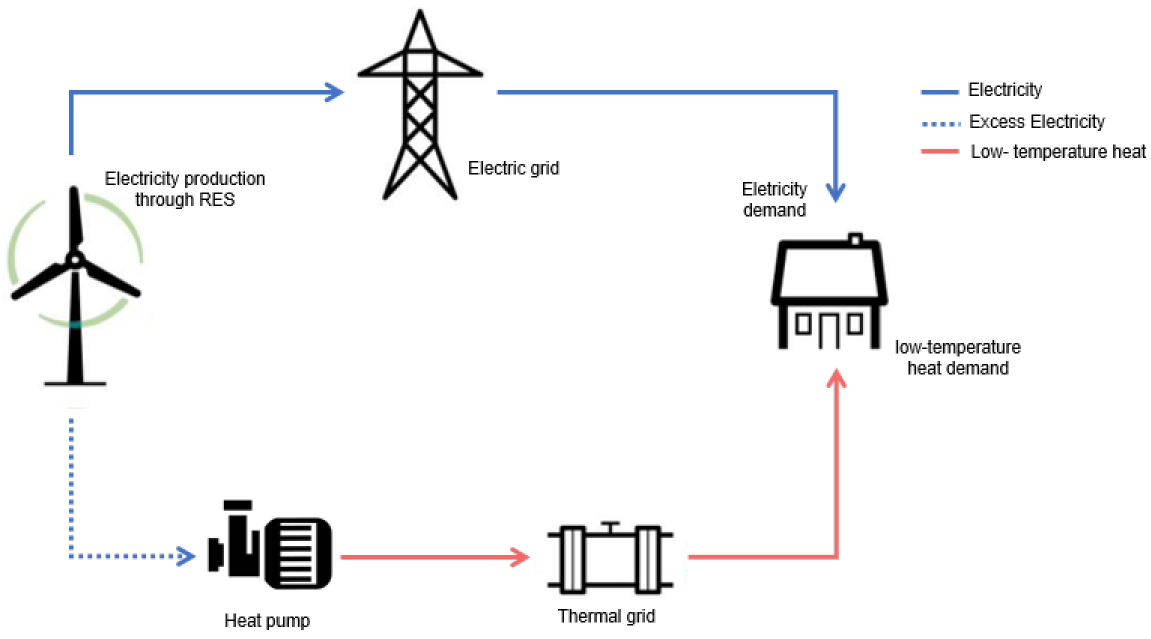

Figure 13 - Power-to-heat scheme used in Scenario 3.

The heat demand for district heating is, at this point, of 67.4 TWh/year and the demand for individual heating represents 22.4 TWh/year. Compression heat pumps capacity was raised up to 2000 MWe covering 33% of the district heating demand. As mentioned above in Scenario 2, spreading the district heating grid brings consequences: some as the grid losses are bad for the system and others such as recovering excess heat from industrial processes are beneficial. The losses in the district heating grid were lifted to 14% as the heat has to travel further distances. Additional 4 TWh/year of geothermal heat pumps with COP 3 was installed to supply the demand and the excess heat recovered was 7% of the total potential which represents 11 TWh/year of heat being injected into the thermal grid. The heat storage was also increased to 78.09 GWh.

Sensitivity Analysis

Currently, as much as 60% of the biomass used in the Netherlands has to be imported. (Bout et al., 2019) Considering that the production of green gas will add extra demand for biomass, it is important to know how much more dependent the country will be on importations by having power-to-gas technologies. The sensitivity analysis was performed to understand the impact that the ‘green gas’ production has in the overall system, especially on biomass consumption.

Two alternative scenarios were shaped where the individual natural gas boilers were substituted by individual heat pumps and the production of green gas was eliminated. The heat demand previously supplied with gas is now supplied by electricity feeding the individual heat pumps.

In Scenario 1, this results in having a heating demand on individual heat pumps of 12.4 TWh/year, and 5.94 TWh/year in Scenario 2. The electricity demand was adjusted to the new reality and the RES were optimized again with a CEEP not greater than 10%. The share of district heating in the alternatives was kept the same as in scenarios 1 and 2 - 22% and 50% respectively. This allows to compare the three main scenarios as none of them is now using green gas to supply the heating demand.

This approach represents a radical change to the techno-institutional regime in the way that both discontinue the gas infrastructure. The same way as in Scenario 3, these alternatives present a discontinuity solution and create a new techno-institutional regime by phasing out gas technologies from the heating sector.

Analysis of the results

Now that the scenarios for decarbonising the Dutch heating sector have been designed, how to evaluate and compare the alternatives?

The aim of this thesis is to show how to decarbonise the Dutch heating sector. Thus, an obvious parameter to evaluate is the CO_2 emissions to understand to what extent the decarbonisation goal has been achieved. One can argue that the bigger the reduction, the better the solution, but this may not be entirely true. Other factors must be considered together with the reduction of the emissions such as costs, investments and sustainability of the solutions. A solution can seem perfect from the emissions point of view but be impracticable and/or unsustainable from an economic perspective. All scenarios were designed to lower the emissions on the heating sector, thus there is room for complementary analysis. Foremost, it has been said before that the decision behind which alternative to choose is a political one. In this sense, socio-economic data was presented ignoring taxes and subsidies as there is no way way to know for sure how taxes and subsidies may look like by 2050. In this way, the real costs related to increasing or decreasing a certain infrastructure or technological solution are the ones presented allowing for comparison without the 'bias' imposed by old path dependency. Based on real costs, political strategies and decisionmakers can define the strategy towards a certain solution setting the path for new policies to achieve the 2050 vision of carbon neutrality.

Furthermore, the efficiency of the system and the penetration of renewable energy are both aspects that should be evaluated. Energy produced from renewable energy sources has a direct impact on overall fuel consumption (and price). Primary Energy Supply (PES) is the energy needed for the system to function. Looking back to figure 6 representing a Smart Energy System, PES represent the resources needed for the conversion technologies. Having less PES means that less energy is needed for the system to function which is a sign of an increase in the efficiency.

Analysing the PES, biomass should be carefully analysed due to the small potential in the Netherlands and the increasing demand for this fuel worldwide. The increasing demand for this fuel especially by countries willing to achieve carbon neutrality can jeopardize its sustainability in the long term.

6. Results Analysis

The results for the scenarios described in the previous chapter are now presented and analysed. In the Netherlands, the heating sector is locked-in on natural gas and natural gas technologies. The alternatives demonstrate possibilities to unlock the fossil fuel-based heating sector into low carbon ones. Foremost, it is not the aim of this thesis to decide which alternative is the best. The results present different strategies for decarbonizing the Dutch heating sector and it is up to de decisionmakers to decide which path suits best the country's interests. End-of-pipe, continuity and discontinuity solutions presented in Chapters 3 (Theoretical Approach) and designed in Chapter 5 (Designing the Scenarios), are analysed based on the changes to techno-institutional regimes.

Firstly, the heating sector is analysed from a technologies point of view. Secondly, district heating is examined in terms of demand and production. Further, the Primary Energy Supply (PES) is analysed to understand the contribution of renewable energy in each alternative. The fuel mix and the corresponded CO_2 emissions are presented and compared Lastly, the costs are presented by technology, so the investments needed in each scenario become clear.

(Note: the outputs from EnergyPLAN for all scenarios are available at the Chapter 10 – Appendix)

The heating sector

The focus of this thesis is in the Dutch heating sector, therefore it is relevant to analyse how the heating sector looks like in the modelled scenarios. As explained in Chapter 5 (Designing the Scenarios), the approach for designing the end-of-pipe, continuity and discontinuity solutions followed power-to-gas and power-to-heat technologies. This was obtained by incrementally expand the thermal grid including district heating related technologies. Figure 14 shows the difference between these strategies for the same heating demand.

The individual heating contemplates several technologies depending on which fuel it uses. The natural gas in scenarios 1 and 2 was replaced by green gas and the remaining technologies (individual heat pumps and individual electric heating) are run on electricity and, due to its small share, it was assumed that the electricity is produced by renewable energy sources.

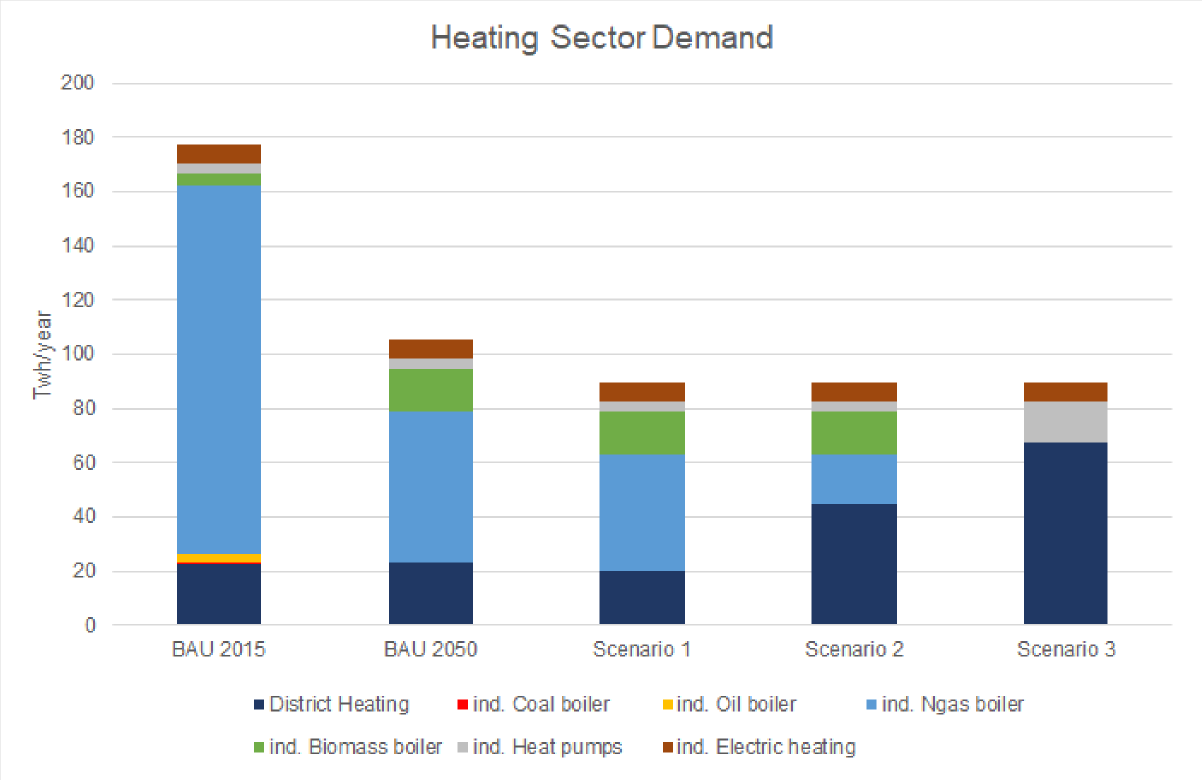

Figure 14 - Heating sector demands including both district heating and individual heating technologies.

Individual heating allows for the end-user to choose which technology it prefers. One can argue that it provides freedom of choice and adds some flexibility to the sector by being a decentralised (local) production of heat, where the conversion point is on the demand side.

Even though it is not possible for the end-user to choose which technologies are part of the district heating, it is also possible to have the heat produce from several sources as it is next.

Analysing closely the district heating results, the main contributors for the heat productions are large-scale heat pumps and CHP plants. This represents a synergy between the electricity sector and the heating sector which is what contributes to the higher efficiency seen in scenarios with higher district heating as it was explained in the previous section. The heat sources feeding the thermal grid can be seen in figure 15.

As the district heating grid expands, more heat sources are included in the system to satisfy the demand. In Scenario 3, where the gas grid was phased out, large scale heat pumps are the major contributor by supplying 33% of the heat demand. The reason for this is because heat pumps are a very efficient technology producing heat. A COP of 3 was used in the scenarios with large-scale heat pumps, but this can be even higher depending on the temperature of the heat sources. Higher sources of heat can provide higher efficiency (David et al., 2017) and, looking forward 2050, heat sources and heat pump technologies can be further refined than today.

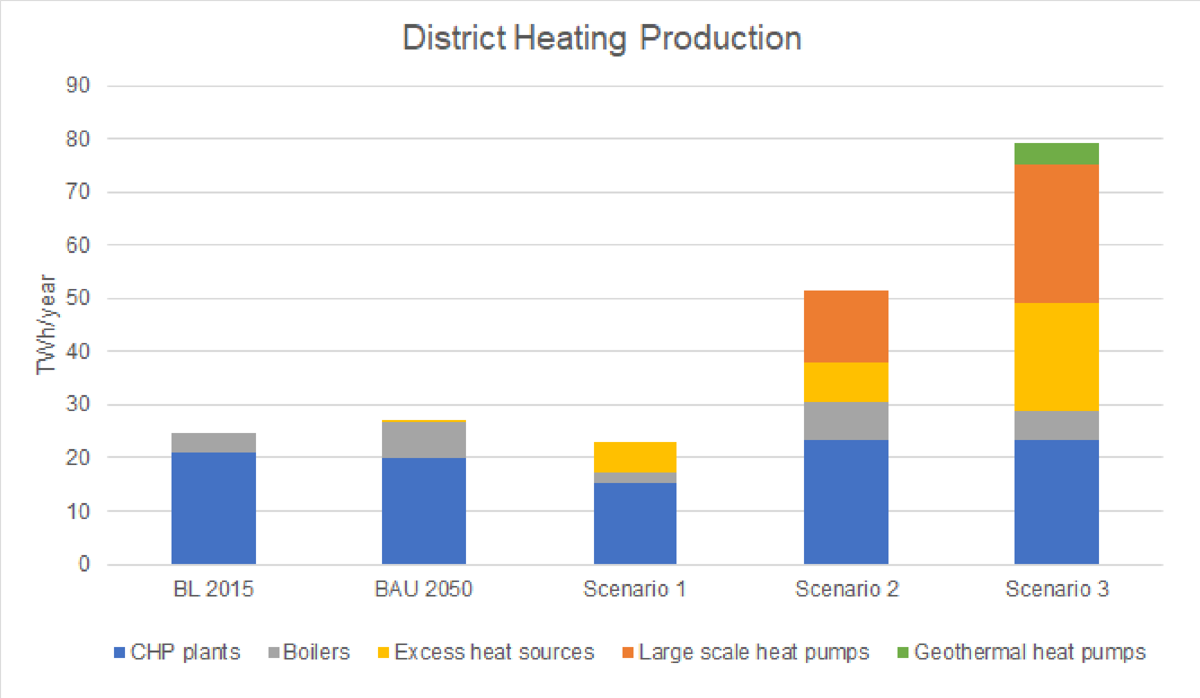

Figure 15 - District heating production.

Heat pumps are mostly working in a flexible production depending on the availability of renewable energies. Therefore, thermal storage can increase even more the share of renewable energies in the heating sector increasing its flexibility.

Followed by large-scale heat pumps, CHP plants are the one following in the heat production supplying 29% of the demand. CHP plants have electricity as their main product, but heat is produced as well as a by-product of electricity. Thus, this is another synergy found between the electricity and heating sectors. Whether the electricity production is high or low, CHP plants and heat pumps together with thermal storage can create flexibility in the district heating systems with high efficiency. (Paardekooper et al., 2018) Nonetheless, the fuels used in CHP plants in all alternative scenarios are coal, biomass and natural gas meaning that one cannot be entirely sure if the heat supplied is fully decarbonised. To ensure the 100% carbon neutral heat produced from CHP plants, it would be necessary to safeguard the carbon neutrality of the fuel. To overcome this challenge, it was made the decision of converting one-third of the coal-powered CHPs into biomass and assuming that this would be enough to decarbonise the heat produced by CHP plants. This is particular important in Scenario 3 because of the high demand for heat for the district heating system. In figure 15, it is possible to see that the heat supplied by CHP plants for the district heating system is almost the same in Scenarios 2 and 3 even though the demand in the last one is much higher. Another strategy to reduce the consumption of the heat produced by CHP plants was to introduce other heat sources in the district heating systems, such as geothermal heat pumps and excess heat sources. The increasing on thermal storage also contributes for the penetration of more heat sources. In Scenario 2 and 3, excess heat sources represent 14% and 25% of the total heat demand. It is important to remember at this point that only 3.5% of the total excess heat potential was used in Scenario 2 and this amount was of 7% in Scenario 3. Since excess heat can be provided by several industrial process (and not only), it provides inexpensive heat from a variety of sources contributing to the flexibility of district energy systems by diminishing the PES.

Decarbonisation and efficiency

All scenarios were designed to decarbonise the heating sector. Analysing the figure 16, all three present high decarbonisation levels, especially compared to 2015 levels. To be precise, the reduction in CO_2 emissions is 29.7% in Scenario 1, 32.5% in Scenario 2 and 32.7% in Scenario 3 compared to BL 2015.

The difference of CO_2 emissions between BAU 2050 and the alternatives is not as obvious - between 10% and 13.7% reduction. A reason behind these results may be found in the electric sector. The approach in this thesis was to focus on the heating sector while changing the electric sector the least possible to be able to create comparable alternatives. Thus, keeping the same baseload technologies and merely adjust accordingly to the electricity demand may prevent the CO_2 emissions to reduce further, but on the other hand, it reveals how the heating sector behaves and how it interacts with the electricity sector. Nonetheless, comparing to BAU 2050, all alternatives achieve a deeper decarbonisation which means that ambitious energy savings on the demand together with efficiency in the supply can increase the overall decarbonisation of a system.

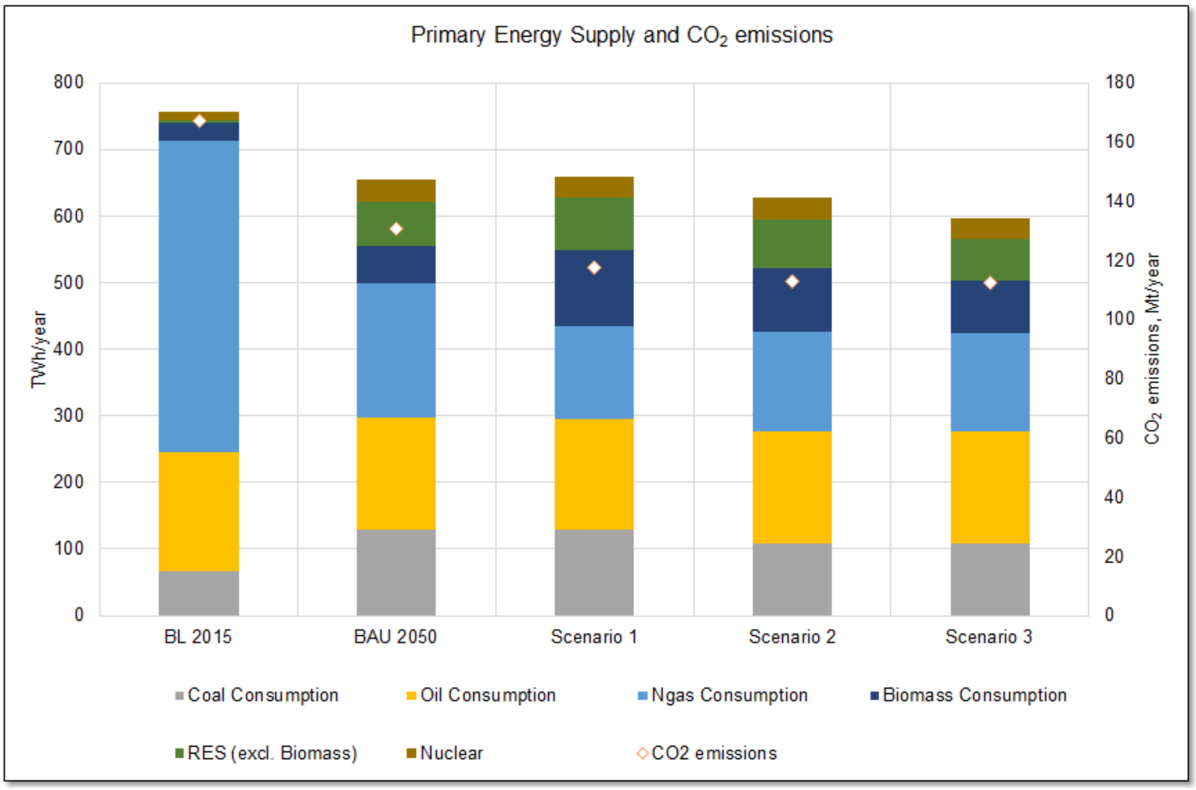

Figure 16 - Primary Energy Supply by source and total CO_2 emissions.

Considering the Primary Energy Supply, as the heat demands are the same in the three alternatives, a reduction of PES is a sign of the overall efficiency of the system in the sense that less fuel is needed to operate it. Scenario 3 has the lowest PES, totalizing 9% and 21.1% reduction compared to BAU 2050 and BL 2015 respectively. The additional 15% heat saving in the demand side, the integration of industrial excess heat and the better integration between electric and heating sectors through the heat pumps are contributing to reducing the fuel demand. Compared to BAU 2050, this is not observed in Scenario 1 which needs more PES to operate. The increase on PES can be explained by the energy needed for the electrolysers for hydrogen production. Even though Scenario 1 has the same percentage of heat savings in the demand like the other alternatives, the production of green gas is making the system the least efficient of all scenarios, including the BAU 2050 where the heat savings were not increased.

Regarding the amount of renewable energy used, Scenario 1 is the one which allows for more renewable energy production. A total of 105.25 TWh/year is produced from RES (including biomass) in the first scenario compared to 97.04 TWh/year in Scenario 2 and 83.25 TWh/year in the third scenario. The reason for this lies in the use of biomass. The first scenario is also the one with the most biomass consumption totalizing 115.96 TWh/year. Partly is used in the production of green gas by biomass conversion and partly to fuel the CHP plants. By decarbonising the heating sector alone, the presence of RES in primary energy supply accounts for percentages above 23% and the electricity production from renewable energy sources is around 55% in all alternatives.

As for the biomass consumption, all alternatives show a clear increase in biomass consumption compared to BAU 2050 and BL 2015 (see figure 17).

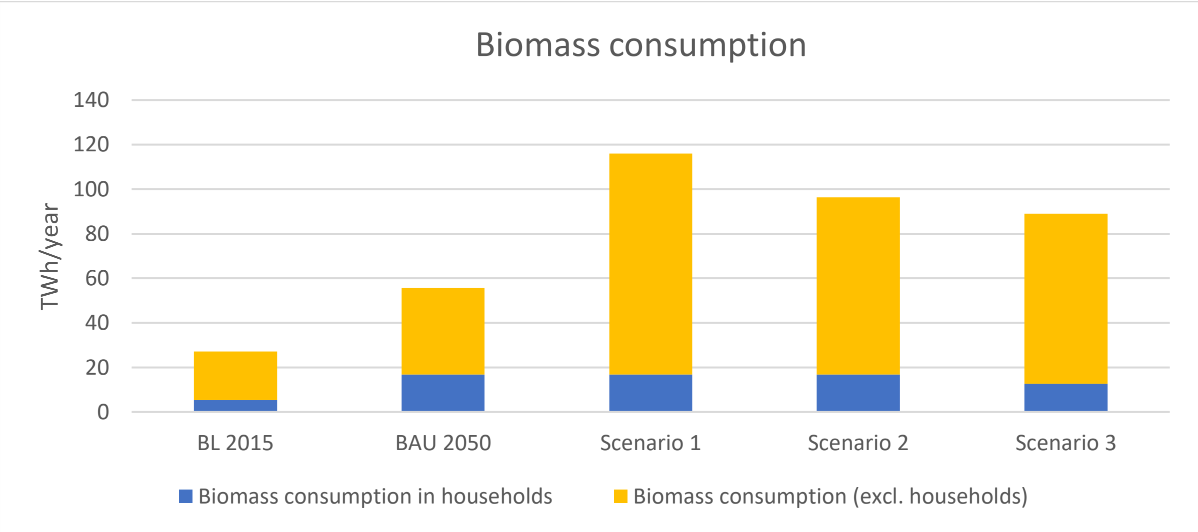

Figure 17 – Total biomass consumption.

A rather small portion of the consumption is related to biomass boilers used in households. Most of the biomass is consumed in conversion technologies such as CHP plants. Scenario 1 presents the highest increase on consumption because, besides the use in CHP plants, biomass is also used in conversion technologies to produce green gas.

Biomass is a scarce fuel and the tendency for the future is to be even scarcer as the demand increases worldwide. Scenario 3 presents the lowest biomass consumption of the three alternatives even though it is 1.5 higher compared to BAU 2050 while in Scenario 1 the consumption is more than 2 times higher.

Costs

A parameter that highly influences the feasibility of a solution is the costs related to it. For the decisionmakers and especially in national energy systems, the socio-economic analysis shows how much investments are needed, the operation cost of a particular solution and the variable cost associated with it. Most of the cost needs to be supported by public money coming from the taxpayers making the decision one that cannot be taken lightly. Figure 18 shows the annualised total costs of the different scenarios.

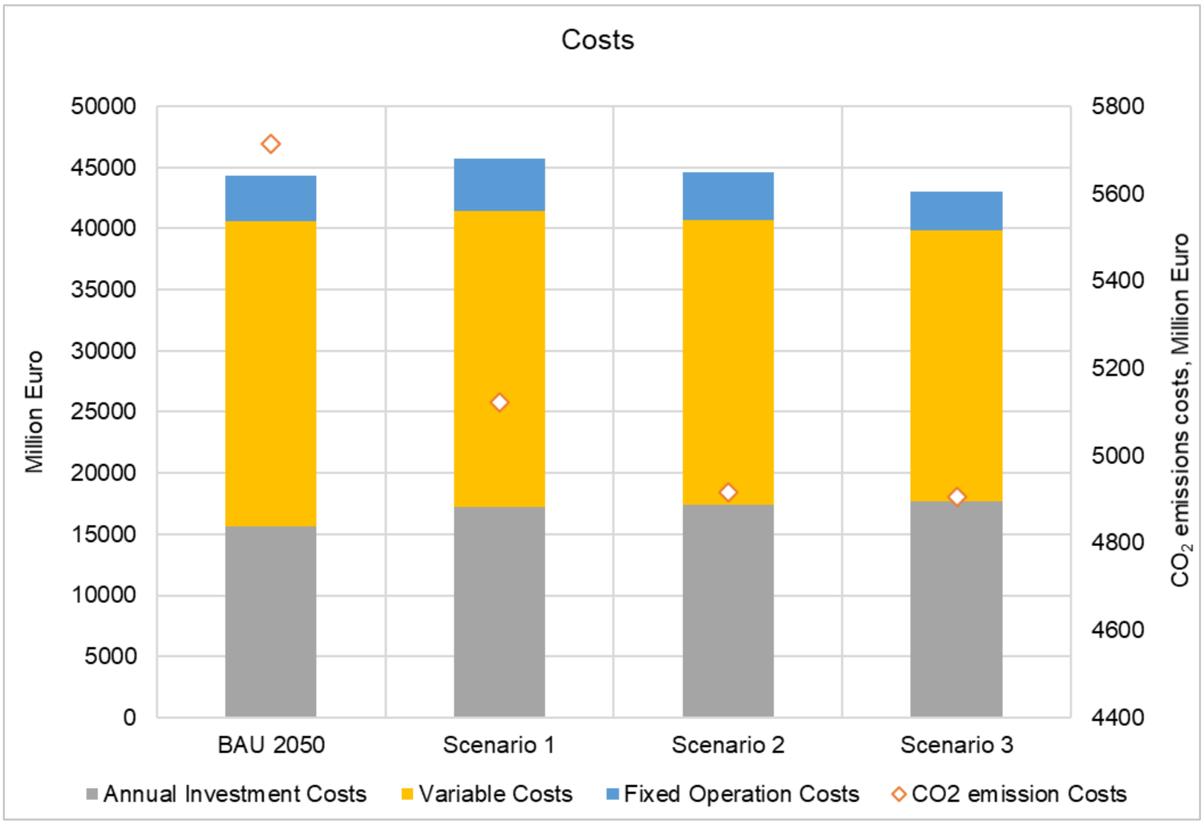

Figure 18 - Total investments cost by cost type.

The first obvious conclusion is that the costs do not vary much between scenarios. Compared to BAU 2050, Scenario 1 presents a 2% increase in the costs, Scenario 2 shows a 1% decrease, and Scenario 3 features 3% decrease being the cheapest solution. It may seem little, but 3% reduction equals 1,554 Million Euros.

Analysing the cost breakdown, firstly it is evident the decrease in CO_2 emissions related costs. As all alternatives present deep decarbonisation in the heating sector, this has a direct impact on money spent on carbon emissions. Secondly, the variable cost which includes expenses with fuels portrays a reduction tendency which is aligned with the PES analysis done above. The first scenario has the highest fuel consumption, especially concerning biomass and natural gas, which may explain the high variable costs. The annual investments cost related to infrastructure and investments in technologies such as wind turbines or heat pumps. All three alternatives show higher values of annual investments compared to BAU 2050. This can be explained by the investments in renewable energy technologies (namely wind turbines and solar PV) and, especially in Scenario 3, the investment in the expansion of the district heating grid.

In Chapter 5 (Designing the Scenarios), was mentioned that additional 15% of heating saving measures in the demand side were considered in relation to BAU 2050. These measures relate to renovations and improvements on buildings such as insulation, doors, windows, etc.

As figure 19 shows, adding 15% of heating saving represents an additional investment of almost 500 million euros in all alternatives on top of the investments already considered for BAU 2050. It a very ambitious target as previously stated, stressing that efficient and effective policies pointing in this direction are imperative.

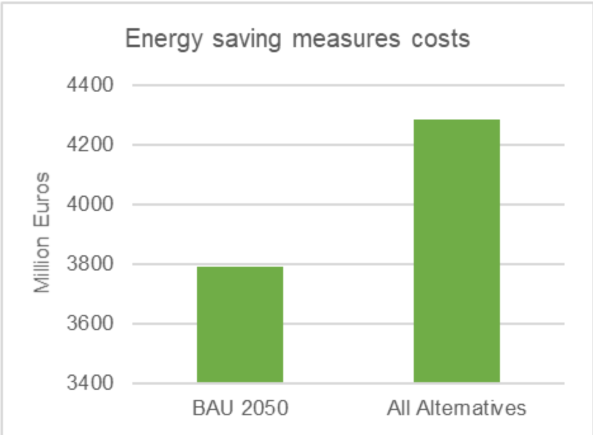

Figure 19 -Annualised investments in heat saving measures.

Energy saving measures are by far the greatest investment. Looking to figure 20, where this cost has been withdrawn, the annual investments costs and respective technologies are presented to analyse the differences between the scenarios concerning the different technological choices.

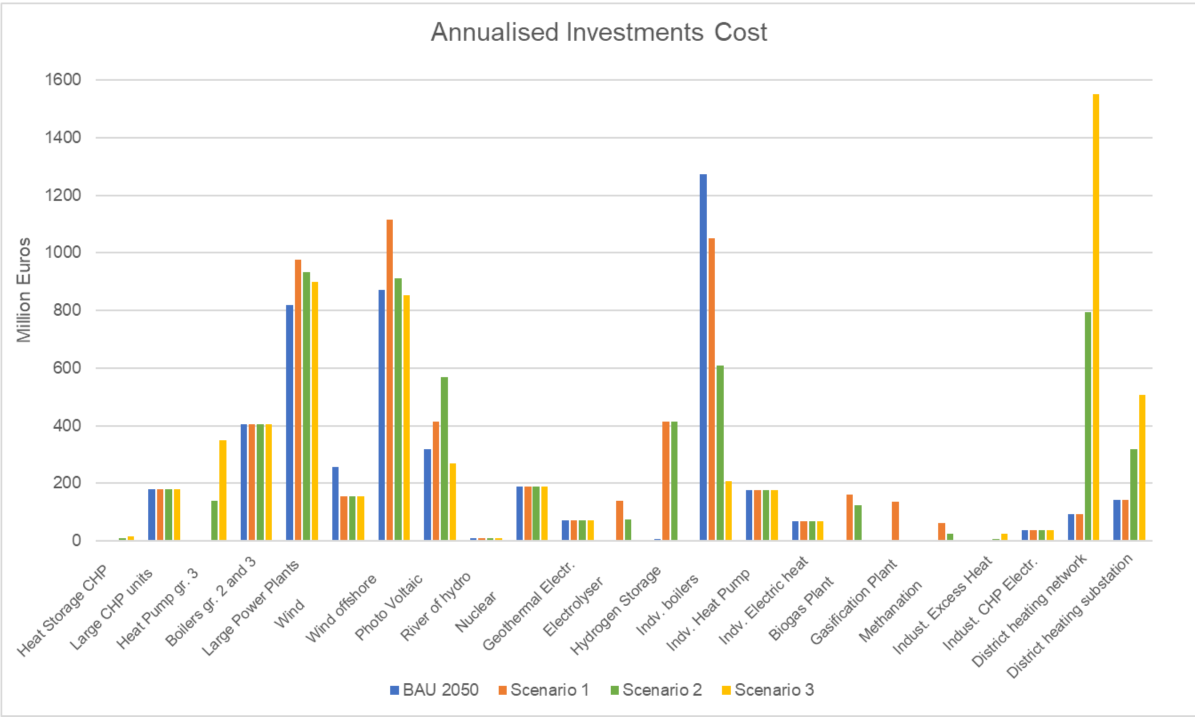

Figure 20 - Annualised investments costs by specific technology excluding investments cost for heat savings.

Some investments are high in all scenarios such as large power plants and offshore wind. The main differences lie on the specific technologies corresponding to the strategies used for designing the scenarios. For instance, when it comes to investments in individual boilers, the costs are high for BAU 2050 and Scenario 1 but less significant for Scenario 2. Of course, the costs for replacing the gas grid for a thermal grid also represents higher costs in scenarios 2 and 3 due to the expansion of the district heating network and the installation of district heating substations. This investment is particularly high in Scenario 3 as expected.

Sensitivity Analysis

As previously mentioned, 60% of the biomass used in the Netherlands must be imported. Adding to this situation, the approach used in Scenarios 1 and 2 was to prioritise the biomass potential for the green gas production which may be rather unrealistic. Therefore, it is important to put this solution into perspective. Two alternative scenarios were modelled where the need for green has production was withdrawn. Further, the impacts on Primary Energy Supply, CO_2 emissions, biomass consumption and costs are analysed.

In figure 21 the Primary Energy Supply and CO_2 emissions are presented. The impact of green gas production is unquestionable. Scenario 1 + ind. HP shows a significant reduction on PES compared to Scenario 1 summing 8% of reduction. The difference between Scenario 2 + ind. And

Scenario 2 is not as obvious HP, but it still represents 3% of reduction in PES. Both new alternatives present greater levels of efficiency compared the green gas scenario.

Following the same tendency, the CO_2 emissions are further reduced. In fact, both present lower

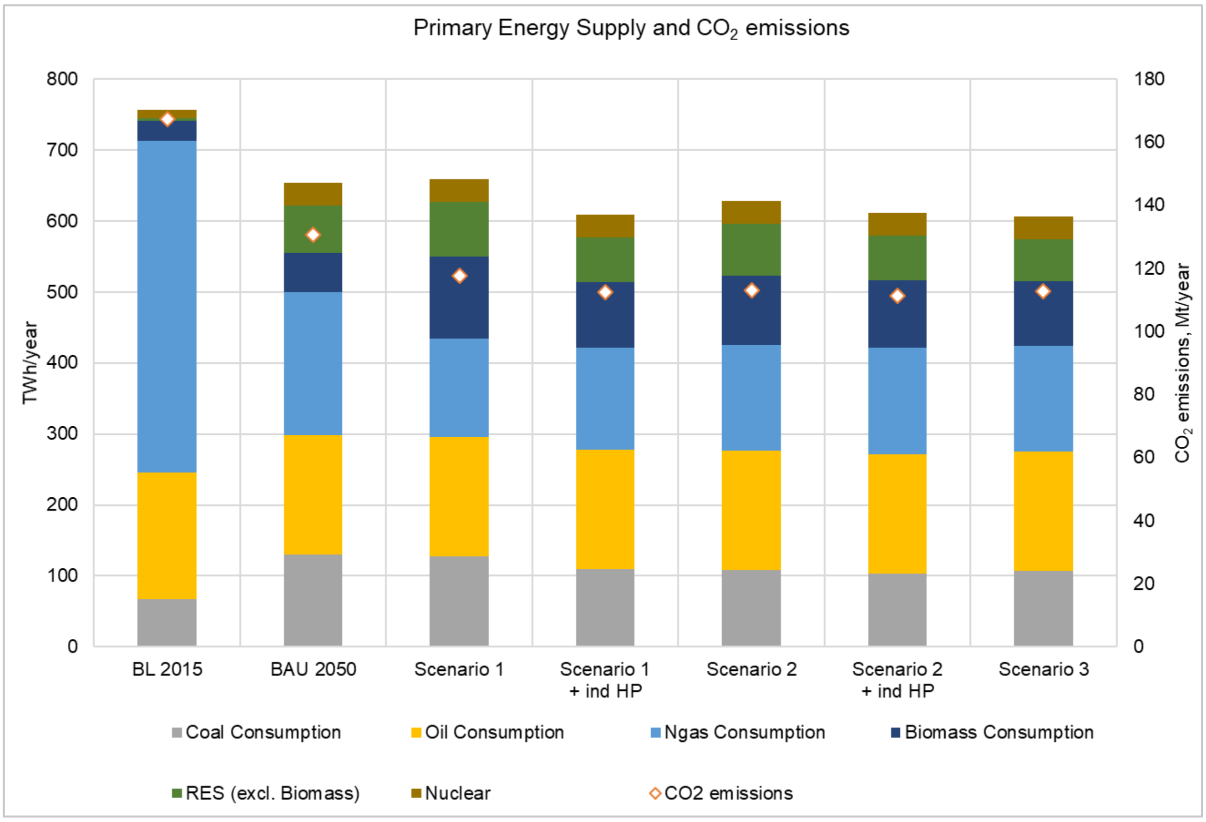

Figure 21 - Primary Energy Supply by source and total CO_2 emissions.

levels than the three main scenarios making them more efficient solutions in decarbonising the energy system. The one with the least CO_2 emissions is Scenario 2 + ind. HP, having less 33% and 15% emissions compared to BL 2015 and BAU 2050 respectively.

Regarding the amount of renewable energy used, both present lower share on PES, 87.8 and 85.88 TWh/year. Scenario 3, however, is still the one with the least share of RES on Primary Energy Supply (83.25 TWh/year).

As for the biomass consumption see figure 22. The gap between Scenario 1 and Scenario 1 + HP is undeniable proving green gas production is consuming a great amount of biomass. As the share of gas grid diminish as in Scenario 2, the savings on biomass consumption by substituting individual natural gas boilers for individual heat pumps are not as evident. There is a slight reduction of 2% in Scenario 2 + HP compared to Scenario 2, but the one using less biomass is still Scenario 3. Again, comparing with BL 2015 and BAU 2050 the demand for biomass is around the double which may represent a wicked challenge due to the high need of imports to secure the demand.

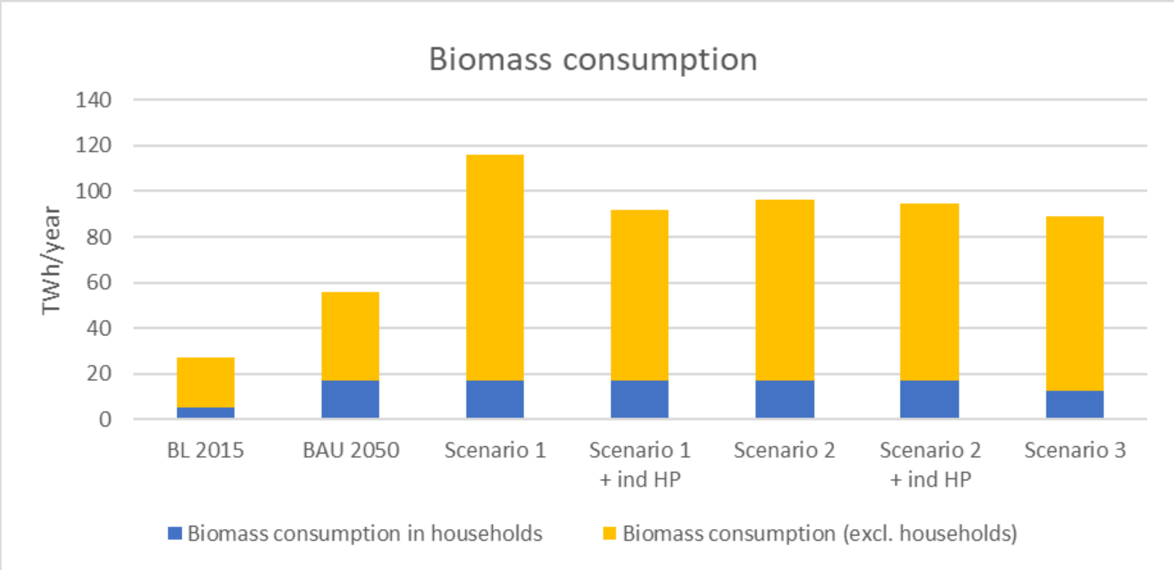

Figure 22 – Total biomass consumption.

Analysing the costs, the results show that all scenarios with no green gas production present the lowest costs. Breaking down the costs, the two alternatives have costs much similar to Scenario 3. The exception is on fixed operation costs where Scenario 1 + HP presents a slightly higher value. The variable cost expresses the same tendency as before, mainly due to PES reduction. It is evident the decrease in expenses related to CO_2 emissions.

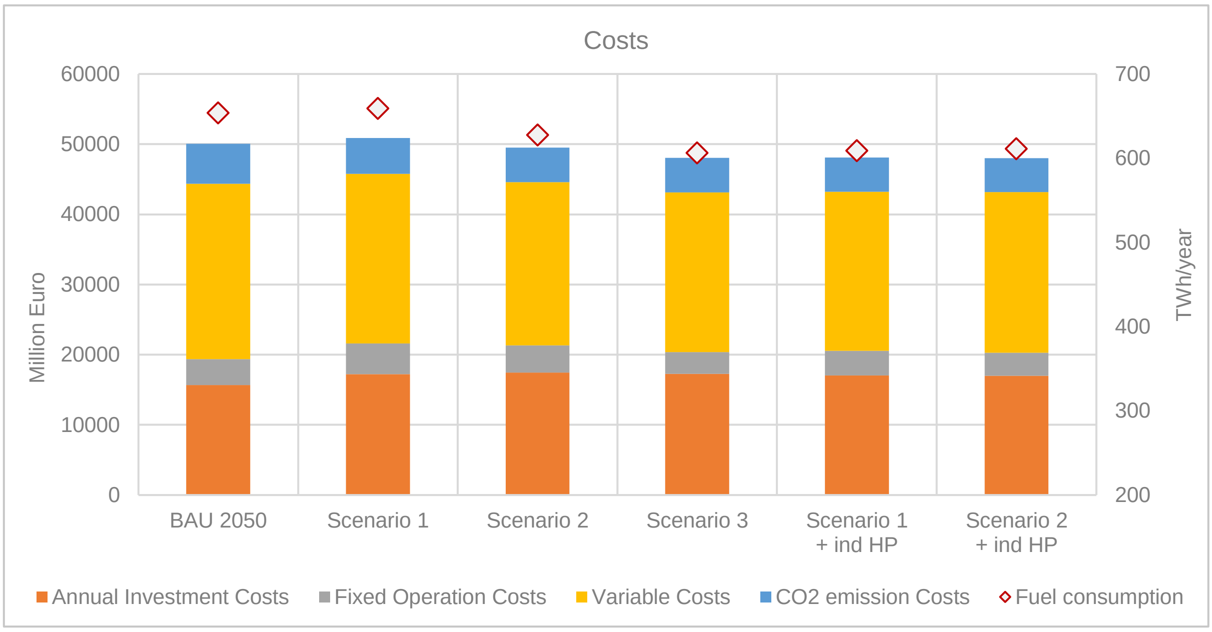

Figure 23 - Total investments cost by cost type.

7. Discussion

The analysis done in the previous chapter showed that decarbonising the heating sector in the Netherlands will create technical and institutional changes. Depending which alternative followed, the impact of those changes is also different. The results are affected by the theoretical approach used for designing the alternative, the assumptions and data used, and the choice of methods. These discussions are addresses in this chapter.

Methods and results

The Dutch heating sector has its own characteristics and subtleties that contribute to the carbon lock-in on gas technologies and infrastructure. This is a very context specific carbon lock-in which means that the results found cannot be replicated in another context. In fact, if the focus of this thesis was on the Dutch electricity sector other carbon lock-in would probably arise. Energy systems vary significantly from country to country depending on domestic resources, strategies and national plans, reinforcing the idea that these results are dependent from the choice of the case of the Netherlands.

The findings are closely related to the delimitations and the assumptions made. Transport and industry were kept out of the analysis as well the cooling sector. No changes were made in these sub-sectors in any of the alternatives. From a Smart Energy System concept, it is not ‘smart’ to leave sub-sectors out. An energy system should include all its components to find better synergies and greater renewable energies sources penetration. As an example, having district cooling and district heating operating together would create a very efficient synergy through heat pumps using the excess heat from the cooling in the district heating grid.

Assumptions on technologies efficiency, capacities and costs were also performed which have a direct impact on the results. Looking forward to 2050 some of these assumptions may be difficult to predict. Technologic breakthrough and economic crises are likely to occur during this 30-year potentially affecting some of the assumptions made. Some counter-measures are needed. Although, all the assumptions were based on existing mature technology which means this system, from a technological point of view, can be implemented today as it is not depending on technology development.

A weakness on this thesis results is that it presents results for how the Dutch energy system and the techno-institutional regime can look like in 2050, but it does not show the path to reach it.

Further planning strategies on economic, technological and policy level would be the next phase if a scenario was to be implemented. The main challenge is how to create the political and social conditions needed for the techno-institutional regime and, at the same time, allow investments and economic growth. As mentioned before, this is a political decision and is up to the government to analyse the political and institutional frameworks and set the strategic path.

The strategies chosen to unlock carbon lock-in situations enable to design three different scenarios. The aim was to present different paths to achieve carbon neutrality in the heating sector in the future and the results show a decrease in the CO_2 emissions in all alternatives. However, the results relate to the entire energy system and not the heating sector alone, which makes it difficult to understand if the heating sector was completely decarbonised. The electricity sector is closely connected to the heating sector and the electricity sector has not been decarbonised. In this sense, even though the alternatives present higher levels of RES compared to BAU 2050, the energy used in green gas production, large-scale heat pumps and CHP plants may not come from a carbon neutral source. CHP plants are a considerable source of heat for the district heating and the fuel burned on CHP plants is mainly coal with smaller shares of biomass and natural gas. This challenge was addressed by converting one third of the coal CHP plants into biomass CHP plants, but without decarbonising the electricity sector, it is hard to state without any doubt that the heating sector has been fully decarbonised.

The process of methanation has substantial losses, especially in the form of heat (Vlap, H. et al., 2015), which can be an interesting solution to explore if the system has a thermal grid to utilise this heat source. The results do not present the amount of heat losses in the system, it would be interesting to analyse how much heat is being wasted from conversion technologies and how much could be re-integrated into the system. Nonetheless, alternatives with thermal grid showed greater efficiency the more share of district heating was included with less CO_2 emissions. The results show that thermal grids are more cost and PES effective at reducing CO_2 emissions than gas grids. The heat pumps are working as conversion units to integrate renewable energy sources such as wind, solar and excess heat, in the district heating grid. According to David et al. (2017), large-scale heat pumps affect the efficiency of the energy systems. This was witnessed through the reducing on PES in Scenarios 2 and 3. Heat pumps were considered with a COP of 3, however it is possible to achieve a COP of 4 (or more) having excess heat sources at a higher temperature than the district heating. The higher the temperature of the excess heat source, the higher the heat pump COP. In this sense, it would be interesting to analyse the sensitivity of the heat pumps and how different levels of COP would influence the results. Due to time limitations this was not possible.

Biomass consumption

The biomass consumption increased substantially in all scenarios, being above 1.5 times in the alternatives compared to BAU 2050. Although the main consumption is witnessed in the electricity sector, the sensitivity analysis also showed that green gas production affects the overall consumption of biomass. For instance, in Scenario 1 the whole potential domestic biomass was used in the productions of green gas and additional had to be imported to cover the demand for the natural gas boilers. Scenario 2 eliminated the need for imports as the domestic biomass could cover the production for green gas, but it used almost all the available biomass. Nevertheless, it is reasonable to think that there are other ends for domestic biomass other than gas production for the heating sector which means that the imports will probably be higher when considering other sectors such as industrial sector and transport sector. This represents a challenge that cannot be ignored.

The rising consumption of this resource will make the Netherlands dependent on biomass imports for its energy system. It is expected that the biomass prices will increase following the demand. Being dependent on large amounts of imports represents a major challenge to the energy security as the oil crises back in the 70' evidenced. Additional biomass can be produced internally through crops, but this raises an old discussion when it comes to biomass production for energy production: should land be used to grow food crops or energy crops? This debate has been growing for several years, especially due to the increasing demand for biomass for energy purposes from developed countries to lower their CO_2 emissions. Another debate has to do with the sustainability of biomass as a renewable resource. The CO_2 emissions are not accounted for in biomass as it is considered a carbon-neutral fuel - the emissions on combustion are compensated by regrowth of biomass. Nonetheless, the regrowth scheme can be questioned, especially if the imports come from countries with high levels of corruption. The questions related to the sustainability of the resource on the long-term and its impacts on the biosphere have been increasing. This was the main reason why the European Commission assess the sustainability of biomass and its contribution for reducing emissions. (European Commission, 2016)

For the reasons explained above this can create a major challenge in the long-term for the Netherlands. Having the energy system based on biomass can create a new lock-in, in this case on biomass technologies. To avoid for new lock-in to settle, it is desirable that the energy system stays as flexible as possible allowing energy from several sources to be part of the techno-institutional regime.

Costs

Cost are a major factor for analysing the viability of a solution. From a technological perspective, Scenarios 2 and 3 presented high costs related to district heating infrastructure while Scenario 1 presented high cost with individual natural gas boilers and hydrogen storage. The question here lies on who is paying for this cost.

Individual heat technologies are placed inside the buildings, on the demand side, making them private. In this sense, while the government supports the cost on large-scale technologies and infrastructure investments, the investments done on the user's level is done by the owners. In this sense, personal preferences and personal income play a role. Some people may not be willing to support this cost if other cheaper solutions are available. scale technologies over individual one. The way the scenarios were modelled excluded subsidies and taxes, revealing the raw cost of the alternatives. The government can favour some technologies over other through subsidies and taxes, influencing end-users to choose a particular direction, but in principle it is an expense on the end-user side. Continuing the reasoning, investments on infrastructure, large power plants, large-scale heat pumps and renewable energies, represent a lower impact for the end-user as these investments are decided and negotiated by the government.

From a socio-economic point a view, it is better to invest in permanent infrastructure and technologies which will benefit the whole society, rather than spend money on variable cost such as fuel. Fuel prices are volatile as the 1970 oil crises showed, making it dangerous to rely on energy importation through fuel. To avoid insecurity on the supply, local and regional energy sources such renewable energy sources are preferable. On the other hand, investing in large-scale technology and infrastructure ensures that the money is spent internally by creating business, jobs and expertise capital (Lund et al., 2017) allowing for local economic growth.

Techno-institutional regimes

Favouring low-carbon alternatives can create a new path dependency escaping the carbon lock-identified in this thesis. The scenarios present the technological changes but, from a techno-institution point of view, this is not enough to unlock the system. It is the close interactions between technologies and institutions that create path dependencies towards carbon lock-in so, it will take more than just technology change to unlock it.

The technological and economic aspect previous addressed can lead the way for planning a new architecture of a decarbonised energy system. Although, without the right institutional, societal and organisational framework the transition may not occur. Society needs to be informed and 'nudged' into making better decisions considering low-carbon technologies. End users practices and choices can greatly influence the market by demanding low-carbon technologies to heat their homes forcing the organisations to adjust the supply. In the end, strong policies favouring low-carbon solutions over fossil fuel solutions are crucial for the transition towards a decarbonised energy system. The results show that from a technological point of view the lock-in can be overcome. It is now up to the governments to set the rules for this path dependency to be possible.

In Chapter 3 (theoretical Approach) it is mentioned that policymakers tend to prefer end-of-pipe solutions. But, as the results show, greater decarbonisation at a lower cost can be found in solutions with greater ambitious towards change such as Scenario 2 and 3. It was also demonstrated that scenarios with more energy sources are more efficient and, having flexibility on the supply can prevent a new lock-in to settle in the future. Having more technologies as part of the techno-institutional regime avoids that a technology becomes dominant preventing the system to be relying in one major energy source as it was the case with natural gas. More diversity also allows for domestic energy sources to be explored such as wind and solar at a smaller cost for society than gas alternatives.

Final remarks

In Scenario 1, the decarbonisation was achieved by changing the nature of the fuel, aligned with the end-of-pipe approach. No other relevant modifications were made. In this sense, the techno-institutional regime was kept in the same path dependency. Biogas and biomass hydrogenations process were included, and electrolysers are used to supply the necessary hydrogen for the processes. Including more technologies like these ones for producing green gas makes the Dutch heating sector decarbonised but still locked-in in gas technologies. The system continues dependent on this type of fuel to operate making the heat supply less flexible. Overall, as the analysis presents, the green gas alternatives are more costly, use more PES and have lower levels of decarbonisation which represents, in the end, another market failure.

Scenario 2 balanced the share of district heating with individual heating. The natural gas was substituted by green gas, so the alternative would be aligned with the continuity approach. Changes in the techno-institutional regime start to appear as more customers are connected to the district heating network. A new path dependency is shaped where the gas stakeholders share their power with new ones rising from the increasing thermal grid. The results show that new technologies related to the increasing of the thermal grid appear meaning that there is a higher share of the market for those technologies. In other words, a share of the appliances, business, jobs, etc. migrate from gas technologies towards district heating technologies shaping a different techno-institutional regime.

In the last alternative, Scenario 3 representing the discontinuity strategy, all elements in the techno-institutional regime are changed from gas technologies to thermal technologies (appliances, grid, etc.). Gas technologies as phased out from the techno-institutional regime of the Dutch heating sector. This implies that jobs, business, grid operators, market, policies, are reshape into the new reality. The results show that considerable investments are needed, especially to expand the district heating infrastructure, but overall the total costs are lower than the other two alternatives. A new path dependency is set based on power-to-heat technologies where the government has a major role defining new policies and laws to regulate the sector now based on a thermal grid.

8. Conclusion

Urgency in dealing with climate change and limiting the global temperature to increase above 1.5°C of the pre-industrial levels is pressing governments all over the world to find solutions to lower their emissions. This represents major challenges, especially in carbon locked-in energy systems as is the case of the Netherlands.

Decades of domestic natural gas exploitation set the path dependency towards a robust techno-institutional based on natural gas. Political strategies, economic circumstances and historic tradition, all led to a carbon lock-in situation in the Netherlands. Space heating is responsible for 45 million of tonnes of CO_2 emissions. The final energy demand for space heating is 139 TWh and 97-98% of Dutch households are heated with natural gas. Nowadays, the country is trying to find solutions and alternatives to decarbonise its energy system.

In this chapter are presented the conclusions to this thesis and the answer to the Problem Formulation:

How can the Netherlands achieve the decarbonisation of the heating sector by 2050?

Looking forward to 2050, three alternatives were presented for decarbonisng the Dutch heating sector using an energy system analysis tool, where different decarbonising approaches were explored reflecting different degree of ambition towards change: end-of-pipe, continuity and discontinuity.

Scenario 1 representing end-of-pipe approach, followed a power-to-gas strategy to reach decarbonisation. Natural gas was substitute with green gas being produce through electrolysis and hydrogenation process.

Scenario 2 representing continuity approach, followed a mix of power-to-gas and power-to-heat strategies. The share of individual heating technologies and district heating technologies were balanced where each one had 50% share of the heating demand.

Scenario r representing discontinuity approach, followed power-to-heat strategy by increasing the share of district heating to 75% and phasing out natural gas technologies from the heat demand.

All alternatives included intermittent renewable energy sources in the most effective way by in line with Smart Energy System Concept. In power-to gas strategy, excess energy produce from renewable energy sources was used to power the electrolysers to produce hydrogen. In power-to-heat strategy, the incorporation of renewable energy sources was used to power large-scale heat pumps. The results show that it is possible to achieve around 30% reduction on CO_2 emissions compared to 2015 levels. Alternatives with power-to-heat strategy prove to be more cost-effective at lowering the CO_2 emissions. Comparing all three scenarios, Scenario 3 is the one with higher reduction on CO_2 emissions at a lower cost.

From a technological perspective, all three alternatives show that it is possible to escape from the existing carbon-based path dependency in the heating sector into a decarbonised one. All three scenarios used technologies available and already mature meaning that there is no need for further technological development. Although, all present a high consumption on biomass. This can present a challenge as the Netherlands does not produce enough biomass to fulfil the demand. The country will have to rely on imports which, as past fuel crises showed, represents a risk to the security of the energy system.

In order to decarbonise the Dutch heating sector, more than just changes in technologies are needed. A new techno-institutional regime based on low-carbon technologies needs to be created. This means that besides technology changes, societal, organizational and institutional changes must happen. The decision on how to decarbonise is a political one. The Dutch Government has the responsibility to set the right framework for a new low-carbon path dependency by designing strategies and policies favouring low-carbon solution over polluting ones.

Concluding, there several possible ways to decarbonise the Dutch heating sector. Some conditions must be considered to fasten the transition towards a low-carbon heating sector. From a technological point of view, the technologies needed for 2050 are available so, technological change can virtually start today. Institutional present much higher resistance to change. Thus, to decarbonise the Dutch heating sector this is where the focus should start. Developing new policies and strategies are mandatory for overcoming organisational and societal barriers imposed by the carbon lock-in, opening the path for low-carbon technologies to gain momentum into the techno-institutional regime.

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10. Appendix

Scenario 1

Input 1 Final.txt — **The EnergyPLAN model 14.1**

Electricity demand (TWh/year):		Flexible demand	6,36
Fixed demand	115,28	Fixed imp/exp.	0,00
Electric heating + HP	7,74	Transportation	27,99
Electric cooling	4,92	Total	162,30

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	22,77	22,77
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	22,77	22,77

Wind	3400 MW	6,66	TWh/year	0,00	Grid
Offshore Wind	15200 MW	52,54	TWh/year	0,00	stabili-
Photo Voltaic	13900 MW	14,85	TWh/year	0,00	sation
River Hydro	37 MW	0,05	TWh/year	0,00	share
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	1568 MW	12,72	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0,40	0,50	
Heat Pump	0	0			3,00
Boiler		0		0,50	
Group 3:					
CHP	3499	3937	0,40	0,45	
Heat Pump	0	0			4,00
Boiler		9448		0,90	
Condensing	26750			0,52	

Heatstorage: gr.2: 0 GWh gr.23 GWh
Fixed Boiler: gr.2:2,5 Per cent gr.5,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	13,12	0,00

Regulation Strateg	Technical regulation no. 2	
CEEP regulation	234500000	
Minimum Stabilisation share	0,00	
Stabilisation share of CHP	0,00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0,50	
Maximum import/export	0	MW

Distr. Name :	const.txt	
Addition factor	0,00	EUR/MWh
Multiplication factor	0,00	
Dependency factor	0,00	EUR/MWh pr. MW
Average Market Price	0	EUR/MWh
Gas Storage	0	GWh
Syngas capacity	1610	MW
Biogas max to grid	1784	MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficien elec.	The
Hydro Pump:	0	0	0,75	
Hydro Turbine:	0		0,75	
Electrol. Gr.2:	0	0	0,40	0,50
Electrol. Gr.3:	0	0	0,40	0,50
Electrol. trans.:	5544	1000	0,66	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomas
Transport	0,00	159,53	0,00	0,00
Household	0,00	0,00	46,88	16,84
Industry	24,99	3,91	69,57	19,85
Various	2,19	4,62	26,85	0,27

Output WARNING!!: (1) Critical Excess;

	District Heating: Demand Distr. heating MW	DH Production: Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Electricity Consumption: Elec. demand MW	Flex.& Transp MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Electricity Production: Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste-CSHP MW	CHP MW	PP MW	Balance: Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million EUR	Exp Million EUR
January	4649	0	505	0	3316	0	135	707	0	-14	14588	3850	232	4113	1446	0	0	10923	0	1581	1493	2948	7316	100	0	31	31	0	0	0
February	4767	0	505	0	3633	0	135	479	0	15	14272	3939	238	4113	1486	0	0	8235	0	1582	1493	3229	9516	100	0	6	6	0	0	0
March	4023	0	505	0	3107	0	135	276	0	0	13596	3973	198	4113	1236	0	0	9210	0	1577	1493	2762	8101	100	0	27	27	0	0	0
April	3247	1	505	0	2486	0	135	146	0	-26	12797	3829	157	4113	978	0	0	6708	0	1533	1493	2210	9933	100	0	3	3	0	0	0
May	2244	1	505	0	1478	0	135	130	0	-4	12768	3973	103	4113	643	0	0	8333	0	776	1493	1313	9686	100	0	1	1	0	0	0
June	669	1	505	0	0	0	135	130	0	-101	13429	3954	19	4113	118	0	0	7176	0	1111	1493	0	11852	100	0	0	0	0	0	0
July	669	1	505	0	0	0	135	130	0	-101	13815	3845	19	4113	118	0	0	7743	0	1406	1493	0	11266	100	0	0	0	0	0	0
August	680	1	505	0	9	0	135	130	0	-99	13689	3973	19	4113	121	0	0	6618	0	1546	1493	8	12252	100	0	3	3	0	0	0
September	1714	0	505	0	949	0	135	130	0	-6	13515	3889	75	4113	466	0	0	7153	0	1560	1493	844	11011	100	0	4	4	0	0	0
October	2727	0	505	0	1958	0	135	130	0	-1	13514	3911	129	4113	804	0	0	4957	0	1571	1493	1740	12709	100	0	0	0	0	0	0
November	2803	0	505	0	1975	0	135	192	0	-3	14174	3954	133	4113	830	0	0	11521	0	1569	1493	1755	6894	100	0	28	28	0	0	0
December	2993	0	505	0	2127	0	135	214	0	13	14068	3846	143	4113	893	0	0	12612	0	1578	1493	1890	5529	100	0	39	39	0	0	0
Average	2592	1	505	0	1747	0	135	232	0	-27	13684	3911	122	4113	759	0	0	8437	0	1449	1493	1553	9670	100	0	12	12	0	Average price	
Maximum	6469	4	505	0	3936	0	135	4365	0	3904	19937	10341	329	5544	2053	0	0	27112	0	1582	1493	3499	23242	100	0	11136	11136	0	(EUR/MWh)	
Minimum	669	0	505	0	0	0	135	130	0	-2219	334	0	0	0	0	0	0	109	0	766	1493	0	0	100	0	0	0	0	0	0
TWh/year	22,77	0,00	4,43	0,00	15,35	0,00	1,19	2,04	0,00	-0,24	120,20	34,36	1,07	36,13	6,67	0,00	0,00	74,11	0,00	12,72	13,12	13,64	84,94		0,00	0,10	0,10	0,00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	1,35	-	-	99,48	-	-	-	-	-	-	-	-	-	-	-	-	-	27,18	128,01	-0,12	127,88	45,39	45,35
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	159,53	-	8,53	168,07	0,00	168,07	44,11	44,11
N.Gas	-	-	27,22	-	-	14,12	-	-	-	-	0,00	-46,88	-	-	-	-	-	0,00	46,88	96,42	137,76	-0,02	137,75	28,22	28,22
Biomass	-	-	5,54	-	2,27	49,74	-	-	-	-	21,46	-	-	-	-	-	-	-	16,84	20,11	115,96	-0,06	115,90	0,00	0,00
Renewable	-	-	-	-	-	-	3,06	-	-	-	-	-	6,66	14,85	52,54	0,05	0,00	-	-	-	77,17	0,00	77,17	0,00	0,00
H2 etc.	-	-	0,00	-	0,00	0,00	-	-	-	-23,75	-29,81	53,56	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	0,00	-	-	-	-	-	-	-	-2,84	-	-	-	-	-	-	2,84	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	32,22	-	-	-	-	-	-	-	-	-	-	-	-	-	32,22	0,00	32,22	0,00	0,00
Total	-	-	34,11	-	2,27	163,35	35,28	-	-	-23,75	-11,19	6,68	6,66	14,85	52,54	0,05	0,00	162,37	63,72	152,24	659,20	-0,20	658,99	117,72	117,67

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Output specifications 1 Final.txt The EnergyPLAN model 14.1

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Storage MW	Gr.2 Balance MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Storage MW	Gr.3 Balance MW
January	4649	0	505	3316	0	135	707	0	10704	-14
February	4767	0	505	3633	0	135	479	0	10590	15
March	4023	0	505	3107	0	135	276	0	14353	0
April	3247	1	505	2486	0	135	146	0	19052	-26
May	2244	1	505	1478	0	135	130	0	19774	-4
June	669	1	505	0	0	135	130	0	20830	-101
July	669	1	505	0	0	135	130	0	20862	-101
August	680	1	505	9	0	135	130	0	20862	-99
September	1714	0	505	949	0	135	130	0	21069	-6
October	2727	0	505	1958	0	135	130	0	20209	-1
November	2803	0	505	1975	0	135	192	0	13537	-3
December	2993	0	505	2127	0	135	214	0	13099	13
Average	2592	1	505	1747	0	135	232	0	17097	-27
Maximum	6469	4	505	3936	0	135	4365	0	22770	3904
Minimum	669	0	505	0	0	135	130	0	0	-2219
Total for the whole year TWh/year	22,77	0,00	4,43	15,35	0,00	1,19	2,04	0,00		-0,24

	RES specification RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 aic MW	Total MW
January	1310	8998	611	4	10923
February	763	6266	1175	31	8235
March	854	6573	1775	8	9210
April	405	3665	2630	7	6708
May	630	5200	2496	6	8333
June	473	3963	2735	5	7176
July	569	4701	2472	1	7743
August	401	3801	2415	1	6618
September	524	4887	1741	1	7153
October	297	3473	1184	3	4957
November	1362	9584	573	2	11521
December	1504	10623	480	4	12612
Average	758	5981	1691	6	8437
Maximum	3312	15169	10494	37	27112
Minimum	12	67	0	1	109
Total for the whole year TWh/year	6,66	52,54	14,85	0,05	74,11

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)

Total Fuel ex Ngas exchange =	14000	
Uranium =	0	
Coal =	1106	
FuelOil =	0	
Gasoil/Diesel=	2939	
Petrol/JP =	4725	
Gas handling =	1106	
Biomass =	4124	
Food income =	0	
Waste =	0	
Total Ngas Exchange costs =		4612
Marginal operation costs =		452
Total Electricity exchange =		0
Import =	0	
Export =	0	
Bottleneck =	0	
Fixed imp/ex=	0	
Total CO2 emission costs =		5121
Total variable costs =		24185
Fixed operation costs =		4358
Annual Investment costs =		17223
TOTAL ANNUAL COSTS =		45767

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Individual MW	Transport MW	Indu. Var. MW	Demand Sum MW	Biogas MW	Syngas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Storage MW	Sum MW	Import MW	Export MW
January	0	5882	1216	10161	0	10977	28236	0	0	0	5337	0	0	22899	22899	0
February	0	6444	1582	10438	0	10977	29441	0	0	0	5337	0	0	24103	24103	0
March	0	5511	1347	8693	0	10977	26529	0	0	0	5337	0	0	21191	21191	0
April	0	4410	1652	6872	0	10977	23910	0	0	0	5337	0	0	18573	18573	0
May	0	2621	1611	4519	0	10977	19728	0	0	0	5337	0	0	14390	14390	0
June	0	0	1971	826	0	10977	13773	0	0	0	5337	0	0	8436	8436	0
July	0	0	1873	826	0	10977	13676	0	0	0	5337	0	0	8339	8339	0
August	0	16	2037	853	0	10977	13884	0	0	0	5337	0	0	8546	8546	0
September	0	1684	1831	3276	0	10977	17768	0	0	0	5337	0	0	12430	12430	0
October	0	3472	2113	5653	0	10977	22215	0	0	0	5337	0	0	16878	16878	0
November	0	3502	1146	5831	0	10977	21456	0	0	0	5337	0	0	16119	16119	0
December	0	3772	919	6278	0	10977	21946	0	0	0	5337	0	0	16609	16609	0
Average	0	3099	1608	5337	0	10977	21021	0	0	0	5337	0	0	15684	15684	0
Maximum	0	6982	3865	14430	0	10977	35140	0	0	0	5337	0	0	29803	29803	0
Minimum	0	0	0	826	0	10977	11803	0	0	0	5337	0	0	6465	6465	0
Total for the whole year TWh/year	0,00	27,22	14,12	46,88	0,00	96,42	184,65	0,00	0,00	0,00	46,88	0,00	0,00	137,76	137,76	0,00

RES Share: 29,3 Percent of Primary Energy 56,7 Percent of Electricity 105,2 TWh electricity from RES

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Scenario 2

Input 2 Final.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	6,38
Fixed demand	115,11	Fixed imp/exp.	0,00
Electric heating + HP	7,74	Transportation	27,99
Electric cooling	4,92	Total	162,13

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	51,46	51,46
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	51,46	51,46

Wind	3400	MW	6,66	TWh/year	0,00	Grid
Offshore Wind	12400	MW	42,86	TWh/year	0,00	stabili-
Photo Voltaic	19200	MW	20,52	TWh/year	0,00	sation
River Hydro	37	MW	0,05	TWh/year	0,00	share
Hydro Power	0	MW	0	TWh/year		
Geothermal/Nuclear	1568	MW	12,72	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0,40	0,50	
Heat Pump	0	0			3,00
Boiler		0		0,50	
Group 3:					
CHP	3500	3937	0,40	0,45	
Heat Pump	800	3200			4,00
Boiler		9448		0,90	
Condensing	25750		0,52		

Heatstorage: gr.2: 0 GWh gr.51 GWh
Fixed Boiler: gr.2:2,5 Per cent gr.5,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	13,12	0,00

Regulation Strate(Technical regulation no. 2		
CEEP regulation	234500000	
Minimum Stabilisation share	0,00	
Stabilisation share of CHP	0,00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	0,50	
Maximum import/export	0	MW

Distr. Name :	const.txt	
Addition factor	0,00	EUR/MWh
Multiplication factor	0,00	
Dependency factor	0,00	EUR/MWh pr. MW
Average Market Price	0	EUR/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	1373	MW

Fuel Price level:

	Capacities	Storage	Efficienc	
	MW-e	GWh	elec.	Ther
Hydro Pump:	0	0	0,75	
Hydro Turbine:	0		0,75	
Electrol. Gr.2:	0	0	0,40	0,50
Electrol. Gr.3:	0	0	0,40	0,50
Electrol. trans.:	2933	1000	0,66	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomas
Transport	0,00	159,53	0,00	0,00
Household	0,00	0,00	20,09	16,84
Industry	24,99	3,91	69,57	19,85
Various	2,19	4,62	26,85	0,27

Output WARNING!!: (1) Critical Excess;

	District Heating										Electricity																			Exchange	
	Demand	Production									Consumption						Production								Balance					Payment	
	Distr. heating MW	Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste-CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million EUR	Exp Million EUR
January	10508	0	780	0	3557	3105	69	3000	0	-3	14569	3850	1008	2105	1446	0	0	9498	0	1581	1493	3163	7249	100	0	7	7	0	0	0
February	10774	0	780	0	3745	3191	69	2988	0	1	14253	3939	1036	2105	1485	0	0	7529	0	1582	1493	3329	8886	100	0	1	1	0	0	0
March	9093	0	780	0	3648	2951	69	1647	0	-3	13576	3973	936	2105	1237	0	0	8676	0	1577	1493	3243	6868	100	0	30	30	0	0	0
April	7338	1	780	0	3724	2211	69	549	0	5	12777	3829	710	2105	978	0	0	7035	0	1533	1493	3311	7047	100	0	20	20	0	0	0
May	5071	1	780	0	3348	888	69	54	0	-69	12749	3973	325	2105	643	0	0	8327	0	776	1493	2977	6242	100	0	20	20	0	0	0
June	1512	1	780	0	361	301	69	0	0	0	13410	3954	94	2105	118	0	0	7489	0	1111	1493	321	9271	100	0	6	6	0	0	0
July	1512	1	780	0	364	298	69	0	0	0	13795	3845	93	2105	118	0	0	7820	0	1406	1493	323	8928	100	0	15	15	0	0	0
August	1538	1	780	0	392	297	69	0	0	0	13669	3973	94	2105	121	0	0	6839	0	1546	1493	348	9757	100	0	22	22	0	0	0
September	3873	0	780	0	2649	331	69	1	0	42	13495	3889	158	2105	466	0	0	6917	0	1560	1493	2355	7788	100	0	1	1	0	0	0
October	6163	0	780	0	3694	1442	69	167	0	11	13494	3911	490	2105	804	0	0	4768	0	1571	1493	3284	9687	100	0	1	1	0	0	0
November	6335	0	780	0	3221	1639	69	608	0	18	14155	3954	543	2105	830	0	0	9974	0	1569	1493	2864	5694	100	0	7	7	0	0	0
December	6765	0	780	0	3492	2061	69	369	0	-5	14048	3846	658	2105	893	0	0	10838	0	1578	1493	3104	4547	100	0	10	10	0	0	0
Average	5859	1	780	0	2679	1555	69	775	0	0	13665	3911	511	2105	759	0	0	7980	0	1449	1493	2382	7659	100	0	12	12	0	Average price	
Maximum	14621	4	780	0	3937	3200	69	7337	0	5022	19917	10341	1129	2933	2053	0	0	27916	0	1582	1493	3500	22216	100	0	10291	10291	0	(EUR/MWh)	
Minimum	1512	0	780	0	0	293	69	0	0	-3310	314	0	73	0	0	0	0	96	0	766	1493	0	0	100	0	0	0	0	0	0
TWh/year	51,46	0,00	6,85	0,00	23,53	13,66	0,61	6,81	0,00	0,00	120,03	34,36	4,49	18,49	6,67	0,00	0,00	70,09	0,00	12,72	13,12	20,92	67,28		0,00	0,10	0,10	0,00	0	0

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	2,06	-	-	78,80	-	-	-	-	-	-	-	-	-	-	-	-	-	27,18	108,04	-0,12	107,92	38,31	38,27
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	159,53	-	8,53	168,07	0,00	168,07	44,11	44,11
N.Gas	-	-	41,74	-	-	11,19	-	-	-	-	0,00	-20,09	-	-	-	-	-	0,00	20,09	96,42	149,35	-0,02	149,33	30,59	30,59
Biomass	-	-	8,49	-	7,57	39,40	-	-	-	-	3,92	-	-	-	-	-	-	-	16,84	20,11	96,33	-0,06	96,27	0,00	0,00
Renewable	-	-	-	-	-	-	3,06	-	-	-	-	-	6,66	20,52	42,86	0,05	0,00	-	-	-	73,16	0,00	73,16	0,00	0,00
H2 etc.	-	-	0,00	-	0,00	0,00	-	-	-	-12,15	-12,06	24,21	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-2,84	-	-	-	-	-	-	2,84	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	32,22	-	-	-	-	-	-	-	-	-	-	-	-	-	32,22	0,00	32,22	0,00	0,00
Total	-	-	52,30	-	7,57	129,38	35,28	-	-	-12,15	-10,97	4,12	6,66	20,52	42,86	0,05	0,00	162,37	36,93	152,24	627,17	-0,20	626,97	113,01	112,96

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Output specifications 2 Final.txt The EnergyPLAN model 14.1

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Stor-age MW	Gr.2 Ba-lance MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Stor-age MW	Gr.3 Ba-lance MW
January	10508	0	780	3557	3105	69	3000	0	1701	-3
February	10774	0	780	3745	3191	69	2988	0	2270	1
March	9093	0	780	3648	2951	69	1647	0	3339	-3
April	7338	1	780	3724	2211	69	549	0	13189	5
May	5071	1	780	3348	888	69	54	0	21085	-69
June	1512	1	780	361	301	69	0	0	51464	0
July	1512	1	780	364	298	69	0	0	51464	0
August	1538	1	780	392	297	69	0	0	51464	0
September	3873	0	780	2649	331	69	1	0	41084	42
October	6163	0	780	3694	1442	69	167	0	18275	11
November	6335	0	780	3221	1639	69	608	0	15016	18
December	6765	0	780	3492	2061	69	369	0	8173	-5
Average	5859	1	780	2679	1555	69	775	0	23248	0
Maximum	14621	4	780	3937	3200	69	7337	0	51464	5022
Minimum	1512	0	780	0	293	69	0	0	0	-3310
Total for the whole year TWh/year	51,46	0,00	6,85	23,53	13,66	0,61	6,81	0,00		0,00

	RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 aic MW	Total MW
January	1310	7340	844	4	9498
February	763	5112	1624	31	7529
March	854	5363	2452	8	8676
April	405	2990	3633	7	7035
May	630	4242	3448	6	8327
June	473	3233	3778	5	7489
July	569	3835	3415	1	7820
August	401	3101	3336	1	6839
September	524	3986	2405	1	6917
October	297	2833	1635	3	4768
November	1362	7819	791	2	9974
December	1504	8667	664	4	10838
Average	758	4879	2336	6	7980
Maximum	3312	12374	14496	37	27916
Minimum	12	55	0	1	96
Total for the whole year TWh/year	6,66	42,86	20,52	0,05	70,09

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)
Total Fuel ex Ngas exchange = 12920
Uranium = 0
Coal = 933
FuelOil = 0
Gasoil/Diesel= 2939
Petrol/JP = 4725
Gas handling = 819
Biomass = 3503
Food income = 0
Waste = 0

Total Ngas Exchange costs = 5000

Marginal operation costs = 427

Total Electricity exchange = 0
Import = 0
Export = 0
Bottleneck = 0
Fixed imp/ex= 0

Total CO2 emission costs = 4916

Total variable costs = 23263
Fixed operation costs = 3868

Annual Investment costs = 17445

TOTAL ANNUAL COSTS = 44576

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	0	6310	1205	4355	0	10977	22847	0	0	0	2287	0	0	20560	20560	0
February	0	6642	1478	4473	0	10977	23570	0	0	0	2287	0	0	21282	21282	0
March	0	6470	1142	3726	0	10977	22315	0	0	0	2287	0	0	20027	20027	0
April	0	6605	1172	2945	0	10977	21699	0	0	0	2287	0	0	19411	19411	0
May	0	5939	1038	1937	0	10977	19891	0	0	0	2287	0	0	17603	17603	0
June	0	640	1542	354	0	10977	13513	0	0	0	2287	0	0	11225	11225	0
July	0	645	1485	354	0	10977	13460	0	0	0	2287	0	0	11173	11173	0
August	0	695	1622	366	0	10977	13660	0	0	0	2287	0	0	11372	11372	0
September	0	4698	1295	1404	0	10977	18374	0	0	0	2287	0	0	16087	16087	0
October	0	6551	1611	2423	0	10977	21562	0	0	0	2287	0	0	19274	19274	0
November	0	5713	947	2499	0	10977	20135	0	0	0	2287	0	0	17848	17848	0
December	0	6193	756	2691	0	10977	20617	0	0	0	2287	0	0	18329	18329	0
Average	0	4752	1274	2287	0	10977	19290	0	0	0	2287	0	0	17002	17002	0
Maximum	0	6982	3694	6184	0	10977	27215	0	0	0	2287	0	0	24927	24927	0
Minimum	0	0	0	354	0	10977	11331	0	0	0	2287	0	0	9043	9043	0
Total for the whole year TWh/year	0,00	41,74	11,19	20,09	0,00	96,42	169,44	0,00	0,00	0,00	20,09	0,00	0,00	149,35	149,35	0,00

RES Share: 27,0 Percent of Primary Energy 56,6 Percent of Electricity 97,0 TWh electricity from RES 07-June-2019 [07.36]

Scenario 3

Input 3_Final.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	6,36
Fixed demand	115,11	Fixed imp/exp.	0,00
Electric heating + HP	7,74	Transportation	27,99
Electric cooling	4,92	Total	162,13

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	78,09	78,09
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	78,09	78,09

Wind	3400	MW	6,66	TWh/year	0,00	Grid
Offshore Wind	11600	MW	40,1	TWh/year	0,00	stabili-
Photo Voltaic	9100	MW	9,72	TWh/year	0,00	sation
River Hydro	37	MW	0,05	TWh/year	0,00	share
Hydro Power	0	MW	0	TWh/year		
Geothermal/Nuclear	1568	MW	12,72	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	Efficiencies COP
Group 2:					
CHP	0	0	0,40	0,50	
Heat Pump	0	0			3,00
Boiler		0		0,50	
Group 3:					
CHP	3500	3937	0,40	0,45	
Heat Pump	2000	8000			4,00
Boiler		9448		0,90	
Condensing	24900		0,52		

Heatstorage: gr.2: 0 GWh gr.3: 78 GWh
Fixed Boiler: gr.2: 2,5 Per cent gr.3: 5,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	13,12	0,00

Regulation Strate(Technical regulation no. 2
CEEP regulation 234500000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0,50
Maximum import/export 0 MW

Distr. Name : const.txt
Addition factor 0,00 EUR/MWh
Multiplication factor 0,00
Dependency factor 0,00 EUR/MWh pr. MW
Average Market Price 0 EUR/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficien elec.	Ther
Hydro Pump:	0	0	0,75	
Hydro Turbine:	0		0,75	
Electrol. Gr.2:	0	0	0,40	0,50
Electrol. Gr.3:	0	0	0,40	0,50
Electrol. trans.:	197	0	0,66	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Biomas
Transport	0,00	159,53	0,00	0,00
Household	0,00	0,00	0,00	12,63
Industry	24,99	3,91	69,57	19,85
Various	2,19	4,62	26,85	0,27

Output WARNING!!: (1) Critical Excess;

	District Heating										Electricity																			Exchange	
	Demand	Production									Consumption						Production							Balance						Payment	
	Distr. heating MW	Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste-CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million EUR	Exp Million EUR
January	15944	0	2288	0	3545	7367	0	2780	0	-36	14569	3850	2074	0	1446	0	0	8580	0	1581	1493	3152	7158	100	0	26	26	0	0	0
February	16348	0	2288	0	3795	7584	0	2684	0	-3	14253	3939	2134	0	1485	0	0	6345	0	1582	1493	3374	9022	100	0	5	5	0	0	0
March	13798	0	2288	0	3736	6560	0	1225	0	-12	13576	3973	1838	0	1237	0	0	7040	0	1577	1493	3322	7216	100	0	23	23	0	0	0
April	11135	1	2288	0	3891	4609	0	294	0	52	12777	3829	1309	0	978	0	0	4931	0	1533	1493	3459	7477	100	0	0	0	0	0	0
May	7695	1	2288	0	3619	1888	0	26	0	-127	12749	3973	575	0	643	0	0	6239	0	776	1493	3217	6214	100	0	0	0	0	0	0
June	2294	1	2288	0	0	445	0	0	0	-440	13410	3954	130	0	118	0	0	5293	0	1111	1493	0	9719	100	0	5	5	0	0	0
July	2294	1	2288	0	0	445	0	0	0	-440	13795	3845	130	0	118	0	0	5776	0	1406	1493	0	9212	100	0	0	0	0	0	0
August	2334	1	2288	0	30	445	0	0	0	-429	13669	3973	131	0	121	0	0	4884	0	1546	1493	26	9944	100	0	1	1	0	0	0
September	5877	0	2288	0	2863	621	0	4	0	100	13495	3889	230	0	466	0	0	5394	0	1560	1493	2545	7092	100	0	5	5	0	0	0
October	9351	0	2288	0	3790	3207	0	96	0	-30	13494	3911	931	0	804	0	0	3725	0	1571	1493	3370	8980	100	0	0	0	0	0	0
November	9612	0	2288	0	3203	3634	0	448	0	39	14155	3954	1042	0	830	0	0	9053	0	1569	1493	2848	5055	100	0	39	39	0	0	0
December	10266	0	2288	0	3376	4330	0	276	0	-5	14048	3846	1226	0	893	0	0	9930	0	1578	1493	3002	4049	100	0	39	39	0	0	0
Average	8890	1	2288	0	2649	3417	0	647	0	-112	13665	3911	976	0	759	0	0	6436	0	1449	1493	2356	7590	100	0	12	12	0	Average price	
Maximum	22186	4	2288	0	3937	8000	0	8729	0	5826	19917	10040	2329	0	2053	0	0	20407	0	1582	1493	3500	21390	100	0	11315	11315	0	(EUR/MWh)	
Minimum	2294	0	2288	0	0	445	0	0	0	-6911	314	0	111	0	0	0	0	90	0	766	1493	0	0	100	0	0	0	0	0	0
TWh/year	78,09	0,00	20,10	0,00	23,27	30,02	0,00	5,68	0,00	-0,98	120,03	34,36	8,57	0,00	6,67	0,00	0,00	56,53	0,00	12,72	13,12	20,69	66,67		0,00	0,10	0,10	0,00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	2,04	-	-	78,08	-	-	-	-	-	-	-	-	-	-	-	-	-	27,18	107,30	-0,12	107,18	38,05	38,01
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	159,53	-	8,53	168,07	0,00	168,07	44,11	44,11
N.Gas	-	-	41,28	-	-	11,09	-	-	-	-	-	-	-	-	-	-	-	0,00	-	96,42	148,79	-0,02	148,77	30,48	30,47
Biomass	-	-	8,40	-	6,31	39,04	-	-	-	-	3,92	-	-	-	-	-	-	-	12,63	20,11	90,42	-0,06	90,36	0,00	0,00
Renewable	-	-	-	-	-	-	3,06	-	-	-	-	-	6,66	9,72	40,10	0,05	0,00	-	-	-	59,60	0,00	59,60	0,00	0,00
H2 etc.	-	-	0,00	-	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	0,00	-	-	-	-	-	-	-	-2,84	-	-	-	-	-	-	2,84	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	32,22	-	-	-	-	-	-	-	-	-	-	-	-	-	32,22	0,00	32,22	0,00	0,00
Total	-	-	51,72	-	6,31	128,21	35,28	-	-	-	1,09	-	6,66	9,72	40,10	0,05	0,00	162,37	12,63	152,24	606,39	-0,20	606,19	112,63	112,59

07-June-2019 [07.26]

Output specifications 3_Final.txt The EnergyPLAN model 14.1

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Storage MW	Gr.2 Balance MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Storage MW	Gr.3 Balance MW	RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 aic MW	Total MW
January	15944	0	2288	3545	7367	0	2780	0	20445	-36	1310	6867	400	4	8580
February	16348	0	2288	3795	7584	0	2684	0	26821	-3	763	4782	770	31	6345
March	13798	0	2288	3736	6560	0	1225	0	28359	-12	854	5017	1162	8	7040
April	11135	1	2288	3891	4609	0	294	0	31356	52	405	2797	1722	7	4931
May	7695	1	2288	3619	1888	0	26	0	31702	-127	630	3969	1634	6	6239
June	2294	1	2288	0	445	0	0	0	78090	-440	473	3025	1791	5	5293
July	2294	1	2288	0	445	0	0	0	78090	-440	569	3587	1619	1	5776
August	2334	1	2288	30	445	0	0	0	78090	-429	401	2901	1581	1	4884
September	5877	0	2288	2863	621	0	4	0	37308	100	524	3729	1140	1	5394
October	9351	0	2288	3790	3207	0	96	0	44696	-30	297	2650	775	3	3725
November	9612	0	2288	3203	3634	0	448	0	29543	39	1362	7314	375	2	9053
December	10266	0	2288	3376	4330	0	276	0	16342	-5	1504	8107	314	4	9930
Average	8890	1	2288	2649	3417	0	647	0	41793	-112	758	4565	1107	6	6436
Maximum	22186	4	2288	3937	8000	0	8729	0	78090	5826	3312	11576	6870	37	20407
Minimum	2294	0	2288	0	445	0	0	0	0	-6911	12	51	0	1	90
Total for the whole year TWh/year	78,09	0,00	20,10	23,27	30,02	0,00	5,68	0,00		-0,98	6,66	40,10	9,72	0,05	56,53

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)

Total Fuel ex Ngas exchange = 12448		
Uranium =	0	
Coal =	927	
FuelOil =	0	
Gasoil/Diesel=	2939	
Petrol/JP =	4725	
Gas handling =	591	
Biomass =	3266	
Food income =	0	
Waste =	0	
Total Ngas Exchange costs =		4981
Marginal operation costs =		425
Total Electricity exchange =		0
Import =	0	
Export =	0	
Bottleneck =	0	
Fixed imp/ex=	0	
Total CO2 emission costs =		4900
Total variable costs =		22755
Fixed operation costs =		3132
Annual Investment costs =		17248
TOTAL ANNUAL COSTS =		43135

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Individual MW	Transport MW	Indu. Var. MW	Demand Sum MW	Biogas MW	Syngas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Storage MW	Sum MW	Import MW	Export MW
January	0	6287	1190	0	0	10977	18454	0	0	0	0	0	0	18454	18454	0
February	0	6731	1500	0	0	10977	19208	0	0	0	0	0	0	19208	19208	0
March	0	6626	1200	0	0	10977	18803	0	0	0	0	0	0	18803	18803	0
April	0	6901	1243	0	0	10977	19122	0	0	0	0	0	0	19122	19122	0
May	0	6419	1033	0	0	10977	18429	0	0	0	0	0	0	18429	18429	0
June	0	0	1616	0	0	10977	12593	0	0	0	0	0	0	12593	12593	0
July	0	0	1532	0	0	10977	12509	0	0	0	0	0	0	12509	12509	0
August	0	53	1654	0	0	10977	12683	0	0	0	0	0	0	12683	12683	0
September	0	5078	1179	0	0	10977	17234	0	0	0	0	0	0	17234	17234	0
October	0	6723	1493	0	0	10977	19193	0	0	0	0	0	0	19193	19193	0
November	0	5682	841	0	0	10977	17499	0	0	0	0	0	0	17499	17499	0
December	0	5989	673	0	0	10977	17639	0	0	0	0	0	0	17639	17639	0
Average	0	4699	1262	0	0	10977	16938	0	0	0	0	0	0	16938	16938	0
Maximum	0	6982	3557	0	0	10977	21516	0	0	0	0	0	0	21516	21516	0
Minimum	0	0	0	0	0	10977	10977	0	0	0	0	0	0	10977	10977	0
Total for the whole year TWh/year	0,00	41,28	11,09	0,00	0,00	96,42	148,79	0,00	0,00	0,00	0,00	0,00	0,00	148,79	148,79	0,00

RES Share: 24,7 Percent of Primary Energy 50,9 Percent of Electricity 83,3 TWh electricity from RES

07-June-2019 [07.26]

Scenario 1 + HP

Input 1 + HP.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	6,36
Fixed demand	115,11	Fixed imp/exp.	0,00
Electric heating + HP	19,10	Transportation	27,99
Electric cooling	4,92	Total	173,49

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	22,77	22,77
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	22,77	22,77

					Grid stabili-sation share
Wind	3400	MW	6,66	TWh/year	0,00
Offshore Wind	11800	MW	40,79	TWh/year	0,00
Photo Voltaic	12400	MW	13,25	TWh/year	0,00
River Hydro	37	MW	0,05	TWh/year	0,00
Hydro Power	0	MW	0	TWh/year	
Geothermal/Nuclear	1568	MW	12,72	TWh/year	

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0,40	0,50	
Heat Pump	0	0			3,00
Boiler		0		0,50	
Group 3:					
CHP	3499	3936	0,40	0,45	
Heat Pump	0	0			4,00
Boiler		9448		0,90	
Condensing	26000		0,52		

Heatstorage: gr.2: 0 GWh gr.23 GWh
Fixed Boiler: gr.2:2,5 Per cent gr.5,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	13,12	0,00

Regulation Strate(Technical regulation no. 2
CEEP regulation 234500000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0,50
Maximum import/export 0 MW

Distr. Name : const.txt
Addition factor 0,00 EUR/MWh
Multiplication factor 0,00
Dependency factor 0,00 EUR/MWh pr. MW
Average Market Price 0 EUR/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficien elec.	The
Hydro Pump:	0	0	0,75	
Hydro Turbine:	0		0,75	
Electrol. Gr.2:	0	0	0,40	0,50
Electrol. Gr.3:	0	0	0,40	0,50
Electrol. trans.:	0	0	0,66	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Biomas
Transport	0,00	159,53	0,00	0,00
Household	0,00	0,00	0,00	16,84
Industry	24,99	3,91	69,57	19,85
Various	2,19	4,62	26,85	0,27

Output WARNING!!: (1) Critical Excess;

	District Heating										Electricity																		Exchange	
	Demand	Production									Consumption						Production							Balance					Payment	
	Distr. heating MW	Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste-CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million EUR	Exp
January	4649	0	0	0	3538	0	0	1128	0	-16	14568	3850	2695	0	1446	0	0	8844	0	1581	1493	3145	7517	100	0	21	21	0	0	0
February	4767	0	0	0	3795	0	0	954	0	18	14252	3939	2768	0	1485	0	0	6707	0	1582	1493	3373	9290	100	0	0	0	0	0	0
March	4023	0	0	0	3603	0	0	419	0	0	13576	3973	2306	0	1237	0	0	7548	0	1577	1493	3203	7289	100	0	19	19	0	0	0
April	3247	1	0	0	3077	0	0	183	0	-14	12777	3829	1823	0	978	0	0	5604	0	1533	1493	2735	8044	100	0	2	2	0	0	0
May	2244	1	0	0	2124	0	0	130	0	-11	12748	3973	1199	0	643	0	0	6900	0	776	1493	1888	7509	100	0	4	4	0	0	0
June	669	1	0	0	535	0	0	130	0	3	13409	3954	219	0	118	0	0	5995	0	1111	1493	476	8627	100	0	2	2	0	0	0
July	669	1	0	0	538	0	0	130	0	0	13795	3845	219	0	118	0	0	6425	0	1406	1493	479	8173	100	0	0	0	0	0	0
August	680	1	0	0	552	0	0	130	0	-2	13669	3973	226	0	121	0	0	5507	0	1546	1493	491	8956	100	0	5	5	0	0	0
September	1714	0	0	0	1581	0	0	130	0	2	13495	3889	869	0	466	0	0	5872	0	1560	1493	1405	8398	100	0	10	10	0	0	0
October	2727	0	0	0	2589	0	0	135	0	2	13494	3911	1499	0	804	0	0	4052	0	1571	1493	2301	10290	100	0	0	0	0	0	0
November	2803	0	0	0	2535	0	0	280	0	-12	14155	3954	1546	0	830	0	0	9315	0	1569	1493	2253	5893	100	0	39	39	0	0	0
December	2993	0	0	0	2729	0	0	252	0	12	14048	3846	1665	0	893	0	0	10183	0	1578	1493	2426	4812	100	0	41	41	0	0	0
Average	2592	1	0	0	2262	0	0	332	0	-2	13664	3911	1415	0	759	0	0	6916	0	1449	1493	2010	7894	100	0	12	12	0	Average price	
Maximum	6469	4	0	0	3936	0	0	4763	0	3771	19917	10034	3827	0	2053	0	0	22801	0	1582	1493	3499	22500	100	0	11319	11319	0	(EUR/MWh)	
Minimum	669	0	0	0	0	0	0	130	0	-2771	314	0	0	0	0	0	0	92	0	766	1493	0	0	100	0	0	0	0	0	0
TWh/year	22,77	0,00	0,00	0,00	19,87	0,00	0,00	2,91	0,00	-0,01	120,03	34,36	12,43	0,00	6,67	0,00	0,00	60,75	0,00	12,72	13,12	17,66	69,34		0,00	0,10	0,10	0,00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	1,74	-	-	81,21	-	-	-	-	-	-	-	-	-	-	-		-	27,18	110,13	-0,12	110,01	39,05	39,01
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	159,53	-	8,53	168,07	0,00	168,07	44,11	44,11
N.Gas	-	-	35,24	-	-	11,53	-	-	-	-	-	-	-	-	-	-	-	0,00	-	96,42	143,19	-0,02	143,17	29,33	29,33
Biomass	-	-	7,17	-	3,24	40,61	-	-	-	-	3,92	-	-	-	-	-	-	-	16,84	20,11	91,89	-0,06	91,83	0,00	0,00
Renewable	-	-	-	-	-	-	3,06	-	-	-	-	-	6,66	13,25	40,79	0,05	0,00	-	-	-	63,81	0,00	63,81	0,00	0,00
H2 etc.	-	-	0,00	-	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	0,00	-	-	-	-	-	-	-	-2,84	-	-	-	-	-	-	2,84	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	32,22	-	-	-	-	-	-	-	-	-	-	-	-	-	32,22	0,00	32,22	0,00	0,00
Total	-	-	44,15	-	3,24	133,35	35,28	-	-	-	1,09	-	6,66	13,25	40,79	0,05	0,00	162,37	16,84	152,24	609,31	-0,20	609,11	112,49	112,44

07-June-2019 [07.24]

Output specifications 1 + HP.txt

The EnergyPLAN model 14.1

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Storage MW	Gr.2 Balance MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year														
TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Storage MW	Gr.3 Balance MW	RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 aic MW	Total MW
January	4649	0	0	3538	0	0	1128	0	12362	-16	1310	6985	545	4	8844
February	4767	0	0	3795	0	0	954	0	13210	18	763	4864	1049	31	6707
March	4023	0	0	3603	0	0	419	0	8912	0	854	5103	1584	8	7548
April	3247	1	0	3077	0	0	183	0	13452	-14	405	2845	2346	7	5604
May	2244	1	0	2124	0	0	130	0	14842	-11	630	4037	2227	6	6900
June	669	1	0	535	0	0	130	0	15851	3	473	3077	2440	5	5995
July	669	1	0	538	0	0	130	0	15750	0	569	3649	2206	1	6425
August	680	1	0	552	0	0	130	0	16658	-2	401	2951	2155	1	5507
September	1714	0	0	1581	0	0	130	0	15997	2	524	3794	1553	1	5872
October	2727	0	0	2589	0	0	135	0	12560	2	297	2696	1056	3	4052
November	2803	0	0	2535	0	0	280	0	11654	-12	1362	7440	511	2	9315
December	2993	0	0	2729	0	0	252	0	12406	12	1504	8247	429	4	10183
Average	2592	1	0	2262	0	0	332	0	13634	-2	758	4643	1509	6	6916
Maximum	6469	4	0	3936	0	0	4763	0	22770	3771	3312	11776	9362	37	22801
Minimum	669	0	0	0	0	0	130	0	0	-2771	12	52	0	1	92
Total for the whole year															
TWh/year	22,77	0,00	0,00	19,87	0,00	0,00	2,91	0,00		-0,01	6,66	40,79	13,25	0,05	60,75

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)

Total Fuel ex Ngas exchange = 12544
Uranium = 0
Coal = 952
FuelOil = 0
Gasoil/Diesel= 2939
Petrol/JP = 4725
Gas handling = 583
Biomass = 3345
Food income = 0
Waste = 0

Total Ngas Exchange costs = 4794

Marginal operation costs = 422

Total Electricity exchange = 0
Import = 0
Export = 0
Bottleneck = 0
Fixed imp/ex= 0

Total CO2 emission costs = 4893

Total variable costs = 22653
Fixed operation costs = 3452

Annual Investment costs = 16570

TOTAL ANNUAL COSTS = 42675

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Individual MW	Transport MW	Indu. Var. MW	Demand Sum MW	Biogas MW	Syngas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Storage MW	Sum MW	Import MW	Export MW
January	0	6275	1250	0	0	10977	18502	0	0	0	0	0	0	18502	18502	0
February	0	6731	1545	0	0	10977	19253	0	0	0	0	0	0	19253	19253	0
March	0	6391	1212	0	0	10977	18580	0	0	0	0	0	0	18580	18580	0
April	0	5457	1338	0	0	10977	17771	0	0	0	0	0	0	17771	17771	0
May	0	3768	1249	0	0	10977	15993	0	0	0	0	0	0	15993	15993	0
June	0	949	1434	0	0	10977	13360	0	0	0	0	0	0	13360	13360	0
July	0	955	1359	0	0	10977	13291	0	0	0	0	0	0	13291	13291	0
August	0	980	1489	0	0	10977	13446	0	0	0	0	0	0	13446	13446	0
September	0	2804	1396	0	0	10977	15178	0	0	0	0	0	0	15178	15178	0
October	0	4592	1711	0	0	10977	17280	0	0	0	0	0	0	17280	17280	0
November	0	4496	980	0	0	10977	16453	0	0	0	0	0	0	16453	16453	0
December	0	4841	800	0	0	10977	16618	0	0	0	0	0	0	16618	16618	0
Average	0	4012	1313	0	0	10977	16301	0	0	0	0	0	0	16301	16301	0
Maximum	0	6982	3741	0	0	10977	21700	0	0	0	0	0	0	21700	21700	0
Minimum	0	0	0	0	0	10977	10977	0	0	0	0	0	0	10977	10977	0
Total for the whole year																
TWh/year	0,00	35,24	11,53	0,00	0,00	96,42	143,19	0,00	0,00	0,00	0,00	0,00	0,00	143,19	143,19	0,00

RES Share: 25,6 Percent of Primary Energy 56,2 Percent of Electricity 87,8 TWh electricity from RES

07-June-2019 [07.24]

Scenario 2 + HP

Input 2 + HP.txt

The EnergyPLAN model 14.1

Electricity demand (TWh/year): Fixed demand 115,11; Electric heating + HP 12,61; Electric cooling 4,92; Flexible demand 6,36; Fixed imp/exp. 0,00; Transportation 27,99; Total 167,00

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	51,46	51,46
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	51,46	51,46

Wind	3400 MW	6,66 TWh/year	0,00	Grid
Offshore Wind	11400 MW	39,4 TWh/year	0,00	stabili-
Photo Voltaic	13100 MW	14 TWh/year	0,00	sation
River Hydro	37 MW	0,05 TWh/year	0,00	share
Hydro Power	0 MW	0 TWh/year		
Geothermal/Nuclear	1568 MW	12,72 TWh/year		

	Capacities MW-e	MJ/s	Efficiencies elec.	Ther	COP
Group 2:					
CHP	0	0	0,40	0,50	
Heat Pump	0	0			3,00
Boiler		0		0,50	
Group 3:					
CHP	3500	3937	0,40	0,45	
Heat Pump	800	3200			4,00
Boiler		9448		0,90	
Condensing	25100		0,52		

Heatstorage: gr.2: 0 GWh gr.51 GWh
Fixed Boiler: gr.2:2,5 Per cent gr.5,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	13,12	0,00

Regulation Strate(Technical regulation no. 2
CEEP regulation 234500000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0,50
Maximum import/export 0 MW

Distr. Name : const.txt
Addition factor 0,00 EUR/MWh
Multiplication factor 0,00
Dependency factor 0,00 EUR/MWh pr. MW
Average Market Price 0 EUR/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficien elec.	The
Hydro Pump:	0	0	0,75	
Hydro Turbine:	0		0,75	
Electrol. Gr.2:	0	0	0,40	0,50
Electrol. Gr.3:	0	0	0,40	0,50
Electrol. trans.:	0	0	0,66	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Bioma
Transport	0,00	159,53	0,00	0,00
Household	0,00	0,00	0,00	16,84
Industry	24,99	3,91	69,57	19,85
Various	2,19	4,62	26,85	0,27

Output WARNING!!: (1) Critical Excess;

	District Heating Demand Distr. heating MW	Production Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Electricity Consumption Elec. demand MW	Flex.& Transp MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Production Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste-CSHP MW	CHP MW	PP MW	Balance Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million EUR	Exp
January	10508	0	642	0	3556	3126	0	3188	0	-5	14569	3850	2069	0	1446	0	0	8638	0	1581	1493	3162	7082	100	0	22	22	0	0	0
February	10774	0	642	0	3783	3194	0	3153	0	1	14253	3939	2121	0	1485	0	0	6601	0	1582	1493	3364	8761	100	0	2	2	0	0	0
March	9093	0	642	0	3699	2987	0	1767	0	-1	13576	3973	1848	0	1237	0	0	7465	0	1577	1493	3288	6832	100	0	21	21	0	0	0
April	7338	1	642	0	3847	2235	0	609	0	5	12777	3829	1429	0	978	0	0	5640	0	1533	1493	3420	6932	100	0	5	5	0	0	0
May	5071	1	642	0	3486	950	0	61	0	-69	12749	3973	810	0	643	0	0	6889	0	776	1493	3100	5922	100	0	5	5	0	0	0
June	1512	1	642	0	570	298	0	1	0	0	13410	3954	179	0	118	0	0	6028	0	1111	1493	507	8523	100	0	2	2	0	0	0
July	1512	1	642	0	571	297	0	1	0	0	13795	3845	179	0	118	0	0	6426	0	1406	1493	508	8103	100	0	0	0	0	0	0
August	1538	1	642	0	597	298	0	1	0	0	13669	3973	182	0	121	0	0	5529	0	1546	1493	531	8854	100	0	8	8	0	0	0
September	3873	0	642	0	2822	357	0	3	0	49	13495	3889	504	0	466	0	0	5831	0	1560	1493	2509	6969	100	0	8	8	0	0	0
October	6163	0	642	0	3745	1566	0	215	0	-5	13494	3911	1108	0	804	0	0	4020	0	1571	1493	3329	8903	100	0	0	0	0	0	0
November	6335	0	642	0	3232	1743	0	690	0	28	14155	3954	1175	0	830	0	0	9092	0	1569	1493	2874	5118	100	0	33	33	0	0	0
December	6765	0	642	0	3428	2201	0	496	0	-2	14048	3846	1346	0	893	0	0	9928	0	1578	1493	3048	4122	100	0	37	37	0	0	0
Average	5859	1	642	0	2774	1600	0	842	0	0	13665	3911	1076	0	759	0	0	6844	0	1449	1493	2467	7171	100	0	12	12	0	Average price	
Maximum	14621	4	642	0	3936	3200	0	7544	0	4540	19917	10341	2628	0	2053	0	0	22878	0	1582	1493	3500	21531	100	0	11305	11305	0	(EUR/MWh)	
Minimum	1512	0	642	0	0	293	0	0	0	-3103	314	0	73	0	0	0	0	90	0	766	1493	0	0	100	0	0	0	0	0	0
TWh/year	51,46	0,00	5,64	0,00	24,37	14,08	0,00	7,39	0,00	0,00	120,03	34,36	9,45	0,00	6,67	0,00	0,00	60,12	0,00	12,72	13,12	21,67	62,99		0,00	0,10	0,10	0,00	0	0

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and Wind off CSP	Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	2,14	-	-	73,78	-	-	-	-	-	-	-	-	-	-	-	-	-	27,18	103,09	-0,12	102,97	36,56	36,51
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	159,53	-	8,53	168,07	0,00	168,07	44,11	44,11
N.Gas	-	-	43,22	-	-	10,47	-	-	-	-	-	-	-	-	-	-	-	0,00	-	96,42	150,12	-0,02	150,10	30,75	30,75
Biomass	-	-	8,79	-	8,22	36,89	-	-	-	-	3,92	-	-	-	-	-	-	-	16,84	20,11	94,77	-0,06	94,71	0,00	0,00
Renewable	-	-	-	-	-	-	3,06	-	-	-	-	-	6,66	14,00	39,40	0,05	0,00	-	-	-	63,18	0,00	63,18	0,00	0,00
H2 etc.	-	-	0,00	-	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	0,00	-	-	-	-	-	-	-	-2,84	-	-	-	-	-	-	2,84	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	32,22	-	-	-	-	-	-	-	-	-	-	-	-	-	32,22	0,00	32,22	0,00	0,00
Total	-	-	54,15	-	8,22	121,14	35,28	-	-	-	1,09	-	6,66	14,00	39,40	0,05	0,00	162,37	16,84	152,24	611,45	-0,20	611,25	111,41	111,37

07-June-2019 [07:25]

Output specifications 2 + HP.txt The EnergyPLAN model 14.1

District Heating Production

	Gr.1				Gr.2									
	District heating MW	Solar MW	CSHP MW	DHP MW	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00

	Gr.3									
	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW
January	10508	0	642	3556	3126	0	3188	0	2460	-5
February	10774	0	642	3783	3194	0	3153	0	3348	1
March	9093	0	642	3699	2987	0	1767	0	3490	-1
April	7338	1	642	3847	2235	0	609	0	11613	5
May	5071	1	642	3486	950	0	61	0	21366	-69
June	1512	1	642	570	298	0	1	0	51464	0
July	1512	1	642	571	297	0	1	0	51464	0
August	1538	1	642	597	298	0	1	0	51464	0
September	3873	0	642	2822	357	0	3	0	38427	49
October	6163	0	642	3745	1566	0	215	0	22830	-5
November	6335	0	642	3232	1743	0	690	0	15086	28
December	6765	0	642	3428	2201	0	496	0	4096	-2
Average	5859	1	642	2774	1600	0	842	0	23134	0
Maximum	14621	4	642	3936	3200	0	7544	0	51464	4540
Minimum	1512	0	642	0	293	0	0	0	0	-3103
Total for the whole year TWh/year	51,46	0,00	5,64	24,37	14,06	0,00	7,39	0,00		0,00

	RES specification				
	RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 MW	Total aic MW
January	1310	6748	576	4	8638
February	763	4699	1108	31	6601
March	854	4930	1673	8	7465
April	405	2749	2479	7	5640
May	630	3900	2353	6	6889
June	473	2972	2578	5	6028
July	569	3525	2330	1	6426
August	401	2851	2276	1	5529
September	524	3665	1641	1	5831
October	297	2605	1116	3	4020
November	1362	7188	540	2	9092
December	1504	7968	453	4	9928
Average	758	4486	1594	6	6844
Maximum	3312	11376	9890	37	22878
Minimum	12	51	0	1	90
Total for the whole year TWh/year	6,66	39,40	14,00	0,05	60,12

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)
Total Fuel ex Ngas exchange = 12596
Uranium = 0
Coal = 891
FuelOil = 0
Gasoil/Diesel= 2939
Petrol/JP = 4725
Gas handling = 593
Biomass = 3448
Food income = 0
Waste = 0

Total Ngas Exchange costs = 5026

Marginal operation costs = 417

Total Electricity exchange = 0
Import = 0
Export = 0
Bottleneck = 0
Fixed imp/ex= 0

Total CO2 emission costs = 4847

Total variable costs = 22886
Fixed operation costs = 3290

Annual Investment costs = 16988

TOTAL ANNUAL COSTS = 43163

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	NATURAL GAS EXCHANGE Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	0	6308	1178	0	0	10977	18462	0	0	0	0	0	0	18462	18462	0
February	0	6711	1457	0	0	10977	19144	0	0	0	0	0	0	19144	19144	0
March	0	6560	1136	0	0	10977	18673	0	0	0	0	0	0	18673	18673	0
April	0	6823	1153	0	0	10977	18952	0	0	0	0	0	0	18952	18952	0
May	0	6184	985	0	0	10977	18145	0	0	0	0	0	0	18145	18145	0
June	0	1011	1417	0	0	10977	13405	0	0	0	0	0	0	13405	13405	0
July	0	1014	1347	0	0	10977	13338	0	0	0	0	0	0	13338	13338	0
August	0	1058	1472	0	0	10977	13508	0	0	0	0	0	0	13508	13508	0
September	0	5005	1159	0	0	10977	17141	0	0	0	0	0	0	17141	17141	0
October	0	6642	1480	0	0	10977	19099	0	0	0	0	0	0	19099	19099	0
November	0	5733	851	0	0	10977	17561	0	0	0	0	0	0	17561	17561	0
December	0	6081	685	0	0	10977	17743	0	0	0	0	0	0	17743	17743	0
Average	0	4921	1192	0	0	10977	17090	0	0	0	0	0	0	17090	17090	0
Maximum	0	6982	3580	0	0	10977	21539	0	0	0	0	0	0	21539	21539	0
Minimum	0	0	0	0	0	10977	10977	0	0	0	0	0	0	10977	10977	0
Total for the whole year TWh/year	0,00	43,22	10,47	0,00	0,00	96,42	150,12	0,00	0,00	0,00	0,00	0,00	0,00	150,12	150,12	0,00

RES Share: 25,8 Percent of Primary Energy 53,8 Percent of Electricity 85,9 TWh electricity from RES 07-June-2019 [07.25]

BAU 2050

Input BAU 2050.txt — The EnergyPLAN model 14.1

Electricity demand (TWh/year):		Flexible demand	6,36
Fixed demand	115,11	Fixed imp/exp.	0,00
Electric heating + HP	7,74	Transportation	27,99
Electric cooling	4,92	Total	162,13

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	26,78	26,78
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	26,78	26,78

				Grid stabilisation share
Wind	5688 MW	11,14	TWh/year	0,00
Offshore Wind	11865 MW	41,01	TWh/year	0,00
Photo Voltaic	10777 MW	11,52	TWh/year	0,00
River Hydro	37 MW	0,05	TWh/year	0,00
Hydro Power	0 MW	0	TWh/year	
Geothermal/Nuclear	1568 MW	12,72	TWh/year	

	Capacities MW-e	MJ/s	Efficiencies elec.	Ther	COP
Group 2:					
CHP	0	0	0,40	0,50	
Heat Pump	0	0			3,00
Boiler		0		0,50	
Group 3:					
CHP	3499	3937	0,40	0,45	
Heat Pump	0	0			4,00
Boiler		9448		0,90	
Condensing	23000		0,52		

Heatstorage: gr.2: 0 GWh gr.27 GWh
Fixed Boiler: gr.2:2,5 Per cent gr.5,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	13,12	0,00

Regulation Strate(Technical regulation no. 2
CEEP regulation 234500000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0,50
Maximum import/export 0 MW

Distr. Name : const.txt
Addition factor 0,00 EUR/MWh
Multiplication factor 0,00
Dependency factor 0,00 EUR/MWh pr. MW
Average Market Price 0 EUR/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficien elec.	The
Hydro Pump:	0	0	0,75	
Hydro Turbine:	0		0,75	
Electrol. Gr.2:	0	0	0,40	0,50
Electrol. Gr.3:	0	0	0,40	0,50
Electrol. trans.:	196	17	0,66	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Biomas
Transport	0,00	159,53	0,00	0,00
Household	0,00	0,00	60,17	16,84
Industry	24,99	3,91	69,57	19,85
Various	2,19	4,62	26,85	0,27

Output WARNING!!: (1) Critical Excess;

	District Heating Demand										Electricity Consumption						Electricity Production							Balance					Exchange Payment	
	Distr. heating MW	Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste-CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million EUR	Exp Million EUR
January	5566	0	0	0	2993	0	5	2573	0	-6	14568	3850	235	151	1462	0	0	9692	0	1581	1493	2661	5222	100	0	383	383	0	0	0
February	5710	0	0	0	3564	0	5	2135	0	6	14252	3939	241	151	1505	0	0	7110	0	1582	1493	3168	6859	100	0	122	122	0	0	0
March	4800	0	0	0	3358	0	5	1437	0	0	13576	3973	200	151	1247	0	0	7944	0	1577	1493	2985	5348	100	0	199	199	0	0	0
April	3850	1	0	0	3386	0	5	462	0	-4	12777	3829	157	151	981	0	0	5585	0	1533	1493	3010	6292	100	0	18	18	0	0	0
May	2623	1	0	0	2467	0	5	168	0	-19	12748	3973	103	151	640	0	0	7055	0	776	1493	2193	6131	100	0	33	33	0	0	0
June	696	1	0	0	535	0	5	152	0	2	13409	3954	16	151	102	0	0	6011	0	1111	1493	476	8561	100	0	19	19	0	0	0
July	696	1	0	0	537	0	5	152	0	0	13795	3845	16	151	102	0	0	6539	0	1406	1493	478	7997	100	0	4	4	0	0	0
August	710	1	0	0	567	0	5	152	0	-15	13669	3973	17	151	106	0	0	5511	0	1546	1493	504	8874	100	0	13	13	0	0	0
September	1974	0	0	0	1797	0	5	152	0	19	13495	3889	74	151	459	0	0	6042	0	1560	1493	1598	7405	100	0	30	30	0	0	0
October	3214	0	0	0	2968	0	5	253	0	-12	13494	3911	129	151	805	0	0	4129	0	1571	1493	2638	8659	100	0	0	0	0	0	0
November	3307	0	0	0	2434	0	5	861	0	7	14155	3954	133	151	831	0	0	10206	0	1569	1493	2163	4144	100	0	351	351	0	0	0
December	3540	0	0	0	2539	0	5	973	0	23	14048	3846	144	151	896	0	0	11185	0	1578	1493	2257	2975	100	0	403	403	0	0	0
Average	3049	1	0	0	2257	0	5	786	0	0	13664	3911	122	151	759	0	0	7255	0	1449	1493	2007	6537	100	0	132	132	0	Average price	
Maximum	7793	4	0	0	3936	0	5	7770	0	3322	19917	9932	334	196	2084	0	0	23826	0	1582	1493	3499	19453	100	0	15058	15058	0	(EUR/MWh)	
Minimum	696	0	0	0	0	0	5	152	0	-2632	314	0	0	0	0	0	0	112	0	786	1493	0	0	100	0	0	0	0	0	0
TWh/year	26,78	0,00	0,00	0,00	19,83	0,00	0,04	6,91	0,00	0,00	120,03	34,36	1,07	1,33	6,67	0,00	0,00	63,73	0,00	12,72	13,12	17,63	57,42		0,00	1,16	1,16	0,00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	1,74	-	-	55,21	-	-	-	-	-	-	-	-	-	-	-	-	-	27,18	84,12	-1,11	83,01	29,83	29,44
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	159,53	-	8,53	168,07	0,00	168,07	44,11	44,11
N.Gas	-	-	35,17	-	-	55,21	-	-	-	-	-	-	-	-	-	-	-	0,00	60,17	96,42	246,98	-1,11	245,86	50,59	50,36
Biomass	-	-	7,16	-	7,67	-	-	-	-	-	3,92	-	-	-	-	-	-	-	16,84	20,11	55,71	0,00	55,71	0,00	0,00
Renewable	-	-	-	-	-	-	3,06	-	-	-	-	-	11,14	11,52	41,01	0,05	0,00	-	-	-	66,79	0,00	66,79	0,00	0,00
H2 etc.	-	-	0,00	-	0,00	0,00	-	-	-	-0,87	-	0,87	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-2,84	-0,61	-	-	-	-	-	3,44	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	32,22	-	-	-	-	-	-	-	-	-	-	-	-	-	32,22	0,00	32,22	0,00	0,00
Total	-	-	44,07	-	7,67	110,42	35,28	-	-	-0,87	1,09	0,27	11,14	11,52	41,01	0,05	0,00	162,98	77,01	152,24	653,88	-2,22	651,66	124,53	123,91

07-June-2019 [07.39]

Output specifications BAU 2050.txt The EnergyPLAN model 14.1

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Storage MW	Gr.2 Balance MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Storage MW	Gr.3 Balance MW	RES specification RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 aic MW	Total MW
January	5566	0	0	2993	0	5	2573	0	2580	-6	2191	7024	474	4	9692
February	5710	0	0	3564	0	5	2135	0	4129	6	1276	4891	911	31	7110
March	4800	0	0	3358	0	5	1437	0	11442	0	1429	5131	1376	8	7944
April	3850	1	0	3386	0	5	462	0	13126	-4	677	2861	2039	7	5585
May	2623	1	0	2467	0	5	168	0	15988	-19	1054	4059	1935	6	7055
June	696	1	0	535	0	5	152	0	15590	2	792	3094	2121	5	6011
July	696	1	0	537	0	5	152	0	15911	0	952	3669	1917	1	6539
August	710	1	0	567	0	5	152	0	17804	-15	671	2967	1873	1	5511
September	1974	0	0	1797	0	5	152	0	12761	19	876	3814	1350	1	6042
October	3214	0	0	2968	0	5	253	0	16700	-12	498	2711	918	3	4129
November	3307	0	0	2434	0	5	861	0	10744	7	2278	7481	444	2	10206
December	3540	0	0	2539	0	5	973	0	13372	23	2516	8293	372	4	11185
Average	3049	1	0	2257	0	5	786	0	12552	0	1269	4669	1311	6	7255
Maximum	7793	4	0	3936	0	5	7770	0	26783	3322	5541	11841	8136	37	23826
Minimum	696	0	0	0	0	5	152	0	0	-2632	20	53	0	1	112
Total for the whole year TWh/year	26,78	0,00	0,00	19,83	0,00	0,04	6,91	0,00		0,00	11,14	41,01	11,52	0,05	63,73

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)

Total Fuel ex Ngas exchange =	11783
Uranium =	0
Coal =	727
FuelOil =	0
Gasoil/Diesel=	2939
Petrol/JP =	4726
Gas handling =	1329
Biomass =	2062
Food income =	0
Waste =	0
Total Ngas Exchange costs =	8269
Marginal operation costs =	391
Total Electricity exchange =	0
Import =	0
Export =	0
Bottleneck =	0
Fixed imp/ex=	0
Total CO2 emission costs =	5417
Total variable costs =	25860
Fixed operation costs =	3722
Annual Investment costs =	15659
TOTAL ANNUAL COSTS =	45241

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Individual MW	Transport MW	Indu. Var. MW	Demand Sum MW	Biogas MW	Syngas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Storage MW	Sum MW	Import MW	Export MW
January	0	5309	5021	13190	0	10977	34497	0	0	0	0	0	0	34497	34497	0
February	0	6322	6595	13553	0	10977	37447	0	0	0	0	0	0	37447	37447	0
March	0	5956	5142	11261	0	10977	33336	0	0	0	0	0	0	33336	33336	0
April	0	6006	6050	8868	0	10977	31901	0	0	0	0	0	0	31901	31901	0
May	0	4376	5895	5776	0	10977	27024	0	0	0	0	0	0	27024	27024	0
June	0	949	8232	922	0	10977	21080	0	0	0	0	0	0	21080	21080	0
July	0	953	7689	922	0	10977	20542	0	0	0	0	0	0	20542	20542	0
August	0	1005	8533	958	0	10977	21473	0	0	0	0	0	0	21473	21473	0
September	0	3188	7120	4142	0	10977	25427	0	0	0	0	0	0	25427	25427	0
October	0	5264	8326	7265	0	10977	31832	0	0	0	0	0	0	31832	31832	0
November	0	4317	3985	7500	0	10977	26778	0	0	0	0	0	0	26778	26778	0
December	0	4503	2861	8087	0	10977	26427	0	0	0	0	0	0	26427	26427	0
Average	0	4004	6285	6850	0	10977	28117	0	0	0	0	0	0	28117	28117	0
Maximum	0	6982	18705	18799	0	10977	53555	0	0	0	0	0	0	53555	53555	0
Minimum	0	0	0	922	0	10977	11899	0	0	0	0	0	0	11899	11899	0
Total for the whole year TWh/year	0,00	35,17	55,21	60,17	0,00	96,42	246,98	0,00	0,00	0,00	0,00	0,00	0,00	246,98	246,98	0,00

RES Share: 18,7 Percent of Primary Energy 44,2 Percent of Electricity 69,6 TWh electricity from RES

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