# Coupling Power and Heat Sectors as a Flexibility Option

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# Coupling Power and Heat Sectors as a Flexibility Option

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# Executive Summary

Wind and solar energy are becoming the dominant renewable electricity sources leading the energy transition and decarbonization of the power sector in the Netherlands. The integration of these technologies into existing power sector is a challenging task since the supply of weather-dependent VRE (Variable Renewable Energy) does not usually follow the load pattern. The focus of the transition was mainly on the power sector for a long time and more progress is needed in the other sectors such as heat and transport. One approach for more sustainable, reliable and cost-effective energy system is sector coupling. Sector coupling refers to the idea of interconnecting the energy consuming sectors agricultural, residential, transport and industry, with the power producing sector. Increasing the coupling between heat and power sectors results in an increase in electricity demand significantly and affects the power system in terms of capacity requirements, system costs and flexibility needs. For this potential to be unlocked the end-users such as industry and households should also economically benefit from the coupling. There are some market regulations that create distortions in the system and prevent the positive business case for end users. As a result of the literature review, it is identified that there are few studies investigating power and heat market integration in a broader power market perspective combined with an analysis of the possible barriers from the end-users side. As a result of the literature study and the identified literature gap, the main research question of this thesis is formulated as follows: "What are the flexibility implications of the increasing sector coupling between heat and power sectors?”

The first part of the research provides insights into the evolution of the heat sector in the future in terms of demand and technology in the Netherlands. For households, three types of heat pump technologies (air, ground, hybrid) are the main technology options for electrification of the heat sector. The market penetration rate of these technologies differ per scenario studies in the literature and determined mostly by the competitiveness and availability of alternative technologies such as green gas and heat networks. For industry, the differentiation between the temperatures makes the power-to-heat technology development more challenging, especially for high and medium temperature heat demand where the most potential exists. A hybrid boiler is one of the commercially available options while technologies such as heat pumps and electric furnaces are still under development. For this research 5.86 TWh and 33 TWh of potential power-to-heat load is identified in 2030 for households and industry, respectively.

In the second part of the research, a scenario analysis is performed by using a power system model, COMPETES (Competitive Market Power in Electricity Transmission and Energy Simulator) which minimizes the total power system costs of the European power market under the technical constraints. Three scenarios No-P2H, InFlex-P2H, and Flex-P2H are designed to investigate the power sector implications of the coupling. The two main aspects that distinguish the scenarios are the existence of the link between heat and power sectors and the existence of heat demand flexibility options. For this study, heat demand flexibility options are identified as demand response and thermal energy storage. It is assumed that 25% of the households are capable of shifting the heat demand by means of thermal energy storage for 5 hours. From the industry side, load shedding is an option by means of a hybrid boiler which is capable of switching between natural gas and electricity. The scenarios are compared based on the determined indicators: system costs, end-user heating costs and savings, $CO_2$ emissions, VRE curtailment, VRE generation revenues, residual peak load, the correlation between VRE generation and power load, total and average up and down ramps. The first part of the analysis reveals the implications of the increasing coupling on the power system if the P2H load

is inflexible. In this case, the expected P2H load in 2030 which is around 39 TWh creates an increase in the need for flexibility in the power system. Even though there is a small decrease in the system costs due to savings from the heat sector side, the extra electrical load increases the generation costs from the power sector and net imports as well. This implies an increase in the dependency on the outer sources. An important benefit of the coupling is the increase in VRE utilization. This shows that the additional P2H demand is satisfied by the VREs to a certain extent. The second part of the analysis reveals the benefits of a flexible P2H load on the power sector and on end-users. It is found out that the flexibility of this additional P2H load can facilitate a more cost-effective coupling and decarbonization of the heat sector. The flexibility from the heat sector serves as an alternative to other options such as smart charging of electric vehicles. The heat demand flexibility also decreases the system costs by 18.4%. An important part of the cost savings is from the operational savings from the heat sector as well as from the decrease in the net imports which also implies more independence from the outer sources.

When the two flexibility options are analyzed more in details, it is observed that due to high natural gas usage of the hybrid boiler, P2H demand from industry does not flatten the residual load curve and increase the off-peak load. Preference of natural gas most of the year also causes a decrease in the electricity prices which results in a decrease in the VRE generator revenues. According to the electricity and natural gas prices from the model, 81% of the year natural gas is more cost-efficient to use for a hybrid boiler in 2030. The load shifting and the increasing percentage of the flexible P2H load from the household side do not affect the residual load significantly while a moderate decrease in VRE curtailment and an increase in VRE generation revenues are observed. The largest system cost decrease due to increasing percentage of the flexible household P2H load occurs in the initial increase of the household flexibility level which is 0% to 25%. This implies that the development of the demand response and the related investments until 2030 are important and will provide the most of the system costs reductions. From the end-user perspective, the analysis reveals that 5 hours of load shifting via thermal energy storage provides only 5% heating cost savings compared to 2 hours of load shifting which can be provided by high-level insulation. The small difference in heating cost savings shows that for a household that already has insulation and heat pump, it is not reasonable to invest in a decentralized thermal storage. A larger size utility or community scale storage can be a better option as it will increase the savings from the heating costs more and reduce the initial costs by allocating them between various actors such as system operator and the aggregators. For the already existing households (that are using natural gas as the main source of heating), the investment costs are quite high for the electrification of the heat demand including investments for heat pumps and insulation which can go up until 45 000 euros.

The final part of the research focuses on the price distortions created by taxes an levies which are potential barriers against the wide-spread use of P2H technologies. In the Netherlands, the taxes and levies include VAT (BTW), energy taxes (Energiebelasting) and a premium sustainable energy (ODE) and constitutes approximately 44% of the total annual energy bill both for electricity and natural gas. It was found out for households, the addition of taxes decreases the cost-effective operational hours of the electricity. This change is limited as for heat pumps using electricity is more cost-efficient most of the time due to the high coefficient of performance. The amount of taxes on natural gas and electricity are more important to determine the payback period of the P2H technologies for households. Current tax structure prevents obtaining more energy savings for the households to cover the costly investments for heat pumps in a shorter time. Small industrial consumers are the ones who are affected most negatively from the taxes and levies while for large industry these taxes do not discourage the usage of electricity. When the heating costs for a hybrid boiler and a natural ga boiler is compared with the current electricity and natural gas taxes and levies, the hybrid boiler does not stand out as a profitable option for both industrial consumers.

Finally, the two-stage tax shift proposed in the Climate Agreement, a package of policy measures that aims to bring 49% of emission reductions by 2030 compared to 1990, is tested. The proposed shift increases the annual heating cost savings up to 55% for a household that uses heat pumps. For small industry, hybrid boiler becomes a cheaper option after the first stage tax shift while the second one is more ambitious on increasing the operational hours of the hybrid boiler and savings as well. For large industrial consumers, the heating cost gap between hybrid boiler and natural gas boiler increases from 0.2 billion euros to 0.85 billion euros providing more energy savings which might be enough to cover the increased network costs.

Even though the aim is to become natural gas free towards 2050, natural gas is still a cost-efficient option in 2030 without any policy interventions. Different types of policy measures are on the agenda of the Dutch government to encourage the end-users. In the process of designing policy instruments, the involvement of various actors is important to make the transition more cost-efficient. The negotiators include environmental organizations, municipalities, housing corporations, energy companies, construction companies and banks. Without additional policy instruments such as the tax shift investigated in this study, it is unlikely that the identified potential benefits of sector coupling will be revealed as the current structure of the electricity and natural gas prices is an important barrier for households and industry.

# 1 Introduction

## 1.1 Research Context

Energy transition is a pathway towards the transformation of the global energy system from fossil-based to zero-carbon during the first half of this century (IRENA, 2018). The main target of this transition is to reduce the energy-related CO2 emissions and as a result, limit climate change. Variety of renewable energy technologies have been developed and in different parts of the world, wind and solar power started to be the dominant renewable electricity sources leading the decarbonization of the power sector. The integration of these technologies into existing power sector is challenging since the supply of weather-dependent VRE (Variable Renewable Energy) does not usually follow the load pattern. This implies that besides developing the necessary sustainable technologies, an important phase of the energy transition is the integration of the growing ratio of renewable technologies and the connections between the end-use sectors (industry, transport, residential). The focus of the transition was mainly on the power sector for a long time and more progress is needed in the other sectors like heat and transport (Schaber, 2013). One approach for more sustainable, reliable and cost-effective energy system is *sector coupling*. Sector coupling refers to the idea of interconnecting the energy consuming sectors agricultural, residential, transport and industry, with the power producing sector (Olczak & Piebalgs, 2018). Benefits of sector coupling would be the integration of the fluctuating electricity generation from VRE and as a result the use of the full potential of VREs with less curtailment. In the end, this will contribute to the decarbonization of other energy sectors and to the reduction of total emissions (Schaber, 2013). The European Commission defines sector coupling as a strategy to ensure greater flexibility to the energy system in order to achieve the decarbonization in a more cost-effective way (NUFFEL, 2018). This can be achieved by utilizing the synergy between these sectors. Two important forms of sector coupling are between electricity and heat (via power-to-heat technologies) or electricity and gas (via power-to-gas technologies).

Sector coupling can provide flexibility for the power sector on the demand side if well-managed (IRENA, 2018). The coupling of two sectors can be analyzed in four different pillars: 1) Infrastructure planning, 2) system and market operation, 3) regulatory framework and research, 4) development, demonstration, and deployment (Olczak & Piebalgs, 2018). Infrastructure planning refers to the planning of an integrated network to deal with the anticipated increase in electricity demand. Enhancement of the transmission grid or adjustments to the gas network falls under this category. These infrastructures are characterized by high investment costs and long pay-back periods. Sector coupling approach should ensure that the existing infrastructure is used in the best possible way and unnecessary investments are avoided.

System and market operations refer to the operational and market challenges. One important market-related challenge is the structure of the current electricity prices. This is one of the most important barriers against sector coupling. At the current commodity prices electrification of the end-use sectors is not the cheapest option for decarbonization. The declining trend of electricity prices due to high renewable capacity can make electricity a more economical option for sector coupling than alternatives such as CCS (Carbon Capturing System). In fact, this level of prices is already achieved in Sweden where the hydropower and nuclear power have a significant share in the generation portfolio. However, for many other countries in Europe even though wholesale prices decrease, the regulated component of electricity price forms an important barrier for sector coupling. This part of the electricity prices consists of grid fees, taxes, and levies. Only a limited percent of the electricity price is set by the market. The high percent of regulated cost component makes electricity based solutions less attractive. The alternative fuel natural gas has relatively low prices. This results in economically unfeasible businesses case for sector coupling. Operational challenges are related to the effects of the coupling on the operation of existing power or the natural gas grid. Sector coupling is expected to provide operational flexibility for the power grid and this needs to be complemented with demand response or reinforcement of the transmission and distribution system. For the gas network, the integration of green gas and hydrogen to the existing gas infrastructure and ensuring a good quality of gas is an important challenge.

Regulatory framework refers to the set of rules for electricity and natural gas markets as well as storage technologies. This regulatory framework is mostly indicated in the EU directives and might vary between countries. One example is the unbundling rules for the gas network. A cross-sectoral regulation, for example between gas and electricity, might be required for an integrated energy market.

Research, development, and deployment refer to the technologies that will determine the limitations of the sector coupling. Efficient and affordable technology development is one of the most important factors to promote sector coupling as an attractive option for decarbonization.

The coupling between power and heat sector is one of the globally discussed decarbonization options. The heat sector needs much more effort and improvement as it still relies on gas and coal as primary energy sources (Schoots, 2015). Heat is one of the largest energy end-use sectors accounting for more than 50% of the global final energy consumption. Half of this demand is from industry, while the remainder is for space, water heating, cooking and agricultural uses. Over 70% of the heat consumption is based on fossil fuels such as natural gas, oil or coal. As a result, globally it was responsible for 39% of the total annual energy-related emissions (12.5 gigatons) in 2015 (Raha, Mahanta, & Clarke, 2014). Thus it is a promising energy sector for sector coupling to reduce CO2 emissions. However, heating technologies that are not directly based on fossil fuels globally account for only a quarter of heat energy use. Over 95% of them is based on biomass while only around 1.5% is on electricity. In general heat pumps and other power-to-heat technologies are still a small segment but also promising with the ongoing research and development of the technology and policy options (Bloess et al., 2018).

The focus of this research is the coupling between power and heat sectors from the system/market operation perspective. The geographical scope of the research is the Netherlands. The Netherlands used to be one of the major gas producers in which 93% of the households are connected to the nation-wide natural gas grid (Schoots, 2015). One of the aims is now to remove gas as a source of heating and cooking for all residential buildings since the government wants to reduce CO2 emissions from the built environment by 80% in 2050 (van Ende, 2018).

The thesis is presented in the following structure: The rest of this chapter provides a brief problem definition and mentions the societal and academic relevance of the thesis. Chapter 2 presents the research questions identified as a result of the literature review and the research methodology. Chapter 3 presents an overview of the heat sector in the Netherlands, the current situation and the potentials of the heat demand flexibility. Chapter 4 describes the modeling approach with the description of the model, data, the limitations, and the scenarios designed to answer the research questions. Chapter 5 presents an analysis of the modeling results. Chapter 6 interprets the results to provide and answer to the main research question and to observe the policy implications. Finally, Chapter 7 presents a conclusion for the research questions and elaborates more on further research areas.

## 1.2 Problem Definition

Preliminary research proves that an effective coupling between power and heat sectors requires adjustments for the system and market operations. The major problem under this pillar is identified as follows:

*Increasing the coupling between heat and power sectors results in an increase of electricity demand significantly and affects the power system in terms of capacity requirements and system costs. This increase of the electric load from power-to-heat technologies makes the notion of flexibility more important for the power system and creates an additional need for flexibility. This need for flexibility can be satisfied from different flexibility supply options. However, for this potential to be unlocked the end-users such as industry and households should also economically benefit from the coupling in return of using power-to-heat technologies as a decarbonization option. There are some market regulations that create distortions in the system and prevent the positive business case for end users. Barriers against the coupling might prevent the optimal potential to be unlocked. The implications of the flexibility that the coupling can provide to the power system need to be explored also considering these barriers and the perspective of end-users.*

## 1.3 Societal and Academic Relevance

The societal relevance of the study comes from the many dimensions that the energy transition includes. Economic, technical and social aspects are integral parts of the transition. All these aspects and different actors that are involved should be included in an analysis to solve any kind of challenges related to energy transition. This thesis aims to analyze the flexibility implications on the power system as one of the important decarbonization options. The perspective of end-users and the barriers that they encounter are also included to complement the system wise analysis. The outcomes will help to reflect what policy instruments are needed for this option to be successful.

Academic relevance of the study comes from its contribution to the knowledge gap that is identified in the following Chapter 2. The thesis presents a range of literature studies that address the problem definition. It follows a structured research methodology to answer the identified research questions and proposes further research points for researchers that work on a similar topic.

# 2 Research Methodology and Research Questions

This section presents the definitions of the key terms that are relevant to the problem definition. A literature review is followed by the identified knowledge gap and the research questions that aim to address the knowledge gap. The research objective and the methodology is presented together with the research phases and the research flow diagram.

## 2.1 Definition of Key Terms

Sector Coupling:

Sector coupling refers to the idea of interconnecting the energy consuming sectors heating, cooling, transport and industry with the power producing sector, in other words, "co-production, combined use, conversion and substitution of different energy supply and demand forms – electricity, heat and fuels" (Appunn, 2018). Electric vehicles in the transport sector and heat-pumps in the heat sector are example technologies for the conversion. A general name used for these technologies is "P2X" representing power-to-heat, power-to-gas, and power-to-fuel (Brown, Schlachtberger, Kies, Schramm, & Greiner, 2018). The scope of this research is chosen as the coupling between electricity and heat sectors.

Power-to-heat:

Conversion of electrical energy into heat. Technologies used for this purpose can either be centralized and carried by a heat network (e.g. district heating) or decentralized and located near a house, flat or block. Resistors, electric boilers, and heat pumps are the main technologies that enable this conversion (Bloess et al., 2018).

Flexibility:

Flexibility is defined as follows in the literature:

"The capability of the power system to maintain a balance between generation and load under uncertainty" (Hsieh & Anderson, 2017).

"The ability of the energy system to respond to the variability and uncertainty of the residual power load within the limits of the electricity grid. The problem (the demand for flexibility) is caused primarily by the power system while the solution (the supply of flexibility) may come from the energy system as a whole" (Sijm et al., 2017).

Demand for Flexibility:

The demand for flexibility is the need of sources to handle the increasing ramps in the power system. The demand for flexibility arises from the variability of the residual load, uncertainty of the residual load (forecast errors) or overloading of the power grid (increase in the electricity demand). The flexibility is demanded by static heat pump and EV loads, non-flexible conventional load or the VRE sources. When a substantial amount of power-to-heat demand is added to the power system, the peak load, the residual load, the ramp up and down needs for power plants would change. These indicators are used to determine the demand for flexibility compared to the case of no additional power-to-heat demand (Sijm et al., 2017).

Supply for Flexibility:

To meet the demand for flexibility, supply options are needed. Power generation from flexible non-VRE sources (e.g. gas-fired power plants) or VRE sources (e.g. hydro, biomas), VRE curtailment (limitation of peak power generation from VRE sources), demand curtailment (limitation of peak power demand), demand response, energy storage, energy conversion technologies (e.g. power-to-gas, power-to-heat, power-to-ammonia), power trade are options of flexibility supply (Sijm et al., 2017).

The traditional approach to provide flexibility in the power sector was using supply-side assets. Thermal generators with advanced cycling capabilities (e.g. open-cycle gas turbines), flexible renewables such as hydro-power, and pumped hydro storage were used to follow the demand fluctuations (IRENA, 2018). However, with the increasing share of renewable energy sources supply side has a considerable amount of uncertainty and variation. The new approach to provide flexibility to the power system includes demand response and energy storage. Sector coupling offers additional opportunities for these approaches to be used. To be able to be successful with the energy transition, the full flexibility potential of the energy system should be utilized. Demand flexibility and sector coupling are especially gaining importance (IRENA, 2018).

Flexibility also starts to become a commodity and the quantification of its value is in the interest of many system operators (Hsieh & Anderson, 2017). Negative pricing, curtailment of the renewable energy sources, loss of load are signs of an inflexible power system (IRENA, 2018).

Heat Load:

Heat demand consists of two parts: low temperature (<100 ºC), medium (100-400 ºC) and high temperature >400 ºC). Low-temperature heat demand includes the built environment, horticulture sector and low-temperature part of the industry. Low temperature is mostly satisfied using natural gas. High and medium temperature heat is used in the industry for producing paper and construction products, steel, food, and chemical substances. This part of the heat demand is mostly satisfied by natural gas, oil, and coal (ECN, 2017). Below the size of the heat demand per sector for the Netherlands can be seen for 2016.

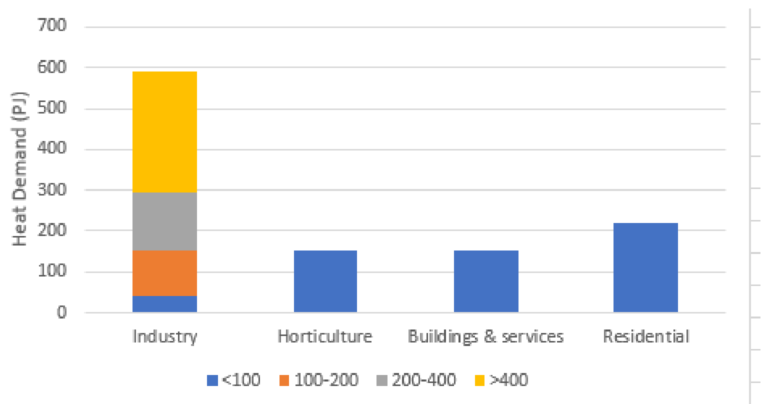



Figure 1: Heat consumption per sector in 2016 (CBS, 2018)

Demand Response:

Demand response is defined as the change in the energy consumption patterns by the customers in response to price signals or to specific requests. The aim is providing flexibility to the electricity system and at the same time also benefiting from this as a consumer (Jiang, 2017). The notion can be both used for heat and electrical demand. If the heat demand is satisfied from power-to-heat technologies than demand response refers to the electrical load.

Demand response includes load shedding (decreasing the peak load) and load shifting (distributing / shifting the load in time). Load shifting can be provided when consumers adjust the time of consumption according to certain signals or incentives under some limitations. Active demand response also known as short-term load shifting includes various different programmes such as dispatchable programs (direct load control, curtailable load, demand bidding) or price-based programmes (real-time pricing, time-of-use pricing, peak pricing). Load shedding reduces the electricity consumption for the specific hour without shifting in time. It can be provided by hybrid power-to-heat technologies which is capable of switching in between electricity and gas.

## 2.2 Literature Review

The literature review presents an overview of the modeling and non-modeling studies that address the flexibility that the coupling of power and heat sectors can provide. Scopus, Google Scholar, Jstore and IEEE are the databases that are used for the literature review. The key terms are used in combinations: "sector coupling models", "power-to-heat", "flexibility", "electricity and heat markets", "linking power and heat sectors".

The increasing sector coupling between power and heat causes an increase in the electricity load significantly. Some studies observe the effect of additional electric heat demand ((Patteeuw et al., 2015), (Boßmann & Staffell, 2015)). Boßmann and Staffell (2015) mentions change in load profiles has important implications such as the need for more flexibility in the power sector. An example provided is the case where France needed to import up to 9 GW electricity by pushing transfer capacities to its limits in a cold wave. This was due to the significant growth of electric heating systems and their contribution to peak load. If France's neighbors follow the same path of electrifying heat, the imports may not be available, resulting in power outages in Europe. This serves an important indication of the consequences for the other countries which plan to use large amounts of electric heating and makes it more important to understand the power sector implications of this coupling.

IRENA (2018) mentions sector coupling as one of the tools that provide power system flexibility. The new investments for electrification technologies can be attractive, especially if they would operate during hours of low electricity prices, storing the heat for later use. Two ways of providing flexibility from the heat demand side can be considered: A hybrid system which can switch in between electricity and gas or shifting the heat demand in time (pre-heat, postpone) according to low electricity prices or storage capabilities.

Existing sector coupling models include different detail levels with a different focus. Brown et al. (2018) compares the options of sector coupling by gradually adding the different sectors to the model. Electricity only, transport scenario and heat scenario are the main scenarios that are compared. Heat demand is grouped as low-density and high-density including central and individual technologies (gas boiler, resistive heater, heat pumps, solar thermal, CHP, thermal energy storage). Only low-temperature residential and service sector heat demand are considered. While the transport scenario has many sub-scenarios with flexibility options such as vehicle-to-grid, fuel-cells, battery electric vehicles and demand management; the Heating scenario demand is added without any extra flexibility options. The system costs and the use of technology options are compared for each scenario with and without extension of transmission.

A study with more focus on alternative heat decarbonization pathways is conducted in Strbac et al. (2018) for the UK. The optimization model IWES in Figure 2 is specific for the UK and it is used to optimize 29 system cost components which can be grouped as five capex and two opex costs. The model includes electricity, gas, hydrogen and heat systems, considering short-term operation decisions and long-term investment decisions at the local district and national/international level. In the study, cross-vector flexibility is already considered within IWES model in a way that costs are minimized in the whole energy system. The study focuses on three core heat decarbonization pathways including hydrogen, electric and hybrid scenarios. In the electric pathway scenario, it is observed that reducing the peak of heat demand by preheating or storage reduces the required generation capacity. The electric pathway consists of heat pumps and resistive heating to meet the heat demand while hybrid pathway includes the combination of electric heating systems and gas for the peak demand. Under different CO2 emission targets, the three alternative pathways are compared with respect to the cost performance, optimal capacity portfolios of the power system and infrastructure (storage, generation, electricity network). The effect of uncertainties related to the modeling assumptions and input parameters are also tested. The model assumes that 50% of the flexibility potential is available (e.g. only 50% of the demand can be shifted) and according to the analysis, this amount already captures the 70%-85% of the benefits. While the initial improvements in flexibility have more value, it is expected the marginal value of added flexibility decreases after a point. An important conclusion is that the household level flexibility which can be facilitated by thermal energy storage or application of preheating has the potential to significantly reduce the system capacity requirements and increase the utilization of renewables. The study briefly mentions these adjustments require market design for flexibility. Incentives for demand-side focused strategies will be especially important. In the electricity sector, there are already incentives to promote flexibility and these should be extended to link all energy-vectors.

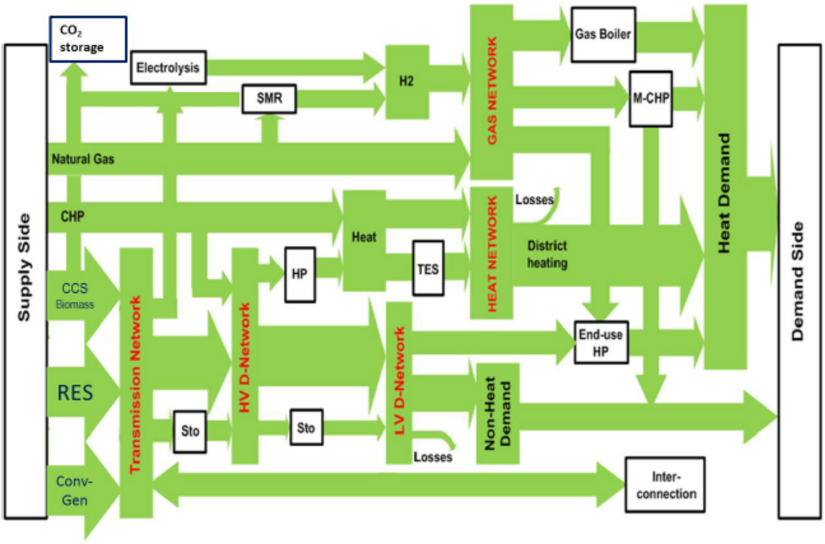



Figure 2: Interaction between electricity, heat and gas in IWES model (Strbac et al., 2018)

Schaber (2013) works on a model based study mainly focusing on the comparison of transmission grid extension and energy sector coupling as tools for VRE system integration for Germany. Energy system model generator URBS (Urban Research ToolBox Energy System) which is seen in Figure 3 is used for the analysis. It is an hourly power plant dispatch model minimizing the total system costs. The author investigates the three points: the sector-wise analysis of cost-optimal coupling technology mixes, the effects of coupling on the electricity market and comparison between building a European super grid. Different gas price scenarios are included and it is observed that fossil fuel options are still online to feed electric heaters and heat pumps to reduce gas consumption. The author uses a fixed heat demand profile to determine the dispatch of the local generation units without considering the potential to shift the heat demand.

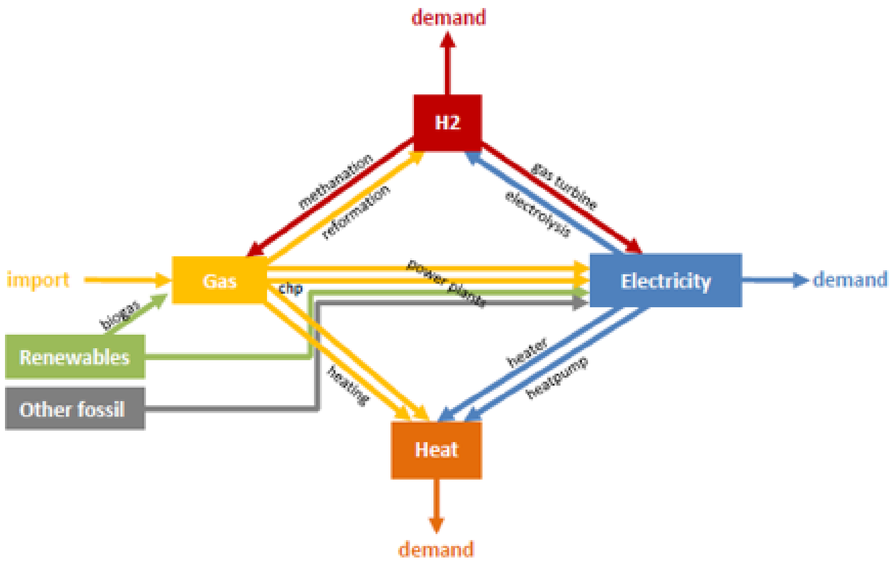



Figure 3: Energy sector coupling in URBS-D: commodities and technologies (Schaber, 2013)

This heat demand-side flexibility is explored in van Etten (2017) in a more local scope.

The focus of the study is investigating the demand response potential of space heating demand supplied by the heat pumps by taking into account the market prices and predefined technical and consumer flexibility constraints. The outputs are the amount of shifted load and operational savings. The effect of three different load profiles in combination with three different comfort levels and four seasons are observed. The amount of the shifted load is obtained for different comfort limits as well as the cost savings. Larger comfort limits result in higher amounts of flexibility and a larger range to shift load. However, comfort limits are usually sensitive and not subject to large changes. The study only focuses on heat pumps but does not provide results on the overall power system.

Patteeuw, Bruninx, and Delarue (2013) present a model that can be used to investigate the effects of active demand response by P2H technologies on the electric power system. The study is again local and conducted with 25 households that represent typical Belgium households. Electric heating systems cover the demand for space and water heating. The demand side response is integrated into a unit commitment model in the form of a mixed integer linear programming model. Electricity demand in the model consists of two parts: fixed and the electricity demand resulting from flexible electric heating systems. A factor that represents market penetration of electric heating systems is also included in the demand function. The flexible part of the demand is an optimization variable in the model and determined by the constraints of the model including thermal comfort constraints. Thermal energy storage (TES) within the building infrastructure is another option to enable up to 4 hours of shifting without affecting the indoor thermal comfort. A hot water storage tank in the model is included to shift the electric power demand of the heating systems in time.

Other studies focus on using the hybrid technology systems that can switch in between electricity and gas as a way of providing flexibility ((Ehrlich, Klamka, & Wolf, 2015), (Kirkerud, Trømborg, Bolkesjø, & Tveten, 2014)). This technological flexibility is a sensible transition path before phasing out natural gas completely. Combining electric boilers with existing gas boilers creates integrated hybrid systems (Joost de Wolff, de Ronde, & Boots, 2018). Kirkerud et al. (2014) use the Balmorel model in Figure 4 to observe the power market impacts of different scenarios for the long term development of the heat sector in Norway. Balmorel is an open partial equilibrium energy system model for simultaneous optimization of generation, transmission, and consumption of electricity and heat under the assumption of perfectly competitive markets (Wiese et al., 2018). The degree of the link between heat and power market is represented by the level of the capacity of the specific technologies. The system flexibility is provided by switching in between these alternative electric and fossil fuel technologies. Kirkerud, Bolkesjø, and Trømborg (2017) tries to quantify how increased use of flexible electricity in the district heating sector affects the VRE market value as a result of the changes in electricity prices. The flexibility is provided when heat pumps or electric boilers replace other boilers in periods when the VRE supply is high indicating low electricity prices. The model runs show that with high use of P2H significantly higher average electricity prices are observed indicating system gain of flexibility.

The modeling studies mentioned above do not particularly include cost components that are possible barriers against sector coupling and might alter the system-wide optimal results. Exclusion of these costs creates sub-optimal results for the end users even though it is optimal for the system. Policy reports such as Praetorius and Lenck (2017), NUFFEL (2018), Stephanos, Höhne, and Hauer (2018) reveal that there are distortions in the system due to significant differences between market prices and end-user prices. The most important barriers against the sector coupling are identified as follows:

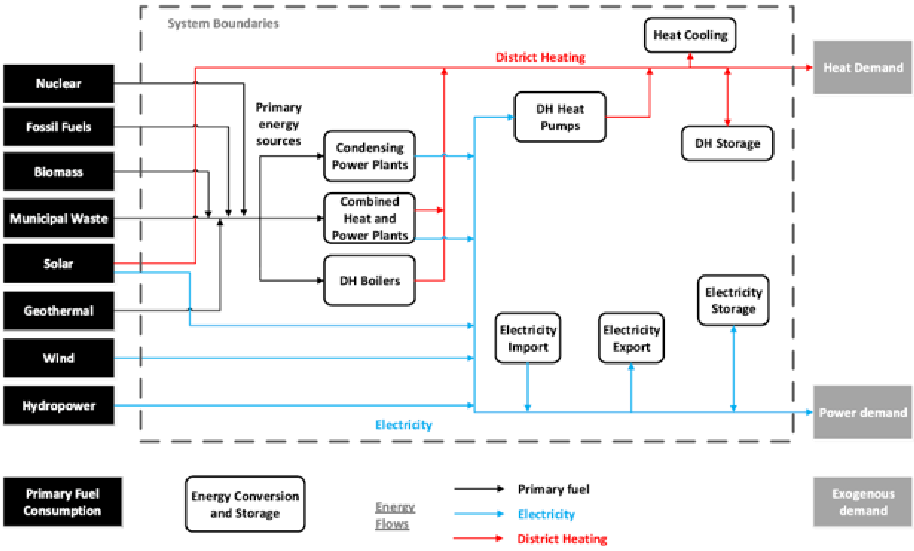



Figure 4: The core structure of the energy system model Balmorel (Wiese et al., 2018)

- Commodity prices: A significant part of the electricity and natural gas prices consist of taxes and levies. This politically determined part is relatively high for electricity and might prevent the market signals from reaching to end-users. Due to the additional cost components, low or negative prices are elevated making the electricity costs higher. As a result, it is most likely that end-users do not tend to change their behaviors to provide flexibility for the power system (e.g. using electricity during VRE abundance). In addition, as most of the times electricity prices are higher than the natural gas, all electric technologies are not attractive. Besides the price distortions due to taxes and levies, there is an unequal treatment of power and heat sectors in terms of charges related to fossil fuel usage. Power sector bears a high burden of charges from CO2 emissions. This creates a distortion between the competition of low-emission technologies that use electricity and high-emission technologies that use fossil fuels (Praetorius & Lenck, 2017).

- Investment costs: High capital costs for household heat pumps is one of the important barriers. Current policies are focused on increasing the demand for heat pumps by providing investment subsidies for P2H technologies. For industry as the required heat capacity is higher, the technology and installation becomes more expensive. Many of the technologies for industry are not yet competitive both regarding the costs and performance.

- Network costs: For industrial end-consumers, network costs are one of the most important barriers for large scale deployment of P2H technologies in industry. A switch to P2H means that the connection capacity needs to increase and as a result transport tariffs (network costs) that are paid by industry increases. The tariff structure is based on the maximum capacity used by a company. This works against the electrification of the industry.

Based on the policy reports, this research focuses on the distortions created by taxes and levies. According to ECN (2017), the electricity price will continue to increase up to 2030, thus intervention related to electricity and gas price structures might be required for a viable business case for P2H technologies.

## 2.3 Knowledge Gap and Research Questions

As a result of the literature review, it is identified that there are relatively fewer studies focusing on the coupling of heat and power sectors as a flexibility option and its implications on the power sector. Studies related to flexibility on the heat side usually focus on heat pumps ((Hedegaard & Münster, 2013); (Bach et al., 2016); (Hedegaard & Balyk, 2013)). Demand response in these studies are only studied in local scope with higher resolution and the effects on the overall power system (grid and market) are not observed.

The heat demand flexibility and power sector flexibility options are either analyzed separately or the studies with coupled models do not reflect on the implications if in practice the flexibility potential is not fully realised due to regulatory barriers and market design. Based on current policy and market development, P2H is not expected to become economically viable, regardless of the operating regime without additional instruments (Joost de Wolff et al., 2018). The capacity of variable renewables keep increasing every year so regulations should aim at releasing the flexibility potential both in terms of demand and technology side in the heat market (Kirkerud et al., 2017).

In conclusion, there are few studies investigating power and heat market integration in a broader power market perspective combined with an analysis of the possible barriers. The modeling studies do not combine their results with an analysis of how much of the optimal potential can be achieved in practice and what kind of regulations and incentives are needed to unlock the flexibility potential. In addition, comparison of the power systems implications with the end-user implications provides more insights of the potential of the flexibility. End-users perspective is also needed to understand the barriers thoroughly. Modeling studies neglect the extra costs for end-users and the conflicting implications for power systems and end-users. It is observed that many modeling studies focus on Germany and Nordic countries, whereas there are no specific modeling studies for the Netherlands. As a result of the literature study and the identified literature gap, the main research question is as follows:

***"What are the flexibility implications of the increasing sector coupling between heat and power sectors?"***

*1) What are the effects of the heat demand flexibility on power sector and end-users?*

The flexibility of the heat demand changes the electrical load curve if power-to-heat technologies are used for heating. This flexibility can be either provided by shifting the heat demand or power-to-heat demand in time or switching in between gas and electricity by the use of hybrid technologies. The first option is viable for households, while the second one is for industry. Shifting the heat demand implies pre-heating, postponing the heating or using thermal storage. The maximum hours that the thermal load can be shifted depends on different factors such as the outdoor and indoor temperature, the comfort limits, the electricity and gas prices and technical parameters of the thermal storage. The effects of this flexibility on the power system (system cost savings) and the value of this flexibility for end-users will be determined by this question.

*2) What are the implications if the flexibility potential is not fully unlocked?*

The flexibility potential is usually only available up to a certain extent which means only a certain percentage of the power-to-heat load is flexible and can be shifted in time or can be satisfied by both sources electricity and natural gas. This is due to the lack of technologies such as thermal energy storage, hybrid technologies or incentives that would promote demand response for end-users. In practice, it might not be possible to unlock 100% of the optimal potential or after a certain percentage of demand flexibility is obtained the marginal benefits might start to decrease. This analysis reveals how much it is worth to unlock the flexibility potential and up to which point. The necessary regulations and changes can be developed to reach that point of flexibility.

*3) What are the effects of price distortions as a barrier against sector coupling ?*

The first question focuses on identifying the potential of the flexibility that the coupling will bring and the second question investigates what are the consequences if this potential is not fully unlocked. The reasons that the full potential is not unlocked is the policy barriers. This question focuses on one of the important policy barriers, the electricity taxes and levies which are up to 75-80 % of the price components for end-users while other energy carriers such as natural gas are charged much less. Thus electricity is much more expensive in comparison to other energy carriers and this is a barrier against its usage in other sectors. The taxes and levies create price distortions and sub-optimal results for end-users. The level of this sub-optimality will be observed together with the effect of changing gas prices.

## 2.4 Research Objective

The research objective is to explore the flexibility implications of the increasing sector coupling between heat and power by using a quantitative power systems model. This method will be supported with qualitative methods such as expert interviews and literature review.

Modeling is widely used in the energy sector to analyze different policies, regulations or challenges. Power systems models focus only on the electrical power system and do not consider the rest of the energy system. On the other hand, energy system models consist of the full energy system and the power system is driven by the combined behavior of all the other sectors. In power system models, the resolution is higher since the focus is only on electricity generation whereas energy system models usually use "time slices" at a lower resolution (Deane, Chiodi, Gargiulo, & Ó Gallachóir, 2012). A second classification of the models is based on temporal scale. Pina, Silva, and Ferrão (2013) and Haller (2012) classify them as models focusing on the long term development, models focusing on the short term, operational system behavior and those in between, the "hybrid" models. Studies that use the last category gain importance and are widely used in the literature. This is because the increasing share of renewable energy sources and the uncertainty of their production requires the modeling of the operational details as well (Schaber, 2013). Most of the energy system models are based on optimization with different objectives of minimizing/maximizing the total costs or welfare under a set of boundary conditions. Short term models focus more on the operational side of one technology (Papadaskalopoulos and Strbac (2013); Finck, Li, Kramer, and Zeiler (2018)) while hybrid ones are used for systems analysis ((Schaber, 2013), (Brown et al., 2018), (Sijm et al., 2017)).

In this research, a power system model, COMPETES (Competitive Market Power in Electricity Transmission and Energy Simulator) is used which is a power optimization model that minimizes the total power system costs of the European power market under the technical constraints of the generation units, the transmission constraints between European countries including transmission capacity and the generation capacity expansion modules for conventional technologies (Sijm et al., 2017). The model includes a wide range of technologies, specifically detailed out with the unit by unit generation in the Netherlands. For the other countries, the units using the same technology and having similar characteristics (i.e., age, efficiencies, technical constraints, etc.) are aggregated. Its particular focus on the Netherlands together with other EU countries, high spatial and temporal resolution to capture the interconnections in the grid and power trade relationships across all EU28+ countries makes it a good choice to observe power sector implications of heat sector flexibility. A drawback of COMPETES is currently it only includes a hybrid boiler for industrial demand and the heat pump for households. The inclusion of domestic flexible options such as demand response and energy storage by means of P2H, P2G or P2A are limited.

The limitations of COMPETES model are the strong points of an energy system model (e.g. OPERA (Option Portfolio for Emissions Reduction Assessment) which optimizes all sectors in the Dutch energy system as a whole. However, in a model which includes the full energy system, the power sector is less detailed compared to COMPETES. Since this study will focus on the heat and power sectors, COMPETES is an adequate and suitable choice to observe the implications on the very detailed power side. Details of the COMPETES model are explained in Section 4.1.

## 2.5 Research Methodology

**Phase A: Heat Sector Overview**

Prior to the scenario analysis by using the power systems model COMPETES, a research is conducted to gain insights on the evolution of the heat sector in the future in terms of demand and technology in the Netherlands. This part presents an overview of the heat sector for the industry and households. The activities to be performed in this section are as follows:

- Heat demand for the Netherlands is identified by sector in terms of size and structure for the years 2015, 2030 and 2050. The demand for households consists of water and space heating with seasonality effects, while industrial heat demand consists of low and high-temperature parts. The profiles for these demand categories obtained to be used in the model.
- The factors that affect the load shifting for these demand profiles are investigated to be later used in the scenario formation.
- The technological options to meet this heat demand in a carbon-free way are identified. The possible supply options consist of full electric technologies driven by renewable electricity or hybrid technologies which still use fossil fuels such as natural gas.

This part of the research presents the real system description and how the interaction between heat and power sectors work. This description is used to explain the parts of the real system that are not included or simplified in the COMPETES model. This reveals the limitations of the model and provides a better background to interpret the scenario analysis. The research methods and the outputs of the phase is given in Table 1.

Table 1: Description of Research Phase A.

| | |
|---|---|
| Research methods for this phase: | - Literature review<br>- Review of scenario studies<br>- Expert interviews |
| Output of this phase: | - Expected heat demand per sector 2030 and 2050<br>- Expected power-to-heat demand per sector for 2030 and 2050<br>- Factors that affect the flexibility of the demand profiles<br>- Power-to-heat technology options<br>- System description of the sector coupling between power and heat |

**Phase B: Modeling and Analysis**

In this phase of the research, firstly the description of the COMPETES model is provided and compared to the real system description. The parts that are simplified or not included in the model are identified and the limitations of the model are discussed. The low and high-temperature heat load profiles to be included in COMPETES model are determined based on the data sources and necessary assumptions. The capabilities of the model and the structure of the data are the important factors in the scenario design phase. Scenario and sensitivity variables are chosen based on the literature review and the research objectives. The analysis to be performed with the scenario and sensitivity runs are described more in details. The initially determined scenarios are as follows:

- Scenario 0: No link between heat and power
- Scenario 1: Fixed P2H demand is added
- Scenario 2: Flexible P2H demand is added.

The research method, required data and output of Phase B is explained in Table 2.

Table 2: Description of Research Phase B

| | |
|---|---|
| Research methods for this phase: | - Literature Review<br>- Scenario Design<br>- Use of the power systems model COMPETES<br>- Sensitivity Analysis<br>- Data Analysis |
| Required data for this phase: | - Annual heat demand<br>- Power-to-heat demand<br>(Heat load profiles of the Netherlands for industry and households)<br>- Maximum hours to shift the load under different<br>assumptions (Comfort limits, Information<br>about thermal storage)<br>- Electricity and gas prices and taxes |
| Outputs of this phase: | Answers to RQ1, RQ2, and RQ3 |

#### Phase C: Discussion of the Results and Policy Implications

The results of the scenario analysis have different implications on the power sector and end-users: industry and households. The outputs from the COMPETES model reveal the impacts on power sector. However, the implications for end-users are also an integrated part of the analysis in order to discuss the barriers and required policies and incentives for sector coupling. In this section the analysis from the previous section will be interpreted in terms of the policy implications. Existing barriers and the possible solutions to overcome these will be discussed by using the results from the previous section. The methods, required data and outputs of this phase is presented in Table 3.

Table 3: Description of Research Phase C.

| | |
|---|---|
| Research methods for this phase: | - Literature Review<br>- Interpretation of the results from previous phase |
| Required data for this phase: | -Results from the previous phase |
| Outputs of this phase: | - Barriers against sector coupling<br>- Possible policy instruments |

Below Figure 5 is the research flow diagram including the above mentioned phases.

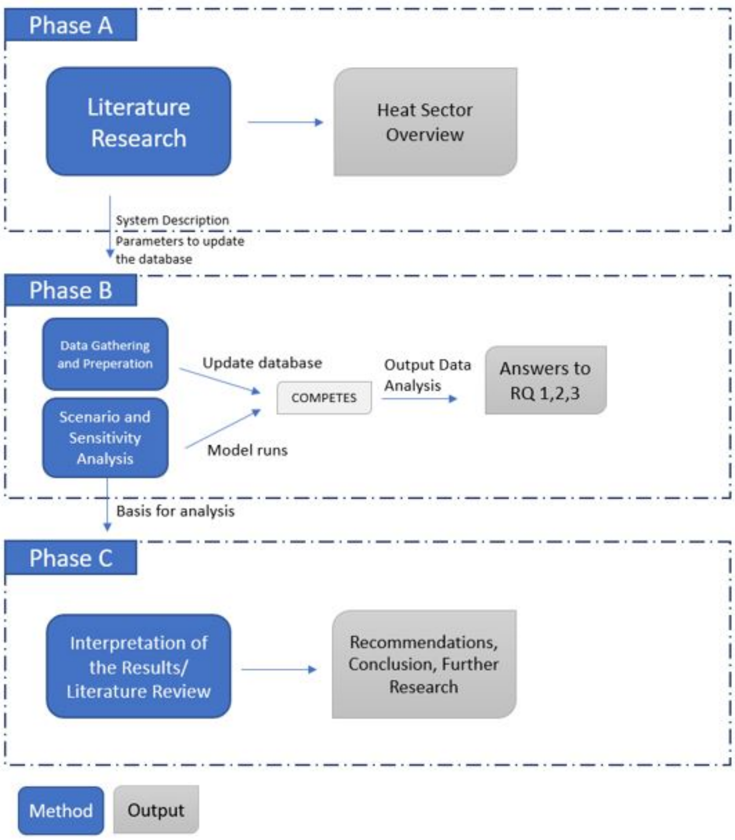



Figure 5: The Research Flow Diagram

# 3 The Heat Sector in Netherlands

In this section, a brief description of the Dutch heat sector and the link between the power and heat sectors is presented to provide a better understanding of the research questions and the restrictions of the power systems model COMPETES. The limitations of the model and the parts of the system description that are excluded are explained and justified by using this section. The design of the necessary scenario runs to address the research questions are also based on the real system description. This section also provides the necessary insights and parameters to update the existing database.

The section covers both the end-use sectors built-environment and industry. Heat demand in the agriculture sector is not in the scope of the study. Firstly the evolution of the heat demand in terms of the size and structure for the years 2015, 2030 and 2050 is presented. Scenario studies are reviewed to gain insights about the expectations on the share of the power-to-heat technologies, their potential and the share of the demand that is satisfied by these technologies. Secondly, technology options are briefly introduced and their usage in the heat sector is explained. As each technology option has their own advantage and disadvantage, the important criteria to evaluate them are the flexibility they can provide and their potential or market penetration in the future which itself depends on the other factors such as costs and regulations. Later, the flexibility potential of the heat demand is examined with the options of storage and demand response. Lastly, the electricity and natural gas price structure is introduced and some background information is provided for the later analysis. Information presented here will be used for the scenario designs to answer the research questions.

Unlike electricity or the production of fuels where there are clearly specialized sectors, heat production is an individual matter depending on the preference of the consumer and the infrastructural availability. Before going into any system description it is important to understand the nature of the heat. Heat is a cross-sectoral and also cross-infrastructural commodity. It can be produced by different energy carriers and the conversion between them. One important restriction related to the provision of heat is that it is dependent on the temperature. This implies that the temperature of the heat source and the heat demand must match each other. Three main energy carriers are used to provide heat: Natural gas, heat (in the form of hot water or steam) and electricity (Oei, 2016). Three different networks for heat can be identified based on these three main energy carriers:

- Heat Networks

  Big heat networks are defined as the heat networks that deliver more than 150 TJ of heat to the consumers. Small heat networks (e.g. district heating) are defined as heat networks that supply heat less than 150 TJ per year. (Menkveld et al., 2017)

- Natural Gas Heating System

  Natural gas is the main energy carrier that is used for heating in the Netherlands. Almost all of the houses are connected to a natural gas grid due to the abundant resources which were found in the North Sea and in province of Groningen. Within time, alternatives for the natural gas has emerged mainly due to the concerns related to CO2 reduction. These alternatives include district heating, wood-fired heating, solar heating, power-to-heat as well as heat savings measures. In countries like the Netherlands, these other options still play a small role due to certain barriers. Natural gas is carried by the natural gas grid.

- Electric Heating System

  The main options for electric heating are heat pumps and electric boilers. The power grid (transmission and distribution grids) is used to access the electricity.

The supply options to satisfy the heat demand are identified as geothermal, solar thermal, bio-energy, fossil sources, residual heat and power-to-heat. Heat is carried to end-users built-environment, industry, and agriculture.

## 3.1 The Built Environment

The built environment consists of the residential (households) and non-residential utility buildings, in other words, the service sector. The non-residential part includes a wide variety of activities and types of buildings such as offices, shops, schools, healthcare facilities, sports halls, hotels, restaurants, swimming pools, theaters and museums, warehouses, data centers, garages.

### 3.1.1 Heat Demand and Technology Options

Heat demand in the built environment is used for three purposes: hot water, space heating, and cooking. For space heating, the demand varies on an hourly basis with the varying consumption pattern of the consumers. In addition to daily variation, there is seasonal variation due to weather changes between seasons. The physical factors that affect the space heating demand can be listed as weather conditions, building and construction structure and materials (e.g. insulation of the building) and indoor temperature. Demand for hot water varies within the year as well. In summer, the demand is almost half of wintertime. (Ma et al., 2014). While the demand for space heating continues to decrease due to efficiency measures, the hot-water demand remains constant and its share increase in the total heat demand for the built environment (Nussbaumer & Thalmann, 2014). Heat demand affects the electricity consumption of a household if power-to-heat technologies are used. Electricity consumption for households is expected to decrease overall due to new electric appliances that are more efficient than before. Lighting and other appliances use less electricity under European Ecodesign requirements. As a result, the electricity consumption of households is expected to fall until 2025. After this year, the total electricity demand is expected to rise again due to the increasing number of electric vehicles, electrification of heating and the number of households (ECN, 2017).

Before considering the sustainable heat supply options, the first step is reducing the heat demand. This can be achieved by better insulation or more efficient technologies. Energy Netherlands, Netherlands Grid, the Ministries of Economic Affairs and the Interior and Kingdom Relations signed an agreement to apply measures of energy savings in the built environment for 10 PJ compared to 2015 levels. In the long term, the idea is to create a market for energy efficiency (ECN, 2017).

After taking the necessary measures to reduce the heat demand, the remaining amount is going to be satisfied from the increasing share of renewable heating sources. The sustainable heat supply options for the built-environment are divided into two categories as centralized and decentralized technologies. In centralized systems heat is carried by heat networks while there is no need for a network in decentralized system. Central biomass plants, residual heat, geothermal, heat buffers, power-to-heat technologies (air heat pumps, ground heat pumps), solar boilers, ground energy, biomass boilers are the technology options for the built environment. These technology options are briefly explained below:

- Biomass Energy:

  Sources for biomass consist of a wide range of options including wood purchased, materials from the own garden of people or other type of pruning wastes. In 2015, the total energy satisfied from biomass for households is 18 PJ. The part that was used for heating is uncertain since the measures are based on surveys and the sources that can be used varies a lot. Usually, wood stoves and fireplaces are used to burn the bio-sources (ECN, 2017).

- Solar-thermal Energy:

  Solar-thermal energy is one of the decentralized forms for heating which provides only a very small amount of the total heat energy. Usage of solar thermal heating increased from 0.4 PJ in 2000 to 0.9 PJ in 2015 (ECN, 2017). Solar boilers are used to provide heating.

- Geothermal Energy:

  Geothermal energy is one of the renewable heating options that is especially promising for district heating. By extracting heat or cold from the subsurface or from the deeper layers of the ground, the heating and cooling needs of the buildings can be satisfied. The first projects are currently in development and only after 2024, a major contribution from geothermal energy is expected via heat networks. It is stated that one of the factors that slow down the production process is the research and preparation that needs to be done to determine the potential and the location before actively using the resource. Technological developments and research are needed into the ground before the funding for the technology are guaranteed (ECN, 2017).

- Natural gas:

  The majority of the houses are heated by high-efficiency natural gas boilers. The boiler heats the water by burning the gas and the pump at the boiler moves the heated water to the delivery system. The cooled water comes back again to the boiler and it is re-heated (Schepers, Meyer, & Burger, 2018). One of the promising options is the replacement of natural gas by green gas for space heating and hot water. Advantages are that no additional procedures are required for the change from natural gas to green gas. It is a proven and inexpensive technique. However, green gas availability is limited and uncertain (Naber et al., 2016).

- Green Gas and Renewable Gas:

  Green gas and renewable gas are alternative sustainable heating options for natural gas. Renewable gas is hydrogen mixtures and is more expensive than fossil-based natural gas since there are also additional costs and challenges associated with its production, transportation, and consumption. Green gas (biomethane, biogas upgraded to natural gas quality) is also more expensive than natural gas but can be injected directly into the gas grid. It can be used in gas boilers, hybrid heat pumps and back up boilers in heat networks. To replace natural gas, a considerable amount of green gas is required (Naber et al., 2016).

- Residual heat from industry:

  Remaining heat from industrial processes can be used as a sustainable heat source for heating households and buildings. Residual heat from the Rotterdam harbor is on the agenda of the Province of South Holland to form a large heat network together with the residual heat from waste incinerators, solar heating, geothermal projects, and biomass-fired CHPs. The aim is to create a large connected heat infrastructure with a wide range of heat sources as a reliable and open system (van Ende, 2018).

The above summarized technology options are alternatives and competitors of the power-to-heat technologies. The assumptions related to the development of these technologies play an important role in determining the market share of power-to-heat technologies in 2030 and 2050 scenarios.

Power-to-heat technologies can be also differentiated as decentralized and centralized technologies. In a centralized system, the electricity is converted into heat at a remote location from the point of the demand. Heat networks are used to transport. In a decentralized system, the power-to-heat options are used at a point very close to the location of the heat demand. In some systems, the distinction might not be very clear since the heat demand can be jointly provided for households in a local neighborhood via a heating network. In this case, the heat source would be again close to households but also provided centrally in a local scope.

A second differentiation is between monovalent/full electric and hybrid technologies. A full electric energy system consists of a heat demand which is only satisfied by electric technologies such as heat pumps during all hours of a year. The energy source is always electricity. In a bivalent/ hybrid system, there might be two different heating options with different energy carriers. An example can be a heat pump backed up by a (fossil-fueled) boiler. (Bloess et al., 2018) The classification of the technologies to convert electricity to heat for the built environment is seen in Figure 6.

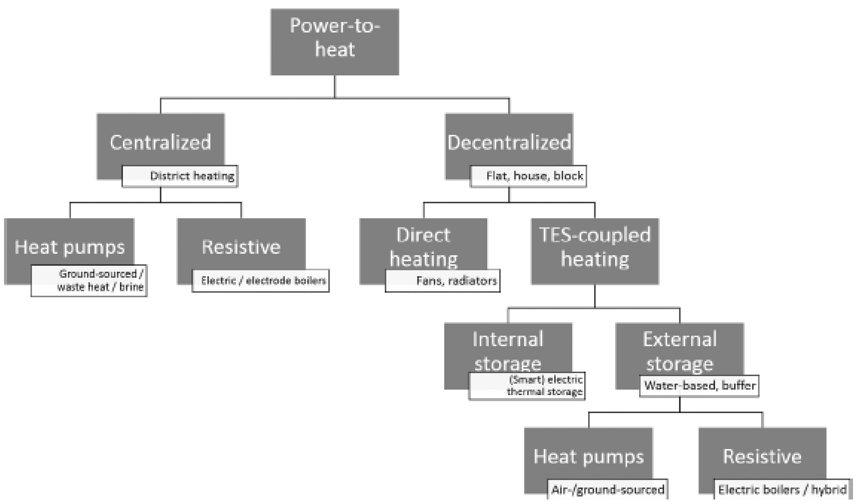



Figure 6: Power-to-heat options for the built environment (Bloess et al., 2018)

Figure 7 summarizes the centralized and decentralized energy infrastructure in connection with the electricity network and heat network. Power-to-heat is an option in both centralized and decentralized systems mostly with the technologies heat pumps and electric boilers as well as hybrid technology. Centralized systems use electricity from the grid by using large scale heat pumps or electric boilers. Electricity is carried via the transmission and distribution grid to the centralized P2H technology. Electricity is then converted into heat and the heat is transported to residential customers via the heat network. Decentralized power-to-heat options do not use heating networks. In addition to the figure, electricity from the distribution grid can be used for decentralized technologies if there are no residential PV and storage.

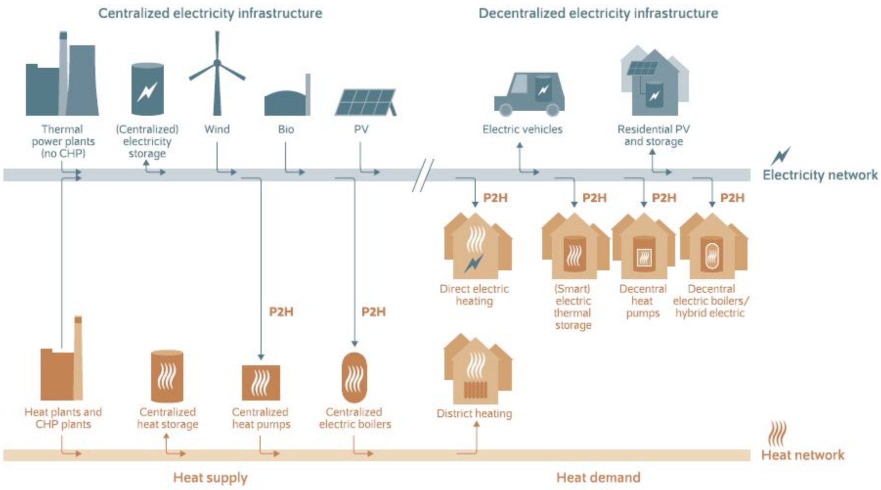



Figure 7: Interconnections between power and heat (Bloess et al., 2018)

Below the power-to-heat technologies are briefly explained:

- Electric Boilers:

  Electric boilers can be used for household heating as centralized or decentralized with or without storage. They work under the same principle as gas boilers. The only difference is they use electricity to heat water instead of gas. They can either use resistive heating to heat water or can use electric current passing directly through the water as an electrode boiler. They can be an ideal option for households that have no access to the main gas supply or that have restrictions on gas boiler installations (Bloess et al., 2018).

- Heat Pumps:

  Heat energy normally is transferred from warmer places to colder places but a heat pump can actually reverse this process. It absorbs heat from a cold space and releases it to a warmer place. This requires some amount of external energy such as electricity (Bloess et al., 2018).

  Heat pumps are more efficient than resistance heaters as less energy is required than the released heat. Most of the energy comes from an external energy source and some part from electricity. In electrically powered heat pumps, the heat produced can be three or four times larger than the electricity needed. This is the coefficient of performance (COP) as 3 or 4 in contrary to a conventional electric heater with a COP 1 (all heat is produced from the input electrical energy).

Heat pumps can be used centralized or decentralized with or without thermal storage. Centralized systems (e.g. in a district heating) can consist of large scale heat pumps which use geothermal energy, waste heat, sewage water, ambient water (sea, lake, river). Smaller scale of heat pumps are air or ground sourced. A heat pump uses energy from the air or soil which is upgraded with electricity. An air heat pump has an outdoor unit and absorbs energy from the air. The ground-source heat pumps use underground heat exchangers as heat source and water as the carrier. Below the ground level temperature is relatively constant throughout the year and the earth can absorb and provide a large amount of heat. The working principle is the same for both types but in ground sourced heat pumps the heat exchange is underground via water pumped in pipes. Ground source heat pumps do not require fan or defrosting systems and can be accommodated inside.

To be utilized in the best way heat pumps require substantial investments especially to better isolate the built-environment. Advantages of the technology are its high efficiency and possibility of cooling. However, reinforcement for the electrical connection might be needed as well as good insulation. Air pumps might produce noise and there is not always enough space for the soil ones. Since it is an all-electric technology it will have impacts on transmission and distribution lines (Schepers et al., 2018).

Usage of heat pumps both in households and the service sector is increasing. For households, heat pumps were used for less than 1PJ (0.28 TWg) of the heat demand in 2015. This number is expected to increase at least 14 PJ (3.89 TWh) by 2030. Heat pumps are increasingly used in the service sector too. The growth mainly took place in the new buildings. In 2015 the usage was 4.5 PJ (1.25 TWh) and it is expected to increase to 12 PJ (3.33 TWh) in 2030 (ECN, 2017).

Heat pumps can provide cross-vectoral flexibility (between heat and power sectors) and facilitate demand response.

- Hybrid Variations:

A hybrid heat pump is the combination of an electric heat pump with a high-efficiency boiler which uses natural gas or green gas. An electric heat pump can provide almost half of the heat demand for space heating or domestic hot water due to the efficiency limitations. Below certain temperatures, the efficiency of the heat pump is lower and the boiler is used instead. Approximately one-fifth of the time, the boiler is used if the heat pump is not enough to satisfy the heat demand. This might happen if the weather is colder than usual or a lot of hot water is needed. The switching mostly takes place according to the heat requirement and the temperature instead of the power supply and prices. Households are not exposed to the changes in the prices as the industry sector. Gas portion supplies the peaks. The change of the energy carrier requires no additional installation. There is no need for grid reinforcement since the peak load is absorbed by the high-efficiency boiler (Schepers et al., 2018).

Hybrid technologies are capable of providing significant flexibility for both households and power grid. In combination with a buffer, hybrid heat pumps can also respond to the variation in renewable energy sources. Electricity would be used when renewable energy is abundant and otherwise green gas will be used. The efficiency of a hybrid heat pump is also highest in well-insulated homes. In poorly insulated houses the boiler has to take over more often and the overall efficiency goes down. This ensures that to be cost-effective an existing house invests in insulation in addition to using hybrid heat pumps. Hybrid heat pumps have the potential to be the transition technology. Less gas is needed compared to a natural gas boiler and the infrastructure does not have to be adjusted (Naber et al., 2016).

However, it is also stated that currently there is not yet a positive business case for the hybrid heat pumps to be used as a replacement for gas boilers. Natural gas in the Netherlands is cheaper compared to electricity. With the replacement of some part of the natural gas consumption with electricity, no financial savings are achieved. Currently to encourage the purchase of the hybrid heat pumps a subsidy of 1000 € to 1500 € is available in the Netherlands. Using hybrid heat pumps is going to be more beneficial as the natural gas prices go up for example with a tax increase or higher CO2 price (Naber et al., 2016).

### 3.1.2 Scenario Studies

Below some scenario studies are examined to identify the change of the household heat demand and the potential of the power-to-heat technologies to satisfy that demand. Studies of National Energy Outlook, Monitoring Heat of ECN, CE Delft, Berenschot (includes a review of the studies: RLI, Gasunie, Berenschot Elektronen, Berenschot Moleculen, KIVI, NvdT) and Ecofys are reviewed.

Table 4: Heat Demand in Built Environment by Energy Carrier

| Energy Carrier (PJ) | 2015 | 2030 | 2050 |
|---|---|---|---|
| (Natural) Gas | (289 + 127) | (215 + 90) | Green / Renewable Gas: [80 - 200] |
| Heat | 16 | [18 - 28] | [30 - 115] |
| Electricity | (7.1 + 1.6) | [25 - 33.1] | [28 - 144] |
| Total | 440.7 | [348 - 370] | [200 - 460] [1] |

Table 4 presents the amount of energy use in the built environment for years 2015, 2030 and 2050 according to different energy carriers. All the numbers are for the whole built-environment. In 2050, it is assumed that no natural gas is used and only green or renewable gas is used. It can be seen that in 2015, total electric used for heating is 7.1 PJ for households. 0.7 PJ was from heat pumps, 6.2 PJ was from heating boilers, 0.2 PJ was electric radiators and underfloor heating. For 2030, in households 14 PJ increase is expected compared to 2015 amount which results in 21.1 PJ electricity demand. For service sector only heat pumps are considered as available technology and contribute relatively small to the P2H demand. (Menkveld et al., 2017). In 2015, P2H demand in service sector is 1.6 PJ and expected to increase to between 3.9 and 12 PJ in 2030. The numbers are obtained from different sources and the detailed explanation can be found in Appendix A.

The total heat demand and electricity usage range for 2030 is relatively small compared to 2050 range. This is because only the two most recent studies are used as references for

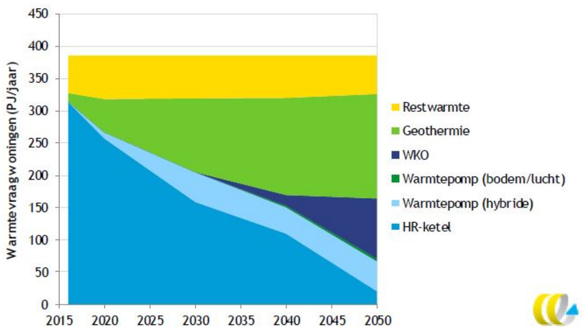
[1] The first number in parenthesis () is for households and the second number is for the non residential buildings. The numbers inside the square bracket [] represents a range for the heat demand.

2030: National Energy Outlook 2017, Climate Agreement Report. For 2050, there are more uncertainties related to green gas availability and difference in between scenarios. This uncertainty results in a larger range for the total heat demand. To get a better understanding of the uncertainty more studies are used as reference: CE Delft (2016), Barenschot (2018), Ecofys, NvdT, KIVI.

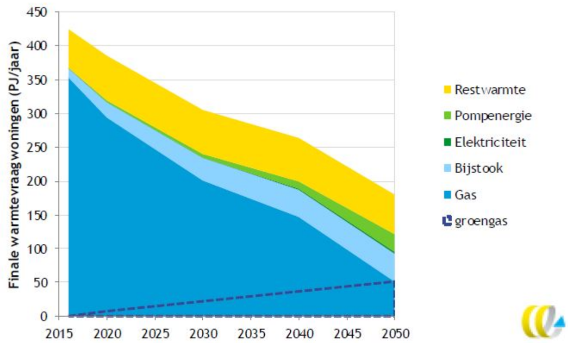
According to the National Energy Outlook, especially there is an expectation for an increase in the number of heat pumps until 2035 under proposed policy implications. Abolishing the obligation of the connection to a natural gas grid in the new homes will remove one barrier in front of the electric heating. In 2030 scenarios, it is seen that natural gas is still the dominant source. There is also a decrease in natural gas usage in the service sector with extra policy measures. This decrease is due to energy savings, demolition, energy-efficient new construction, less need for heating due to warming of climate, heat pumps replacing the gas-fired boilers.

The National Energy Outlook does not cover the case for 2050 but there are other scenario studies with different underlying assumptions which try to identify the final energy demand of the built environment in 2050 by means of various technologies. There are differences between scenarios in the percentage of the electrification based on the underlying assumptions. In the scenarios that anticipate a higher penetration of heat pumps (all-electric), final heat demand is lower compared to cases where gas or heat is the dominant energy carrier. One reason is that those scenarios need to assume a high level of insulation since that is a condition for heat pumps to work efficiently. Secondly, there are efficiency gains since heat pumps have a high coefficient of performance that enables them to satisfy the same heat demand with less electric energy. Ambient heat is not included in the energy statistics.

In the reviewed scenarios the percentage of the electrification depends on the competitiveness of alternative technologies (biogas, residual heat), price of green gas, electricity prices, insulation level and economic and demographic development. The share of the green gas in 2050 depends on the domestic availability and its price. Geothermal and residual heat are assumed to be available in the heat network for some 2050 scenarios. Use of hydrogen is controversial among scenarios and excluded most of the time. "A climate neutral heat for the built environment" study of CE Delft (Naber et al., 2016) presents a broad overview of scenarios and results on the potential of P2H and hybrid technologies for households for 2050. The CEGOIA model is used for the study. The model minimizes the cost of different heat supplies for 12 000 neighborhood in the Netherlands. For this specific study, the hybrid heat pump technology is also added to the CEGOIA model. Savings are also cost optimally determined by the model as a technology option. The assumptions that were made in this study and the results of different scenarios can be found in Appendix B. According to this study, Figure 8 shows the expected transition pathway including the options residual heat, geothermal, thermal storage, hybrid and electric heat pumps and gas boilers. All-electric options start to become attractive around 2030 when the cost of the technology becomes lower and natural gas usage is more restricted.




(a) Transition pathway of scenarios




(b) Transition pathway energy carriers

Figure 8: Transition pathway (Naber et al., 2016)

Market penetration rates and technology mixes from the FlexNet scenario studies are given below in Table 5. Penetration HP Technology is the percent of households that use heat pump technologies. Other percentages represent the share of the technology among the households that already have the heat pump technology, depending on the insulation level.

Table 5: FlexNet Study Heat Pumps Market Penetration (Sijm et al., 2017)

| Insulation Level | Heat Pump Technology | [2]R2015 | R2030 | A2030 | R2050 |
|---|---|---|---|---|---|
| | Penetration HP Technology | 2.1% | 7.9% | 20.0% | 69.0% |
| Middle | Air | 0 % | 0 % | 10.5 % | 0 % |
| | Ground | 0 % | 0 % | 4.5 % | 0 % |
| | Hybid | 0 % | 0 % | 15.5 % | 0 % |
| High | Air | 70 % | 66.5 % | 45.5 % | 63 % |
| | Ground | 30 % | 28.5 % | 19.5 % | 27 % |
| | Hybrid | 0 % | 5 % | 5 % | 10 % |

[2]R represents the reference scenario while A represents the alternative scenario.

## 3.2 Industry

This section presents an overview of the heat demand and technologies for the end-use sector industry. Also the existing scenario studies are examined to gain insights on the industrial heat demand and developing technology options for the years 2030 and 2050.

Industrial production consists of chemicals, refining, food and processing, basic metals, other metals, construction materials (cement), pulp and paper production, textile and other industries. Energy use in the industry comes from the low, medium, high-temperature heat demand, electricity consumption, and transportation (Roelofsen, de Pee, Speelman, & Witteveen, 2017). The heat demand is in the scope of this research.

### 3.2.1 Heat Demand and Technology Options

Energy demand in the industry is mostly about heat for the processes. In 2015, the industry used 840 PJ (233 TWh) of total energy and 567 PJ (157.5 TWh) of it was heat demand according to CBS data. Table 9 shows the distribution of the heat demand based on the temperature. The energy demand per temperature level is estimated based on the ECN internal sources, EU Joint Research Center and Davidse Consultancy. Below the functions of the heat demand based on temperature are briefly explained.

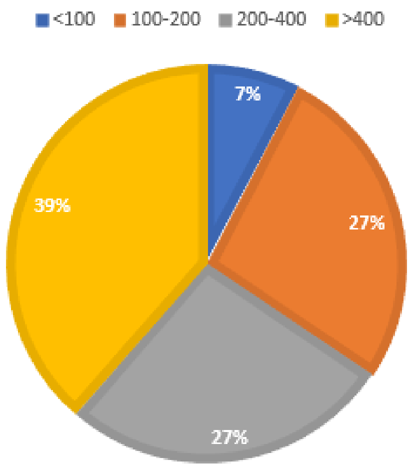



Figure 9: Heat Demand of Industry by Temperature Level (CBS, 2015)

- High-temperature heat production:

  400 °C and above is considered as high temperature for industrial applications. This part involves industrial processes such as steam cracking processes or steel production. This part is generally produced by fossil fuel-powered furnaces. Biobased or electric furnaces can be the future technologies (Roelofsen et al., 2017).

- Medium temperature heat production:

  100-400 °C is considered as medium temperature for industrial applications. This part of the heat demand is used for applications of evaporation and distillation during chemical production, food processing, and driving turbines. This part is produced by burning natural gas in boilers or co-generation units. Dual natural gas/ electric boiler, biogas boiler, hydrogen boiler, cogeneration, natural-gas boiler are the technologies that can be used (Roelofsen et al., 2017).

- Low-temperature heat production:

  Below 100 °C is considered as low temperature for industrial applications. This part of the heat demand is mostly used for drying and distillation. Sometimes it is not produced directly but the residual heat that is left over from medium or high-temperature processes are used. Gas-boiler, electric-boiler, electric heat pump can be used for this part of the heat demand (Roelofsen et al., 2017).

The supply options to satisfy the industrial demand varies. Burning natural gas is not as dominant as it is in the built environment. The industry also obtains a lot of heat from the combustion of petroleum products. It mainly involves residual gases in the petrochemical industry. Also, a lot of heat is bought particularly from CHPs, energy companies or neighboring farms. In recent years CHP is less used in industry. Electricity production from CHP decreased from 16.1 PJ (4.4 TWh) in 2010 to 13.1. PJ (3.64 TWh) in 2015. It is expected that the market conditions will remain unfavorable for CHP and its usage will continue to decrease. Last few years, biomass started to be an attractive option in the industry. In 2015, 5 PJ (1.39 TWh) of biomass was used for the generation of heat. There are also larger installations for specific biomass applications such as waste fats, paper sludge or coffee. In addition, there are smaller installations ranging from 20 kW to 10 MW in which own waste wood of the industry is burned (Menkveld et al., 2017).

In most of the facilities, heat use is cascaded. This means heat is generated at the highest temperature that is required for the process and the residual lower temperature is used for the other parts of the process or in another process. This also implies decarbonization measures require customization according to the process requirements.

Figure 10 shows the mix of energy sources that are used to satisfy the industrial heat demand in 2015.

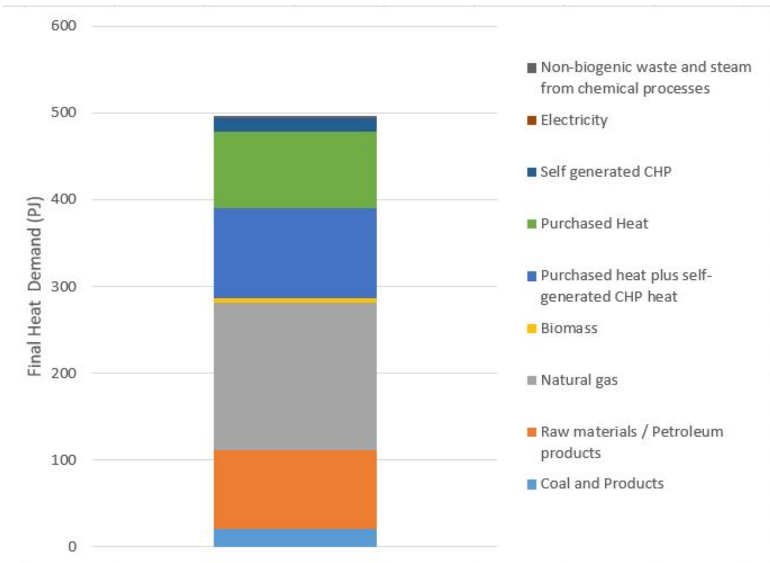



Figure 10: Energy Sources Industrial Heat Demand (Menkveld et al., 2017)

Electricity is not widely used to satisfy the heat demand in the industry. However, according to scenario studies, it will play a major role in decarbonizing the industry. According to the study of McKinsey (Roelofsen et al., 2017), it is one of the six promising ways of decarbonization. Electrification is a promising option for the industry especially for the integration of the off-shore wind farms since industrial areas are also close to the off-shore wind farms (Joost de Wolff et al., 2018). While some electrification technologies are ready for implementation such as hybrid or dual-fuel to generate medium temperature heat, other technologies are expected to be further commercialized by research and development including heat pumps that can produce medium temperature heat and electric furnaces which are capable of providing high-temperature heat in refining and ethylene production. The following criteria are used in most of the studies to evaluate the electrification options for industry: Potential to reduce CO2 by renewable energy, efficiency, flexibility (cost-effective usage when electricity prices are low), full load potential (the possibility to be operated continuously economically) and technology readiness level. Replacement of the old technologies with the new ones which have higher CAPEX is not economical if they operate only when electricity prices are below the average cost. Apart from the flexibility of the technology, the flexibility of the industrial processes is also an important aspect. The process in which the technology is used can be operated in a discontinuous way or storage of the mid-products can allow the process to be decoupled (de Groot & van Delft, 2018).

For the short term electrification, promising decarbonization options are electric boilers, steam recompression, mechanical vapor recompression where energy from steam can be recaptured and reused, electromagnetic radiation and heat pumps. For the medium to long term, electrolysis for production of chlorine, ammonia, and hydrogen, medium temperature heat pumps are considered to have high potential. In the long-term electric furnaces for high-temperature processes are considered to play an important role in the analysis (den Ouden et al., 2017). Also in the long term hybrid and dual-fuel systems are expected to use electricity and hydrogen. Electrification technologies require an upgrade in the connection to the electricity grid and more space. As a result, usually, modifications to the equipment or surroundings are needed (Roelofsen et al., 2017).

Below, the short descriptions of the most important electrification options in industry is presented.

- Heat Pumps:

  Heat pumps that can be used in the industrial processes generally require higher temperature levels compared to the ones that are used in the built environment. In such a case the coefficient-of-performance decreases. In industry heat pumps would be used more efficiently if there is waste heat available at an appropriate temperature which can be fed to the heat pump. Only a certain type of heat pumps would be suitable to address the industrial applications. As an example compression heat pumps can be used for a variety of low and medium temperature applications. However, they can't be used for high-temperature applications.

  Heat pumps can deliver heat to any process (stand-alone) or to a specific process (process-integrated). Heat pumps require further technological development such as higher operating temperatures, increase in the thermal output, higher temperature lifts, increased efficiency. In addition, the business case requires further cost reductions to reach acceptable pay-back times.

  There are also heat pumps that can serve to high temperature heat demand. However, these require more R&D and they are not commercially available yet. These heat pumps are thermo-acoustic (TA) heat pump, stirling heat pump, brayton heat pump and adsorption and resorption heat pump.

- Hybrid or Dual-Fuel Systems:

  Hybrid system can either run on electricity or natural gas depending on the prices replacing a fossil boiler. More electricity can be consumed when electricity prices decrease and when renewable production is high. Gas is used when electricity prices increase and when renewable generation is less. This gives the opportunity to utilize the low electricity prices for the companies and helps to balance the load on the electric grid.

  Right now with the current electricity and gas prices, the business case is not viable for large scale applications of hybrid systems. In 2016, electricity prices were below gas day-ahead prices for only 170 hours. With those prices, the payback period was estimated as 10 years or more. With the increasing renewable generation, cost decreases are observed and the times that electricity is cheaper than the gas is expected to increase. Decreasing electricity prices, increasing natural gas prices, changes in the tax scheme would shorten the payback periods. It is observed that reducing the electricity prices from 50 EUR/MWh (including transmission and distribution costs) to 20 EUR/MWh have major positive implications for the business case (Roelofsen et al., 2017). One other way to create a positive business case is allowing industrial parks to serve as ancillary services to the power system.

- Electric furnaces:

  Electric furnaces are used for high-temperature heat demand replacing the fossil fuel-fired furnaces right now. This technology could reach the market within 5 years if there are demand and research funding available. Electric furnaces can be used in the steel industry. (Roelofsen et al., 2017).

Many of the power-to-heat technologies for the industry are in the first development phase today. Hybrid systems and medium-temperature heat pumps are expected to be fully deployed in the year 2025, high-temperature heat pumps in 2035 (de Groot & van Delft, 2018). Expert views predict heat pumps, 'MVR' (also type of heat pump), electric boilers and hybrid technologies can play a balancing role in the future when combined with an H2 (renewable gas) or green gas boiler.

### 3.2.2 Scenario Studies

The projections on the industrial power-to-heat demand also varies per study and are mostly affected by the research and development related to process efficiencies and technology options.

Table 6 presents the total heat demand of industry for the years 2015, 2030 and 2050 including oil refineries. References used in the formation of the table are Monitoring Heat ECN, Berenschot scenario studies, McKinsey Report, and National Energy Outlook. The electricity that is used for heat purposes is not made clear in all the studies. It is unknown how much electricity the industry uses for heat in 2015 (ECN, 2017). The numbers for total energy demand also includes the non-energetic use including feedstocks. The scenarios for 2030 and 2050 are highly uncertain since the adoption of the technologies heavily depends on the cost reductions and the fuel prices (electricity and gas). The ranges for heat from electricity

Table 6: Energy Usage in Industry

| | 2015 | 2030 | 2050 |
|---|---|---|---|
| Total Energy Demand | 1091 | [670- 1159] | [840-1320] |
| Total Heat Demand (PJ) | 567 | [370-410] | [350-430] |
| Heat from Electricity | ? | [3][60-120] | [100 - 250] |

is relatively small due to the limited number of studies used that predict the electrification of industry. Information sources for the table is explained in Appendix C.

## 3.3 Heat Demand Flexibility

Sections 3.1 and 3.2 provide an overview of the evolution of the heat demand and technology options for the built-environment and industry sectors. As it is identified in the scenario studies, even though the penetration of electric heating technologies differ per study, it is for sure that the increase of electrification will have impact on the power grid which makes the notion of flexibility more important. This section aims to explain the working principles of shifting the heat demand and the flexibility potential from the household and industry demand.

Ways of providing heat demand flexibility was identified in the literature research in Section 2.3. The first option is the storage technologies that changes the electric load by charging during off-peak hours and discharging during peak hours. The second option for the heat demand flexibility is the demand response which is related to the consumer behavior and the availability of hybrid technology options. A hybrid technology uses either electricity or gas depending on the prices. The prices of these two supply options are important for a positive business case. The two identified flexibility options from the heat side are explained below.

### 3.3.1 Demand Response

Definition of demand response is provided in Section 2.1. Demand response includes electrical load shedding (decreasing the load) and electrical load shifting (distributing/shifting the load in time). Electrical load shedding can be done by using hybrid technologies. Electrical load shifting can be facilitated by pre-heating or postponing the heating from P2H technologies within the comfort limits. Comfort limits represent the total amount of people that accept the inside temperature given a certain outside temperature (van Etten, 2017). There are large variations between people in terms of physiological and psychological satisfaction in a given space. By using laboratory and field data comfort limits are defined as the conditions that are comfortable for a certain percentage of people. The personal factors (metabolic rate and clothing level) and the environmental factors (air temperature, mean radiant temperature, air speed, and humidity) affect the comfort limits. Even if those factors change in time, thermal comfort limits are pretty steady and just allow limited temperature variations (Paliaga et al., 2010). Comfort limits are not usually subject to change. The study (Barton et al., 2013), observes that in the UK, if the heating is turned off for more than an hour, the room temperature drops below the thermally comfortable limits depending on the level of the thermal insulation and building thermal mass. This study assumes that heating can be deferred up to 1 hour within the comfort limits.

[3] Brackets [] represents a range for the demand.

Modern technologies are very much adjusted according to the comfort limits, consumer behaviors and desires such as smart thermostats that takes the consumer comfort limit as the priority. The thermostat is a device that keeps the ambient temperature stable. If the house is too cold, thermostat responds by switching on the heating to warm up the house and switches off if a certain temperature level is reached. This provides efficient heating instead of switching on and off manually. The thermostat can adjust the temperature depending on the ambient temperature or the time of the day. In addition to this, a smart thermostat puts the consumer in charge of the remote control of the heating. The heater can be programmed on an hourly basis via a heating plan that represents the lifestyle of the consumer. The latest smart thermostats learn how the consumer manually alters the temperature during the different times of the day and the week. The consumers can also program the heating remotely by using a smartphone application. A consumer can turn on the heat on the way back home and ensure that it is shut down when he is not there. This gives the opportunity for pre-heating which can defer the heating a few hours from the peak hour. In some applications, the location of the consumer and the time that it takes to heat the home is taken into account to start the heating timely. The main function of this system is saving money for the consumers and reducing the wasted energy. This is mainly a consumer-oriented decentralized mechanism which is not connected to a central information system in connection to the power grid.

A decentralised control mechanism with the smart thermostats is driven by consumer behavior while a central control system such as a smart heat grid can enable more effective and optimal coordination between sectors. A smart heat grid uses a central control unit where all system information is fed and algorithms cooperate on efficient operation in real time. Here the decisions such as the conversion of heat to electricity, storing the electricity as heat, usage of excess heat from CHP and solar thermal, which heat generator to use can be made based on economic factors. In such a system, both producers and consumers need to cooperate intelligently. Also, a heat market place is developed allowing consumers to buy heat and producers to offer heat. With the perfect information flow between the sectors, the shifting of heat demand in time can be more effective. The development of such systems is still under test phase. One example is the Smart Heat Grid Hamburg which is being tested in a small town, Wilhemsburg in Germany (*Smart Heat Grid Hamburg*, n.d.).

Demands response in the form of time shifting in the industry is more process oriented and it is technically possible in some cases by revising the production processes or by installing storage capacity for the intermediate products or hot and cold storage (Redl, Pescia, Rious, Hary, & Saguan, 2016). In most of the industries, the potential also depends on the ramp up/down margins of the plants [reference]. For the industry, the difference of shifting the load in time from households is that companies want to maximize their production and any moment the production is stopped or delayed can cause huge losses if there is no compensation. Despite this fact, there is the economic potential of demand response in large scale and energy-intensive processes which rely on a single source of demand (Paulus & Borggrefe, 2011). Some industries with the demand response potential are listed as follows: Food industry, paper industry, chemical industry, glass and ceramics, metal, non-ferrous metal production and processing, vehicle and mechanical engineering (Gruber, von Roon, & Fattler, 2016).

It is identified that in the Netherlands chemical industries (e.g. AkzoNobel) have a more positive approach towards demand response. On the other hand, the iron and steel industry has a neutral position towards demand response. Tata Steel reveals that they have little potential for demand response because of the inflexible consumption required by the traditional processes.

Tata Steel indicates there is not a positive business case for their industry to use demand response yet. Large technical innovation and high imbalance electricity prices are required to encourage them for demand response (Jiang, 2017). The effect of the demand response from industry can be analyzed more effective by using process-specific heat demand data for certain industries.

The overview of the possibilities for demand response reveals that most forms of it is not likely to shift the demand by more than a few hours for industry due to production concerns and for households due to comfort limits. Shifting the heat demand for longer hours without violating the constraints is possible with thermal energy storage. Depending on its size thermal energy storage can increase the maximum shifting hours more than a few hours (Barton et al., 2013).

### 3.3.2 Heat Storage

"Thermal energy storage is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation" (EASE, 2017). A heat storage is able to shift the electrical load in time by charging in off peak times and discharging during the peak hours without the consumers changing their consumption pattern. Usage of a thermal storage would be more efficient when combined with a smart grid system.

There are different classifications for thermal energy storage (TES). The most relevant ones for this research are based on the distribution as centralized, decentralized; based on the storage cycle as short-term, long-term and based on the technical working principle as sensible, latent and thermochemical storage.

A centralized technology has a larger scale and serves to multiple end users in a heat network or used for industrial applications. Centralized systems store waste heat from large industrial processes, conventional power plants, CHPs, and renewable power plants. Tank thermal energy stores, pit thermal energy stores, borehole thermal energy stores and aquifer thermal energy stores are examples of large scale centralized low-temperature thermal storage. (Eames, Loveday, Haines, & Romanos, 2014). On the other hand, decentralized applications have a smaller size and used for a single dwelling. Decentralized options use buffer storage systems to store the heat usually for a shorter time span. This type of storage can provide a considerable amount of daily load shifting capability. The capacity of the buffer depends on the water temperature and the size of the tank. The tank can be loaded during optimal hours in the day time when it is warmer and during the evening / night it can be used when there is more demand.

Many of the widely used storage options as well as the centralized options that are mentioned above are sensible heat storage. Sensible heat storage works by increasing or decreasing the temperature of a liquid or solid storage medium such as water, air. sand, molten salts, rocks or oil to store and release thermal energy. Other types of thermal energy storage are latent heat storage and thermochemical storage. Latent heat storage takes advantage of the energy that is absorbed or released during a phase change at a constant temperature. Thermochemical storage uses chemical reactions and adsorption processes to store energy (EASE, 2017). Decentralized options that can provide daily load shifting capacity requires the development of latent or thermochemical heat storage systems for reasonable storage volumes to be applied (Eames et al., 2014).

The final distinction between the storage types is based on their storage cycle. Short-term thermal energy storage stores heat energy for less than 24 hours to help to neutralize fluctuations on the load side by taking advantage of weather and price conditions. The heat can be stored from solar thermal energy when there is sun or by heat pumps when electricity is cheap. Some short-term storage types that are used are electric storage heaters, hot water storage for water-based residential heating systems and heat pump buffers. Long-term thermal energy storage stores energy for longer periods such as 24-hours or a period of 12-month (summer-winter) period. These are called seasonal storage (Abhat, 1980). Tank thermal energy stores, pit thermal energy stores, borehole thermal energy stores and aquifer thermal energy stores are examples of seasonal storage. In seasonal storage, the store is filled in the summertime with heat that is obtained from solar collectors. The stored heat is used in wintertime and the temperature level is increased if necessary by using a high-efficiency heat pump. This heat can be used for space heating and domestic hot water.

A type of seasonal storage that is used in the built-environment in the the Netherlands is Aquifer Thermal Energy Storage (ATES). Due to the large seasonal variation in space heating, the annual heat load profile is not constant and the peak winter heat load is several times of the summer times. Seasonal storage like ATES can provide seasonal balancing. In ATES, storage and recovery of the thermal energy are achieved by extraction and injection of groundwater with the help of aquifers and groundwater wells. In (Naber et al., 2016), this storage is expected to be used in 2050 for households. The amount of energy that is satisfied by ATES varies between 70-95 PJ (19 TWh - 26 TWh) in the scenarios of 2050 which changes depending on the availability of the other technology options. Also, 22% of the non-residential buildings will be using ATES. The details of this scenario study are mentioned in Section 3.1.2. 19% to 21 % of the heat demand can be satisfied by using ATES in 2050 if the amount of available green gas is 1 bcm (billion cubic meters) or 1.5 bcm.

Another storage technology that provides demand-side flexibility is a power-to-heat storage technology called Smart Electric Thermal Storage (SETS). This is sensible heat storage which is for small local scale applications in which electrical energy is stored as heat inside a heavily insulated core. It is used to meet the space and water heating demands of households. ICT technology provides the opportunity to do this in an efficient and cost-effective manner. It draws electricity during off-peak hours when it is cheaper and the heat that is stored is used in the day within 24 hours. Such intelligent flexibility maximizes the use of VREs and adjusts the heat demand accordingly. These devices can also be connected to a third party that is called aggregator who is responsible for managing the device on behalf of the property owner. (EASE, 2017).

In industry, high-temperature applications of phase change materials to provide process heat are under research and development but not widely used yet. The thermochemical heat storage technologies can also offer higher energy storage capacities. However, they are at the very early stages of development. These storage applications are for industrial processes with variable heat demand (Eames et al., 2014). This implies that it is not possible to use these technologies for processes with an intensive fixed heat demand all the time.

Thermal energy storage size is the factor that determines the ability to shift the load. In the study of UK Energy Research Center, daily winter heat requirements were determined for a large family house in Derby assuming the house aligns with building regulations. Thermal storage is sized to meet the maximum load for a three hour period to allow the operation of heat pumps during low electrical grid load. Thermal energy storage sizing is based on the electricity need of the heat pumps and 3 hours of load shifting. As the load shifting time increases the size of the storage needs to increase as well which requires more space. In the study, the storage is decentralized so the maximum capacity is also limited by the spatial constraints. As a result, 36 kWh of thermal storage is used for a single building to shift the heat generation and the resulting electrical load out of the periods when there is peak electrical load. The electrical load is minimized between 6:00 and 9:00 and 16:00 and 19:00.

The advantages of thermal heat storage include the opportunity to store the solar thermal energy, improving the capacity factor of the plants, improved energy efficiency, more optimum operation of CHP and district heating systems, increased system reliability and shifting of heat generation in time to reduce the peak demand to take advantage of lower tariffs (Eames et al., 2014). This provides a considerable amount of flexibility to the system in combination with district heating. However, TES technologies face certain barriers to market entry, the cost is an important issue. Table 7 presents the overview of the mentioned thermal energy storage types.

Table 7: Thermal Energy Storage Options

| Thermal Energy Storage | Decentralized / Centralized | Long-term / Short-term |
|---|---|---|
| Tank TES | Centralized | Long-term (seasonal) |
| Pit TES | Centralized | Long-term (seasonal) |
| Borehole TES | Centralized | Long-term (seasonal) |
| Aquifer TES | Centralized | Long-term (seasonal) |
| Heat Pump Buffer | Decentralized | Short-term |
| Electric Storage Heater | Decentralized | Short-term |
| Hot Water Storage | Decentralized | Short-term |
| Smart Electric TES | Centralized | Long-term / short-term |

## 3.4 Consumer Price Structures for Electricity and Natural Gas

The previous sections presented the heat sector for built-environment and industry. Later the heat demand flexibility for these end-consumers is explained. This section aims to explain the price structures for the end-consumers for electricity and natural gas. In the literature research, the commodity prices and the energy taxes were identified as important economic barriers against widespread usage of power-to-heat technologies. Analysis 4 in Section 5.4 investigates the impacts of the electricity and natural gas on end-users. This section provides background information on the price structures of electricity and natural gas. In addition, all the prices identified in this part are used for the Analysis 4.

Small and large consumers connected to the electricity grid are differentiated based on the technical structure of the Dutch grid. Very high voltage grid (380 and 220 kV) and high voltage grid (150, 110 and 50 kV) for transmission are at country and regional level. Intermediate voltage grid (3 - 30 kV) supplies to large users such as to industry and low voltage grids (230 - 400 V) are for the connection of retail customers and small enterprises including households (Ongkiehong, 2006). Consumers can also be classified according to their energy consumption although this is not an official definition to distinguish them. However, for this analysis, it is useful to determine which tax interval they belong to based on their annual energy consumption. Table 8 and 9 presents the government taxes for natural gas and electricity. The intervals for energy consumption are annual. Households belong to the first interval for both gas and electricity assuming they consume between 2 500 kWh and 5 000 kWh electricity and 20 GJ (568 m3) to 200 GJ (5686 m3) natural gas annually (Eurostat, 2018). For industry, the consumption is within the last two brackets assuming the annual electricity consumption is more than 50 000 kWh and gas consumption is more than 1 000 000 m3. Industrial users within the last tax bracket are considered as large industrial users. Industrial users pay less taxes compared to households. They use more electricity and can receive it at higher voltages from the intermediate voltage grid, directly from the TSO TenneT. The price of electricity to industrial customers is generally close to the wholesale price of electricity.

Table 8: Government taxes on natural gas 2019, (Belastingdienst, 2019)

| Natural Gas (€/m3) | 0 - 170 000 | 170 001 - 1 million | 1 million- 10 million | >10 million |
|---|---|---|---|---|
| (Energy taxes, VAT, ODE) | 0.41809 | 0.09864 | 0.03597 | 0.01924 |

Table 9: Government taxes on electricity 2019, (Belastingdienst, 2019)

| Electricity (€/kWh) | 0 - 10 000 | 10 001 - 50 000 | 50 001 - 10 million | >10 million | >10 million (business) |
|---|---|---|---|---|---|
| (Energy taxes, VAT, ODE) | 0.1422 | 0.09822 | 0.02614 | 0.00178 | 0.0007018 |

The end-user energy price for electricity and gas consists of Supply Costs, Network Costs, and Government Taxes and Levies. The supply costs have both variable and fixed components and paid to the energy supplier (e.g. Eneco, Nuon, Greenchoice). The variable part is paid based on the amount of energy that is used per kWh for electricity ('leveringskosten elektriciteit') or m3 for natural gas ('leveringskosten gas inclusief regiotoeslag'). Cost for natural gas includes a regional supplement. The further away the end consumer lives from the source of the gas or gas producing region (North of the Netherlands), the higher the amount of this supplement is. In a free energy market, rates for energy supply change during the year in the wholesale or retail market. In addition to the variable part, there is a fixed part of the supply cost for the services that are provided and independent of energy consumption. This is a subscription fee for the services and energy suppliers are free to determine the level. It can be different per supplier and per contract.

Network costs include costs for transport and connection to the gird and charged by grid operators both for distribution and transmission grids. The grid operator which is responsible for the distribution grid cannot be chosen by consumers but it is based on the region. These distribution costs are also recurring and paid usually monthly through the energy supplier. The energy supplier pays these costs back to the network manager (Liander, Enexis, Enduris, Rendo, Stedin, Westland, Cogas/Coteq). For the transmission costs, large industrial customers and network operators pay the tariffs directly to the transmission system operator TenneT while households pay this via their energy supplier. Connection costs include one-time connection fee and in addition a periodic subscription charge, a capacity tariff, per year or month to maintain the connection. This rate depends on the size (capacity) of the connection and changes between the network operators. Households have connection capacity 3x25 for electricity and G6 for gas. Industrial consumers from the third category have connection capacity 3x63 for electricity and G16 for gas. Industrial consumers from the fourth category have connection capacity 3x80 or larger for electricity and G25 for gas (*https://www.vastelastenbond.nl/energie/netwerkkosten-2018/*, n.d.).

The second component of network costs, transport cost, is different for households and industry. For households, transport cost consists of a standing charge, a fixed amount, for both electricity and gas. For large consumers (connection $>$ 3x80 A, Intermediate Voltage with a yearly contracted capacity above 1500 kW), transport dependent tariff is applied. This variable rate for transportation consists of the contracted transmission capacity (kW contracted) and measured maximum capacity (kW max). Contracted capacity is the expected maximum power required by a consumer during the year (€/kW/year). The amount is estimated by the customer but later corrected for the actual maximum load. Measured maximum capacity KW-max is the maximum power used by a terminal in a month or week (€/kW/month (or per week)). If kW max exceeds kW contract, the latter will be increased so that both are aligned. For large industry these costs are 2 to 4 euros per kW. If the operating hours for a connection is less than 600 hours lower rates apply (Hers, Rooijers, Afman, Croezen, & Cherif, 2016). Metering service is also included in network costs as a fixed amount per month for installation, management, and maintenance of the meter. Network costs are determined every three years by the ACM (Authority or Consumers and Markets). These costs are applied to recover transport dependent costs of network operators.

The last component of electricity and gas prices include government levies which are composed of VAT (BTW), energy taxes (Energiebelasting) and a premium sustainable energy (SDE, ODE). VAT (Value Added Tax) rate is 21% in the Netherlands. Energy tax must be paid based on the consumption of electricity (per kWh) and natural gas (per m3). ODE is a government levy which aims to collect grants for sustainable energy projects. These costs are also per kWh and m3 for electricity and gas. Table 8 and 9 includes non-refundable taxes. [4].

[4]Refundable taxes are valid for some business cases where refund on energy tax can be provided if the consumer uses electricity for chemical reduction or electrolytic process, in case electricity connection is shared, natural gas used for district heating. There are various other conditions listed to get a refund on energy tax which can be found in Belastingdienst energy taxes section

Table 10: Electricity and Natural Gas Variable Costs in the Netherlands, 2018

| | Electricity | | | Natural Gas | | |
|---|---|---|---|---|---|---|
| euro / kWh | Households | Industry (Tax Category 3) | Industry (Tax Caregory 4) | Households | Industry (Tax Category 3) | Industry (Tax Category 4) |
| Variable Supply Cost | 0.091355 | 0.0507 | 0.0507 | 0.0374 | 0.0214 | 0.021494 |
| Energy Tax | 0.09863 | 0.01421 | 0.00058 | 0.03 | 0.002439 | 0.001310 |
| VAT | 0.02468 | 0.0045381 | 0.0001848 | 0.0074 | 0.000639 | 0.0003417 |
| ODE | 0.0189 | 0.0074 | 0.0003 | 0.00536 | 0.000603 | 0.0003172 |
| Total without Supply Costs | 0.142 | 0.0262 | 0.00106 | 0.0436 | 0.0036 | 0.00197 |
| Total | 0.2335 | 0.0769 | 0.0517 | 0.081 | 0.025 | 0.0235 |

Table 10 presents the variable costs (variable supply cost, energy tax, ODE and VAT-based on these) of electricity and gas for households and two types of industrial consumers. In this table, fixed costs (fixed supply cost, network cost, and VAT based on these) are not included. The first type of industrial consumers are within the third category of the tax division with natural gas consumption between 1 million- 10 million m3 and electricity consumption 50 000 - 10 000 million kWh. The second type of industrial consumers are within the fourth category of the tax division with natural gas consumption greater than 10 million m3 and electricity consumption greater than 10 million kWh. Variable costs for electricity and natural gas are used from one of the energy suppliers, Nuon, for households and for the industry the average day-ahead electricity price of 2018 which is declared by TenneT is used. Variable supply cost for gas is from Eurostat 2018. Figure 11 presents the composition of the electricity and natural gas prices based on Table 10. For both natural gas and electricity, the prices are per KWh. To compare specifically heating costs, the efficiencies of the technologies are also important. The electricity or natural gas required to obtain one unit of heat is different. This is investigated more in details in Analysis 4 in Section 5.4.

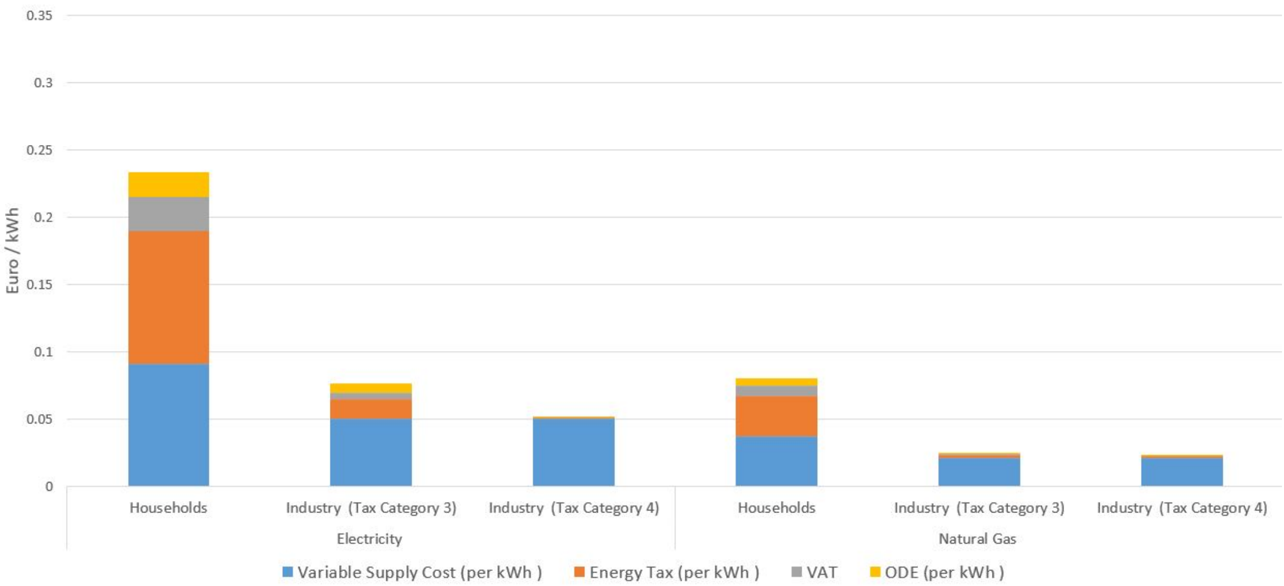



Figure 11: Electricity and Natural Gas Variable Price Components for Household and Industry in the Netherlands (excluding fixed costs)

When the fixed supply and network costs are also included the composition of the prices change. Network costs and fixed supply costs are not based on energy consumption. A household is assumed to use 3500 kWh electricity and 1500 m3 gas per year. Figure 12 shows the overall distribution of the components for households when the network costs for gas and electricity are also included. It is observed that 70% and 66% of the electricity price and natural gas consists of taxes, levies and fixed components, respectively. Fixed network and supply costs form the 25% and 13% of the electricity bill for electricity and natural gas, respectively. These ratios are based on the consumption of an average household. The values are subject to change based on consumption of different households. For the industry, the structure of network costs is more complex compared to households. Transport dependent tariffs are based on the contracted capacity as explained above. There are different type of exemptions and rules also based on the operational hours of the technologies. The capacity contracted can be considered as 1000 kW and 2000 kW for small and large industry, respectively. The price is stated between 2 and 4 euro / kW (Hers et al., 2016). The network costs for industry is not used in calculations in this research.

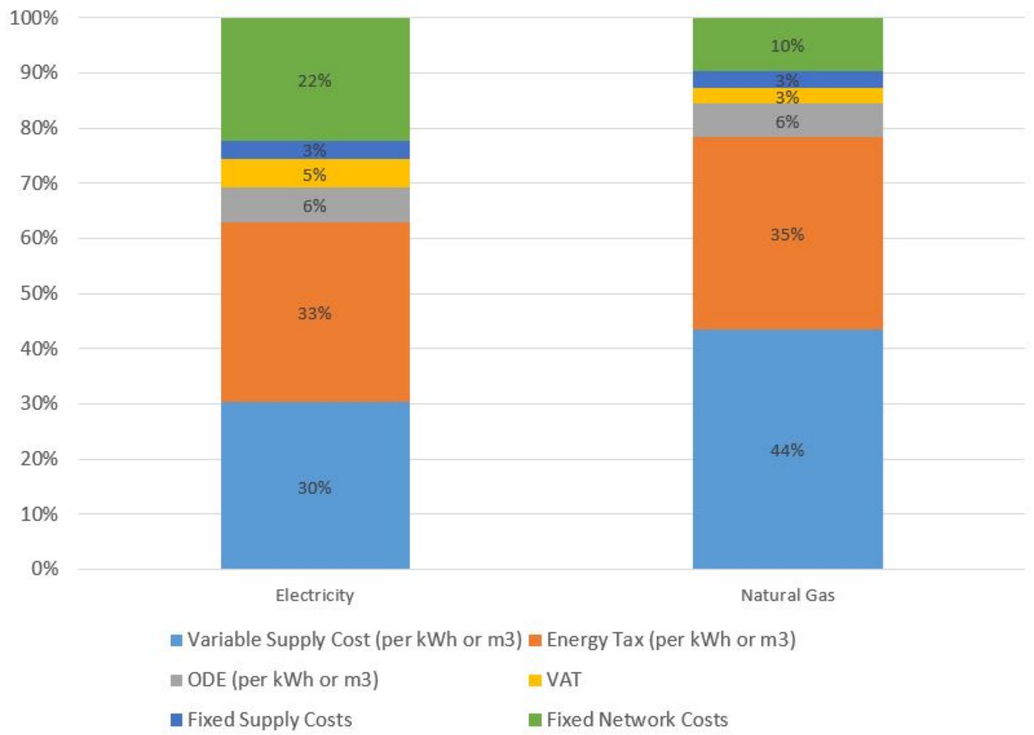



Figure 12: Electricity and Natural Gas Variable Price Components for Household and Industry in the Netherlands (including fixed costs)

Fixed supply costs for electricity and gas are obtained from one of the energy suppliers Nuon. Electricity and gas network costs are the average of the 7 network operators in (*https://www.vastelastenbond.nl/energie/netwerkkosten-2018/*, n.d.). Gas prices are converted from m3 to kWh for comparison by using the Gasunie Unit Converter. All variable costs are in euro / kWh.

For households, it is possible that no connection upgrade is required to install the heat pumps for example if the other electric appliances are energy-efficient. However, it is also possible that when the electricity consumption of heat pumps is combined with conventional electric load a larger connection is required. In this case, the households need to pay a higher capacity tariff. Most of the time it is the case that industry exceeds the contracted kW capacity to use power-to-heat technologies and the deployment of power-to-heat loads lead to substantial additional expenditure from the network tariffs. In this case, network costs become a barrier to P2H technologies. In Figure 13 from (den Ouden et al., 2016) red and blue lines represent two different users with the same total annual demand. The red consumer can use a lower contracted capacity while the black one needs a higher contracted capacity for its peak usages during a limited amount of time. Exceeding the capacity, especially only a few hours is a barrier against the flexibility supply options such as P2H. Once the load from power-to-heat leads to an excess of the contracted capacity even for a limited number of hours, contracted capacity is increased for the whole year. If the benefits obtained from flexibility (energy savings by using a power-to-heat technology) is only a limited amount of time, the additional expenditures from the network costs cancel this benefit. Therefore, it is important to have an idea about the number of hours electricity is used and the energy savings from switching to electricity. Berenschot states that for 1000 to 2000 hours electricity prices should be under the natural gas prices. The energy savings might be interesting for the industry but the risk of increasing the capacity rate for the full year remains as an obstacle. A similar mechanism is also valid for kW max component, instead of a year, this is paid weekly or monthly. Addition of the two tariff components together makes the business case worse.

An overview of the costs for electricity and natural gas can be seen in Figure 14.

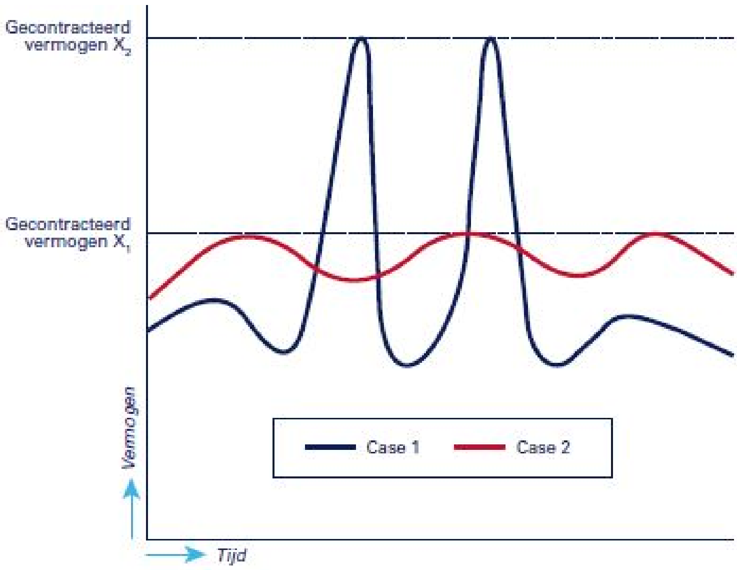



Figure 13: Annual contracted capacity (kW contracted) (den Ouden et al., 2016)

Apart from the taxes and network costs that might result in sub-optimal use of electricity, CO2 prices also have an effect on the choice between natural gas and electricity. The industry is involved in the EU ETS market while household heating is not subject to any kind of carbon trading or CO2 tax scheme. A policy related to CO2 for households heating has the potential to encourage consumers to invest in less carbon-intensive technologies including power-to-heat technologies. Household heating sector can be involved in EU ETS with an upstream approach where producers, traders, importers would be obliged to buy carbon certificates. However, this requires the consent of all member states. Another way of pricing the carbon for the heating sector would be adjusting existing taxes and levies on energy according to their CO2 intensity. It is a relatively easy option to implement nationally with less bureaucracy. The increasing cost burden on the natural gas side for households requires a reduction in the taxes of electricity. For the power sector, C02 costs are already included in the bids of the producers. This creates a distortion between electricity prices and natural gas for households.

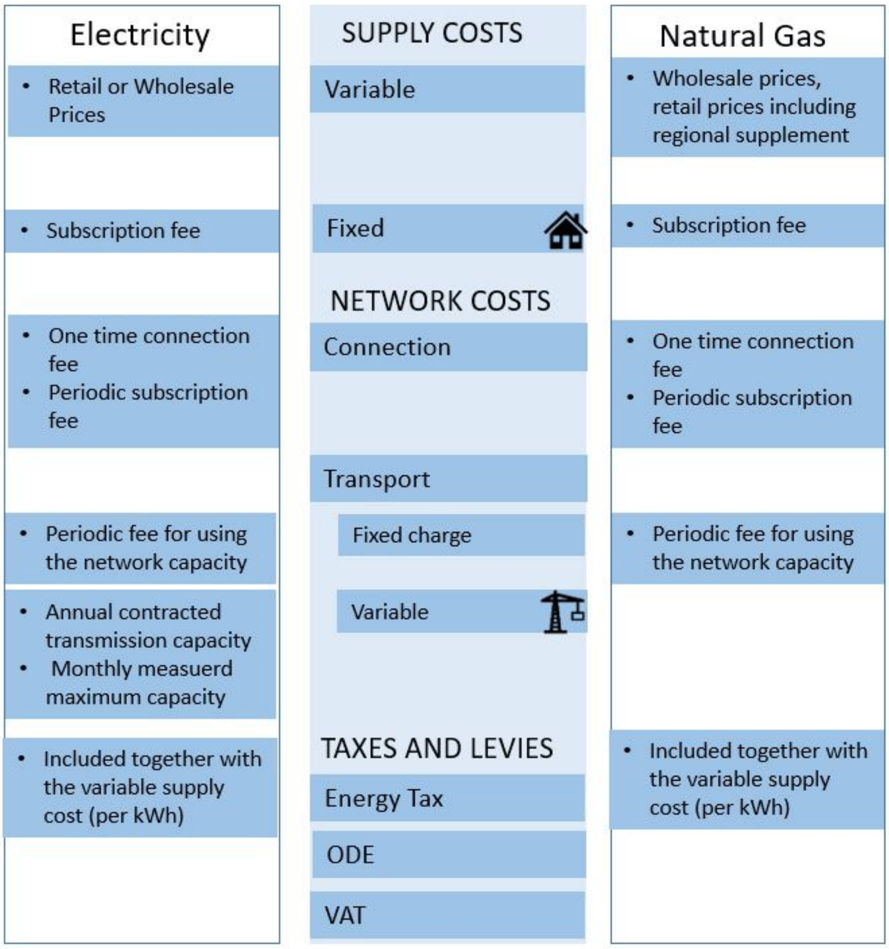



Figure 14: Overview of Electricity and Natural Gas Price Structures

## 3.5 Conclusion

The overview of the heat sector in the Netherlands reveals that there are many different sustainable technology options to satisfy the future heat demand for the end use sectors built-environment and industry. Power-to-heat technologies have a critical position for providing the grid flexibility and emission reductions.

For households, the three types of heat pump technologies (air, ground, hybrid) are the main technology options for electrification. The penetration rate of these technologies differ per scenario studies and determined mostly by the competitiveness and availability of alternative technologies. Among these alternatives availability of green gas becomes prominent both in the latest (28 March 2019) Climate Agreement Report (Dodion & Melotte, 2018) and CE Delft scenario studies. The PBL report underlines the ambition to produce 70 PJ green gas by 2030 of which a significant part can be used in built-environment. This implies that even more green gas might be available for built-environment than the maximum amount of 45 PJ in CE Delft 2050 scenario. In case green gas can also be imported, CE Delft scenario studies foresee that hybrid heat pumps will be used 22.6% more than the air or ground heat pumps. The share of the hybrid heat pumps in the technology mix for households also increased in the latest Climate Agreement Report compared to the FlexNet Project shares which predicted only 5% and 10% share for hybrid heat pumps in 2030 and 2050 respectively.

Installing hybrid heat pumps is stated as a relatively inexpensive method for CO2 reduction also in already existing houses. The switch in the hybrid system depends on the temperature and heat requirement for households more than the prices. The situation will be even more favorable if production costs between natural gas and green gas (via subsidies) are equalized. In this case, hybrid heat pumps are a more attractive option than the alternatives electric heat pumps and district heating (Dodion & Melotte, 2018).

For industry, the differentiation between the temperatures makes the power-to-heat technology development more challenging, especially for high-temperature heat demand. For the high-temperature part of the heat demand before considering the electrification technologies, increasing process efficiency is the first priority. Process efficiency can be increased by heat cascading, heat pumps, steam recompression, and utilization of waste stream. Electrification in the industry focuses on the high-temperature part of the heat demand with electric boilers and furnaces. Technologies that use electricity with high efficiency and enables the reuse of heat will be preferred such as steam and vapor recompression and high-temperature heat pumps. Hydrogen from electricity is not promising because of the high costs. Low-temperature heat demand is mostly satisfied by the residual heat (Dodion & Melotte, 2018). It can be concluded that the higher electrification potential is in the high-temperature part of the heat demand. The uncertainty on technology development also makes the power-to-heat demand from industry very sensitive.

Also for industry hybrid systems (e.g. hybrid boiler) have the potential to be the transition technology from natural gas to electricity. Once the natural gas phases out, the possibility that green or renewable gas can be used in the boilers in the future makes the technology promising. The electricity and gas price tariffs have an important role to determine the switching and the profitability of the hybrid boilers. Most of the time gas is cheaper and used instead of electricity.

Heat demand flexibility is another important part that will have an effect on the integration of the power-to-heat technologies. It is possible to shift the electric part of the heat demand according to the peak and off-peak times of the conventional electric load. The switch in between fuels provides flexibility and changes the heat demand as well as the demand response and heat storage.

For industry, the demand response potential is quite new and requires some process interventions, storage of the intermediary materials or thermal storage. To discover the demand response potential of industry more process specific data is required. Due to the lack of availability of data, this part of the analysis is out of the scope of this research.

For households, insulation or technologies like smart thermostats make it possible to shift the heat demand a couple of hours while individual decentralized thermal storage has the possibility to shift the load for longer times up to 24 hours. One of the promising storage options in the Netherlands is the seasonal storage Aquifer Thermal Energy Stores (ATES). CE Delft predicts 19% - 21% of the heat demand will be satisfied by ATES for households in 2050. The development of thermal storage also depends on various factors and regulatory barriers which is not within the scope of this research. However, the large scale adoption of the thermal storage technologies would still require more time until 2050 until the conditions are more favorable. This implies only a certain percentage of households have flexible heat demand due to the usage of thermal energy storage or demand response. Apart from the technological development, the structure of the electricity and natural gas prices is important for the positive business case of the power-to-heat technologies. Different additional components such as energy taxes cause prices distortions in the energy system and can be barrier against coupling of power and heat sectors.

Below is a summarizing table which presents the major findings of this chapter. The information sources and the assumptions for the table are explained in the Appendix D. The penetration P2H technology refers to the percentage of households that uses heat pump technologies (hybrid or all-electric) for heating. Technology mix refers to the share of the P2H technologies for the households that already use P2H technologies.

The total heat demand for industry and P2H demand for households is going to be used as scenario inputs to COMPETES model. The household data of the FlexNet Project will be updated based on the electrification rate and the share of the technologies that are identified in this chapter. The identified technology options can be added to the heat sector part of the COMPETES model later to improve the model. The colors for the technology mix can be interpreted as follows: Red color represents the percentage obtained based on Draft Climate Agreement Report while the grey colored numbers are from FlexNet study.

Table 11: Heat Sector Overview

| | Built-environment | | Industry | |
|---|---|---|---|---|
| | 2030 | 2050 | 2030 | 2050 |
| Total Heat Demand (PJ) (Heat Energy) | 348 – 370 | 200 - 460 | 370 - 410 | 350 - 430 |
| P2H Demand (PJ) (Electric Energy) | 25 – 33.1 (21.1 for households) | 28 – 144 (14 – 72 for households) | 100 - 120 | 100 -170 |
| Heat Demand Profile | Variable (daily –seasonal) | Variable (daily- seasonal) | Flat or process specific | Flat or process specific |
| Power-to-Heat Demand Flexibility | -Decentralized control by consumer behavior / smart thermostats: Pre-heating. (1-2 hours shift)<br>- Direct Load control<br>-Thermal Energy Storage (Shift depends on the storage type/size)<br>-Switch between electricity and gas | -Centralized control: Smart Heat Grid (optimal shifting)<br>-Thermal Energy Storage (depends on the storage type/size)<br>-Switch between electricity and gas | Process oriented, usually inflexible.<br>-Storage of intermediate products<br>-Heat storage<br>-Switch between electricity and gas | Same as 2030. |
| Penetration P2H Technologies Households | [1] 7.9 % - [2] 20%- [3] 56 % | [4]12% - 22.6 %- 69% | [5]24 % - 32% - 52. 5 % | - |

| **Technology Options** | **HP (Air / Ground)** | **HHP** | **HP (Air / Ground)** | **HHP** | **Electric Furnaces** | **Hybrid / Dual –Fuel Boilers** | **Electric Boiler** | **Heat Pumps** |
|---|---|---|---|---|---|---|---|---|
| Technology Mix | **37%** - 95 % | 5% - **63%** | **17 %** -90 % | 10% - **83 %** | **HT** | **MT**<br>33 TWh – From hybrid systems | **MT** | **LT / MT / HT** |

| **Storage Options (Independent of years)** | **Centralized - Seasonal** | **Decentralized - Daily** | |
|---|---|---|---|
| **Types** | Tank thermal energy stores, pit thermal energy stores, borehole thermal energy stores, **aquifer thermal energy stores** (in 2050 19% - 21% of the heat demand) | Heat pump buffers<br>Electric storage heaters<br>Hot water storage<br>Smart Electric Thermal Storage | -High and medium temperature applications of phase change materials to provide process heat<br>-The thermochemical heat storage<br>- Heat and cold storage |
| **Shifting Potential** | 24 hours – 12 months | 3 to 24 hours | |

HP- Heat Pump HHP, Hybrid Heat Pump, HT - High Temperature, MT- Medium Temperature, LT - Low Temperature

# 4 Modeling Approach

In this chapter, the description of the COMPETES model is presented in two parts as the power sector and heat sector. The heat sector part conceptually describes the components that are included in the model from the real system description. The limitations of the model are explained reflecting which parts from the system description are not in the model. The explanation of the data set that is used for the scenario analysis is also provided. This section is followed by the description of the scenarios and the choice of the indicators that are going to be used in the analysis part.

## 4.1 Description of the Model

**A. Power Sector:**

COMPETES is a network constrained power system optimization and economic dispatch model which minimizes the total power system costs of the European power market under technical constraints of generation units and transmission constraints between countries. A power system model consists of the electric grid, its components, and their characteristics. The components include generators and their characteristics (start-up time, capacities), transmission lines and the electrical load. An economic dispatch and unit commitment model determines the optimal output for electricity generation units in order to satisfy the system load with the lowest possible cost under operational and transmission constraints. 28 European countries are included as nodes in the model. Transmission is according to an integrated EU network with a capacity limited by Net Transfer Capability which is the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner. The currently included border transmission links are according to the ten-year network development plan of ENTSO-E. The model reads the database for a relevant scenario year. It uses hourly time steps in a year for optimization and it is solved at once for each day in a year. Linear programming and mixed-integer programming are used for the formulation of the two modules of the model: Unit commitment and investment. Linear programming (LP) refers to a technique for the optimization including only linear relationships (a linear objective function, subject to linear equality and inequality constraints) whereas in a mixed-integer programming (MIP) problem some decision variables are constrained to be integer values. Figure 15 shows the network representation of the model. In this study, the investment module of the model is not used as it is expected that the model is able to cope with the added demand with the estimated generation capacity for 2030.

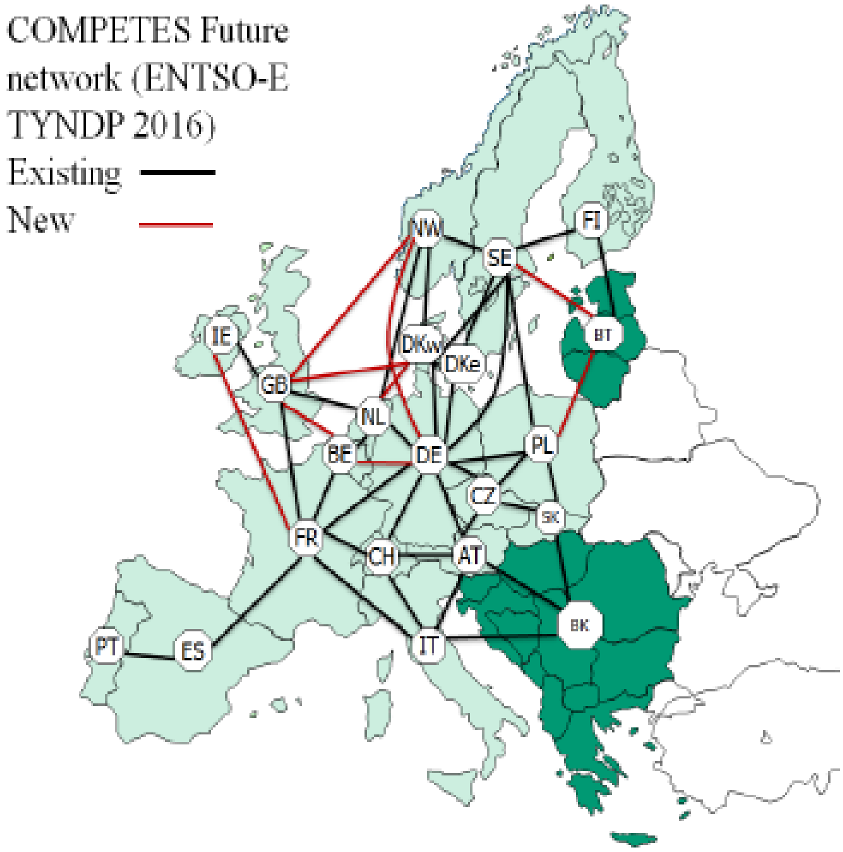



Figure 15: COMPETES Model Network Representation (Ozdemir, 2018)

The unit commitment economic dispatch module is used to determine the least-cost schedule (the (un)committed power plants, in other words, the generation units that are running or not) and economic dispatch (amount of energy generated) under perfect competition over a planning horizon. This part of the model is formulated as a mixed integer program (MIP) and used for the short-term operational decisions in day-ahead markets. Power output from the generators, electricity prices, total electricity consumed, unserved energy, the demand response variables for the electric vehicles, heat pumps and hybrid boiler are the decision variables of the model. The constraints of the model for this section can be divided as System Constraints, Generator Constraints, and Demand-side Constraints. System constraints consist of a market-clearing constraint which matches the supply and demand, and cross-border transmission constraints between countries. Generation constraints consists of minimum generation constraints when a unit is committed, ramping-up and down constraints (Increase/decrease of the production in consecutive hours, depends on the flexibility capabilities of different generation technologies), generation capacity constraints (a generator should not exceed its capacity in production), minimum up and down times for the units in NL, lumpiness in generator start-up decisions and reserve requirements. Demand side constraints in the model are load shifting for electric vehicle (EV) and P2H technologies, load shedding constraint and the constraint related to the shift between electricity and gas for the hybrid boiler.

Capacity expansion module is not used in this research but it is still briefly explained to provide an understanding of the further research suggestions. This module takes exogenous policy driven inputs such as RES penetration, nuclear / coal policies, implementation of capacity markets or increase/decrease of electricity consumption. Endogenous generation and transmission investments are determined according to these inputs. The capacity expansion model is formulated as linear programming. The investment model only includes investments of conventional generation technologies, transmission capacity and conventional hydro pump storage. Investments for renewable, heating technologies and thermal storage are not included.

Below the basic components of the model for the both modules are described:

Electricity Demand: Electricity demand is the final electricity demand in each country. The conventional electric load, additional electric demand for charging electrical vehicles, and household and industry power-to-heat load can be included as electrical load. The heat demand should be included as electrical load for households and as thermal heat demand for the industry.

Conventional Generation Portfolio: Input data of COMPETES includes a variety of generation technologies. The categorization of electricity generation technologies can be seen in Appendix E. The model includes 14 types of fossil-fuel-fired power plants which can operate with CCS or as combined heat and power (CHP) plant. Other technologies included are nuclear, geothermal, biomass, waste, hydro, wind and solar technologies. Technologies are in particular detailed unit by unit for the Netherlands. For the other countries, the same technology units with similar properties (age, efficiency, technical properties) are aggregated.

Electrical Storage:
Two types of electricity storage technologies are included in the model: Pumped Hydro Storage and Electric Vehicles. The amount and the duration of energy that can be provided depends on the input storage characteristics such as power/energy ratings or efficiency.

VRE Power Generation: The maximum hourly power generation from the solar and wind technologies depends on the input hourly load factors and the capacity of the technologies. The hourly load factor represents the variability of wind and solar.

Flexibility supply options in the model: Power generation (e.g. ramp up / down), power trade, electrical storage, VRE curtailment, Demand Shifting with EVs, power-to-heat (time shifting of household heat demand, switch between electricity and gas for hybrid boiler), power-to-hydrogen are the flexibility supply options in the model.

System Costs: The objective function of the model is to minimize system costs. The components of the system costs include fixed production costs (Start-up costs and minimum load costs), variable costs (Fuel-prices: Coal, natural gas, oil; CO2 costs) and other costs (Operation, and Maintenance cost, emission and fuel taxes) and operation costs of the hybrid boiler. Electricity prices that are determined by the model are the wholesale prices. The taxes, levies, grid charges that are later added to end-consumer prices are not included in the model.

**B. Heat Sector:**

The heat sector in the COMPETES model is still in the development phase. The technology options are all-electric heat pumps for the built-environment and hybrid boilers for the industry. Different demand profiles for the end-use sectors (residential, non-residential, industry) can be included in the model. The normalized profiles for a certain year (2030 and 2050) and the annual demand is multiplied to obtain hourly demand profiles.

The built-environment part of the model uses the input data of electric load for household heat pumps. Demand shifting is only possible in time but not in source for households. The demand can be shifted in time based on two parameters: Percentage flexible (shiftable) demand, maximum hours that is allowed for shifting.

Percentage flexible demand is the flexible part of the P2H demand that can be switched in time for hous. This part of the demand can be flexible due to the demand response capabilities including consumer behavior (willingness to shift the load based on incentives and different technologies such as smart thermostats) or any thermal storage technology that exists. Thermal Energy Storage (TES) is not explicitly modeled in COMPETES but represented by the maximum hours to shift the load. Percentage flexible demand can represent the degree of the availability of the demand response capabilities and the thermal storage technologies. The higher this percentage is, the more possibilities for utilizing the price fluctuations by shifting the power-to-heat demand in time. Maximum hours that can be shifted is a constraint that limits the shifting of load in time. It depends on the comfort limits and the size of the storage. Depending on these two parameters (percentage flexible demand, maximum hours to shift) the part of the load which is flexible is shifted.

The algorithm behind time shifting can be referred to as non-ideal shifting since there is a time restriction for the shifting. For a certain hour, it is checked whether the price decreases at a later hour within the maximum specified time limit. In this case, the load is decreased for that hour by the amount of the flexible load. Another possibility is if the price is going to be higher in the next hour within the time limitation, the load is increased for the low price hour and then decreased in the high price hour. The shifting takes place so that the system costs are minimized. How sensitive the shifting to the price difference between time steps is also important. There is a small penalty cost included for shifting in the current version of the model. In the real system, consumers might not want to react to really small price differences.

For the industry the load that needs to be satisfied by the hybrid boiler should be the thermal load since the part of the demand that is satisfied by electricity is endogenously determined by the model. The rest of the demand is satisfied by natural gas depending on the prices of gas and electricity. To supply the heat demand hybrid technology uses the cheapest source. In case the prices are the same model chooses to use either electricity or gas indifferently. Comparison of the electricity and gas prices is based on obtaining one unit of heat taking into account the efficiency of the electric and gas boiler. There might be also cases that electricity is preferred due to its lower price but the increasing electric load also increases the market price. After the point that electricity is more expensive than natural gas, the model chooses to satisfy the rest of the demand by using gas. In the end both electricity and gas are used in the same hour. For the industry, there is only shift between sources but not in time by the use of the hybrid boiler.

Overview of the inputs and the outputs of the model can be seen below in Table 12.

Table 12: Inputs and Outputs of the COMPETES model

| Inputs | Outputs |
|---|---|
| **Demand-side:** | **Demand-side:** |
| Electricity Demand (Hourly load profiles of demand based on the latest historical hourly data given by ENTSO-E.) | Shifted heat pump load profile |
| Power-to-heat demand profile for households | Industry: the amount of load satisfied by natural gas and electricity |
| Thermal heat demand for industry | |
| Percentage of flexible load for EVs and heat pumps | |
| Maximum hours to shift the P2H load for households | |
| Hybrid boiler option: Switch in between gas and electricity | |
| **Generation-side:** | **Generation-side:** |
| Efficiencies of technologies | Investments in conventional generation capacities (capacity expansion module output); |
| Installed power capacities | Hourly and annual power generation mix in each EU28+ country and region |
| Availabilities (seasonal/hourly) | CO2 emissions |
| Minimum load of generation and minimum load costs | |
| Start-up/shutdown costs | |
| Maximum ramp-up and down rates | |
| Minimum up and down times (only for the units in the Netherlands) | |
| Emission factors per fuel/technology | |
| Fuel prices per country, ETS CO2 price, (national CO2 tax) | |
| Hourly time series of VRE technologies (wind, solar, etc.) | |
| RoR (run of river) shares of hydro in each country | |
| Overnight costs for the conventional generation (Euro/MW) | |
| Generation capital expenses | |
| **System:** | **System:** |
| Transmission capital expenditures (CAPEX; Euro/MW) | Investments in cross-border transmission (interconnection) capacities (capacity expansion module output). |
| Net Transfer Capacities (TNC) between nodes | The supply of flexibility options, including power generation (ramp-up and down), power trade, energy storage (pumped hydro and compressed air) and VRE curtailments |
| | Hourly competitive electricity prices per country/region |
| | Power system costs per country/region |

## 4.2 Description of the Data

In this research, the 2030 database of the COMPETES model is used and it is updated based on the information from the latest Climate Agreement Report (Dodion & Melotte, 2018). Climate Agreement Report for the Netherlands is a package of policy measures that aims to bring 49% of emission reductions for the Netherlands by 2030 compared to 1990. Two important data for this research are the household heat pump profiles and the industrial heat demand. For the households, the profiles that were used for the FlexNet project are updated according to Table 11 in Chapter 3 by using the annual power-to-heat demand and technology mix percentages. Industrial heat demand is determined based on the research in Chapter 3. Below, the sources for the model parameters, demand profiles and technologies are explained more in detail.

- The hourly load profiles for conventional electric load are based on the latest historical data provided by ENTSO-E. For the future demand the increase in total (conventional) electricity demand is in line with the "Green Revolution Scenario" of ENTSOE-E.

- Load factor for renewable generation is calculated based on historical hourly generation data of the scenario year provided by ENTSO-E and TSO of different countries.
- The technical details of generation technologies such as generation type, capacity and the location of the technologies are updated frequently based on WEPPS database.
- Fuel and CO2 prices are obtained from public sources: IEA World Energy Outlook
- The transmission and generation capacity for the year 2030 is based on the ten-year network development plan of ENTSO-E and according to the constructions that are already in place and will be operational by 2030.

**Household Profiles:**

The household data set was used in 2014 for the FlexNet Project of ECN (Sijm et al., 2017). Household profiles for space heating and hot water are constructed by a model for a single household based on the solar radiation, outside temperature, building type (e.g. in-between, corner, apartment, isolated house), insulation level and the type of technology (hybrid, air, ground heat pumps). As all types of heat pumps require a high level insulation the profiles are created assuming that the households that have heat pumps are well insulated. 3 types of profiles exist for 3 different technology options. The load profiles for all three type of technologies are electrical load that is required to meet the heat demand of the household with that certain type of technology. Later these profiles are aggregated for different scenario years by using the technology mixes for the types of heat pumps for a specific year. Some corrections are made to make sure that the heat load of the households is not always the same in the same hours and the efficiency improvements of the technologies in the future years are taken into account. The profiles are normalized for different scenario year 2030. The normalized profiles are multiplied by the P2H demand for 2030.

**Industry Profiles:**

Profiles for the industry are usually flat and continuous. For this research, the model input is only the hourly heat demand for the hybrid boiler. This demand is assumed to be flat and continuous all year. An alternative profile for the industry is also described below. However, it is not possible to use it in the model right now without some minor modifications.

A binary production profile can represent the continuity and discontinuity of the production activities. This profile can be applied for both heat and electricity demand as it is assumed that once there is production, there is demand for both. The binary production profile is distinguished for large and small industries. Large industries can be considered as the ones which produce the raw material such as the paper and small industries are where the production is carried out in relatively small establishments (employing up to 100 people) and usually, a secondary product is produced from raw material.

For the large industries which approximately form the 90% of the industrial production in the Netherlands, the production is considered to be continuous and flat. The annual heat demand is distributed among the hours of the year. The remaining 10% constitutes the small industries and follows a discontinuous production profile. This means there is no production during some hours of the day. The data is obtained by following the production process of small industries. The evenly distributed hourly heat demand is multiplied with the binary profile to obtain the discontinuous heat load. The sum of these two profiles gives the total industrial heat demand profile. The percentages for the small and large industries are an approximation of an industry expert at ECN.

This is an alternative approach to represent the discontinuity and the difference between small and large industries. In fact, a significant part of the demand is from the large industry where demand response has the potential for grid flexibility. However, to observe the demand response possibilities more process specific data is required since the process itself is important in determining the heat demand. There is not a wide range of process-specific data available for heat consumption for the industry. This requires close follow-up of the processes. Due to the unavailability of this type of data and model restrictions, the industry profile is assumed to be flat.

## 4.3 Limitations of the Model and the Data

As the heat sector part of the COMPETES model is still under development, some parts from the real system description in Chapter 3 are simplified or not included in the model. These limitations, simplifications, and comparison with the real system description are discussed below. Some of the limitations address the available data sources.

- There is a limited amount of power-to-heat technologies (only one per end use sector) in the model. These technologies were chosen as the most promising ones. Hybrid heat pumps are not included for households as a technology option. The electrical load satisfied from the hybrid heat pump is determined outside of the COMPETES model (based on outside temperature by using another model). The electrical load that is satisfied by the hybrid heat pumps is aggregated with the rest of the electrical demand from the other type of heat pumps depending on the technology mix and provided as an input to the model. In this case, the optimal electricity and gas consumption for households is not determined within the COMPETES model. This limits the analysis in the household level. The literature and scenario studies in Chapter 3 present hybrid heat pumps as a transition technology in the process of electrification of heat sector. In addition, there are no all-electric technologies included in the industry part. However, these technologies still require more research and development and there is more uncertainty on the development of other technology options mentioned in Chapter 3. Exclusion of other technology options for the industry does not restrict the scenario analysis.
- As COMPETES is a power systems model it mainly includes generation side costs and emissions. After the addition of the hybrid boiler for industry, the operating costs for that technology is also included in the objective function. The costs and emissions for household heating are not included in the model if natural gas is used. However if the heat load is satisfied by electricity the heating costs from the household side are included in the costs. This might require some adoptions to the system costs in the scenario analysis part.
- The demand data for the non-residential part of the built environment is not included in the database. In 3, it is observed that power-to-heat technologies also have the potential for the service sector too. Exclusion of this load profile might cause underestimation of the need for flexibility.

- Thermal storage is not separately included in the model with the technical properties such as charge and discharge cycles or the size of the storage but it is represented by maximum hours to shift the load which is the capacity of the storage. Using thermal storage allows the shift of the electrical load in time without the necessity of end-consumers changing their heating schedule. The shifting of the electrical load in time is due to the charging and discharging of the storage. If the model decides to shift the P2H demand at time x to time x-1, this means that the battery is being charged at x-1 and discharged at the time x. If the heat demand is postponed to a certain time x+1 it means at x, battery is discharged and at x + 1 it is charged. The times that battery are charged are during the low price times. This approach assumes at each time step storage is capable of shifting the heat demand within the allowed time limit (max. hours to shift). It is assumed that the charging and discharging amount of the battery is the same without losses. Stinner et al.(2016) (Yin et al., 2016) uses the same assumption in a household heat demand model. Different possible charging/discharging strategies can lead to different load profiles. In this case, the analysis focuses on the flexibility that can be offered when the TES is fully charged in other words, the maximum flexibility that can be offered at each point.
- Additional electricity demand for charging electrical vehicles (EVs) and electrification of heat sector is only included for the Netherlands in the database. Many of the other European countries included in the model are also going through an increasing rate of electrification of the heat demand. Exclusion of the increasing electrical load from the other countries might result in underestimation of the system costs and result in different trade-flows between the countries.
- Investment costs for the demand response or power-to-heat technologies are not included in the model. The benefits from using these technologies should be evaluated separately outside of the model considering the investment costs as well.

## 4.4 Scenario Design

The COMPETES model, which is described in Section 4.1 is used for the scenario analysis to answer the following research questions which are explained in Section 2.3.

RQ1) What are the effects of heat demand flexibility on power sector and end-users?
RQ2) What are the implications if the flexibility potential is not fully unlocked?
RQ3) What are the effects of price distortions as a barrier against sector coupling?

Below is the list of all scenario variables that can be changed for the scenario analysis. Only the most relevant ones are varied to explore the answers for the above research questions. Some of the variables can be directly changed in the COMPETES model while some parameters such as climate conditions and insulation level are inputs to another building model that was used to form the heat pump load profiles.

**Renewable Penetration:** Capacity of renewable technologies is mostly dependent on the subsidies and policies of the government rather than market signals. The capacity of the renewable generation has a significant impact on how the additional P2H demand is integrated into the power grid.

**Insulation level:** Insulation level affects the demand profile of households for the different types of heat pump technologies. Profiles are distinguished between medium (energy rating B) and a high degree of insulation (NOM = zero on the meter).

**Heat demand:** The power-to-heat demand for the year 2030 varies between scenarios due to the uncertainty factors that are mentioned in Chapter 3. For households factors such as availability of the green gas and electricity prices have an impact on determining the range while for the industry the development of the technologies is the most important factor. Considering that power-to-heat demand is almost zero for the industry right now, the demand satisfied by power-to-heat technologies is sensitive based on the research and development.

**Technology Mix:** The technology mix specifies the share of all-electric and hybrid heat pumps for households. It is based on the households that already have a power-to-heat technology. Based on these percentages, a single heat pump profile for households is formed.

**Weather Conditions and Efficiency of P2H Technologies:** The chosen data set reflects average climate conditions. Outside temperature and solar radiance are considered to be in line with the climate year 2012 for the Netherlands. However, an extremely cold winter might have considerable impacts on the power-to-heat technologies by changing the efficiency of the heat pumps and also increasing the electricity demand. In the COMPETES model, the hybrid boiler consists of an electric boiler with 95% efficiency while the efficiency of the natural gas boiler is 85%. For the households, heat pump technology is not explicitly included in the model but only the heat pump load profile is included. The built-environment model which was used to form these profiles uses the coefficient of performance of the heat pump technologies based on the outside temperature. This coefficient of performance tends to decrease with decreasing outside temperature.

**Gas Prices:** One of the most important barriers against power-to-heat technologies is high electricity prices including taxes compared to low gas prices. The recent Climate Agreement Report expects a slow increase of natural-gas free homes until 2024 due to a limited cost reduction of the technology and a limited increase in natural gas prices. It is stated that the early years up to 2030 are very important for the development of power-to-heat technologies. In the early years, if electricity is still more expensive than gas, the technologies will not be purchased more and it is harder to expect capital cost reductions as well. This implies that the power gas price ratio is important to observe to address the regulatory barriers.

**CO2 Prices:** CO2 prices are the market prices from the ETS (Emissions Trading System). Industrial end-users are involved in the CO2 market while household heating doesn't include CO2 prices.

**Hybrid Boiler Operation:** Operation of the hybrid boiler for industry represents another flexibility option which is switching in between electricity and natural gas. This option can be activated or deactivated in the model database.

**% Flexible load for households:** The flexible percentage of the household load represents the part of the load that can be shifted in time for households. This is possible by using thermal energy storage or demand response technologies. However, there are certain barriers such as cost and regulations in front of the large-scale adaption of them. The flexibility potential might not be fully unlocked. The variable in the model represents the available potential despite these barriers. This variable can be changed to investigate the value of unlocking the full potential. This variable in the model is just used for the households. The percentage of the flexible load for the industry directly depends on the heat demand for the hybrid boiler which is 33 TWh for this research. It corresponds to minimum 27.5% of the whole potential according to Table 6 in Chapter 3.

**Max. hours to shift:** The maximum limitation of hours to shift the flexible heat load for households in time. This variable can represent the capacity of the thermal storage or comfort limit of the end-users.

**Number of electric vehicles:** The number of electric vehicles for a specific year.

**Electric Vehicle Controllable Load:** This input parameter determines the flexible percentage of the electric vehicle load and affects the grid to vehicle and vehicle to grid amount.

Three base case scenarios are designed to address the determined research questions of this thesis. The scenarios can be distinguished by mainly two aspects: The existence of the link between heat and power sectors and the existence of heat demand flexibility. To investigate the first aspect a scenario with no link between power and heat sectors is designed (No-P2H). This scenario is compared with InFlex-P2H Scenario where inflexible power-to-heat demand from industry and households are included. In InFlex-P2H Scenario, it is not possible to shift the household heat demand and it is not possible to switch in between the sources for industry. All the heat demand from industry is satisfied by electricity. No-P2H and InFlex-P2H Scenarios are compared to understand the power sector implications of the increasing coupling. To investigate the second aspect, heat demand flexibility, a third scenario with flexible heat demand is designed (Flex-P2H). Flex-P2H Scenario assumes that there is a link between power and heat sectors and both flexibility options from the household and industry side are available. The following variables change between scenarios: Hybrid boiler availability, flexible heat demand percentage and maximum hours to shift the household load. These parameters are representing the heat demand flexibility from the households and industry sides in the model. Their values are determined based on the research from Chapter 3. Table 13 summarizes the basic characteristics of the scenarios.

Table 13: Scenarios for the Analysis

| Scenario | Link Between Power and Heat Sectors | Heat Demand Flexibility |
|---|---|---|
| No-P2H | No | No |
| InFlex-P2H | Yes | No |
| Flex-P2H | Yes | Yes |

Below three base scenarios are presented. The following variables are kept the same for all of the scenarios:

- Renewable Penetration: Climate Agreement Database 2019: Wind on-shore: 9.305 GW, Wind off-shore: 11.264 GW, Solar PV: 25.025 GW

- Insulation level: All the houses with heat pump technology are assumed to have a high insulation level in the year 2030.

- Technology mix: Among the houses that already have power-to-heat technologies 25.9% have an air heat pump, 11.1% have ground heat pump, 63% have hybrid heat pumps. The ratio between air heat pump and ground heat pump is kept same as the FlexNet Project. The ratio between all-electric heat pumps and hybrid heat pumps are updated from Climate Agreement Report.

- Gas Prices: Projected prices from Climate Agreement Report (7.015 euro / GJ)
- CO2 price: Projected prices from Climate Agreement Report (41.81 euro/ton CO2.)
- Number of electric vehicles: 1.28 million
- Electric Vehicle Controllable Load: 70%

**Scenario: No-P2H**
Year: 2030
Household Annual P2H Demand: 0 Twh
Hybrid boiler: Not available
Industry Annual Thermal Load: 0 TWh
% Flexible load for households: 0%
Max. hours to shift the heat load: Not applicable, the load is not flexible.

**Scenario: InFlex-P2H**
Year: 2030
Household Annual P2H Demand: 5.86 Twh
Hybrid boiler: Not available, all heat load satisfied from electric boiler
Industry Annual Thermal Load: 33 TWh
% Flexible load for households: 0%
Max. hours to shift the heat load: Not applicable, the load is not flexible.

**Scenario: Flex-P2H**
Year: 2030
Household Annual P2H Demand: 5.86 Twh
Hybrid boiler: Available
Industry Annual Thermal Load: 33 TWh
% Flexible load for households: 25% [5]
Max. hours to shift the load: 5 hours [6]

Apart from the scenario variables that are varied for the base scenarios, three extra variables are varied to observe the impacts on the model outputs and the indicators: % Flexible Load for households, max. hours to shift and weather conditions. A sensitivity analysis for the first two variables was not performed before on the model as the heat part of the model is still under development. For this research effect of their change is important as they represent the heat demand flexibility. A sensitivity analysis with the extreme weather conditions is important based on the findings from Chapter 3. It was found out that outside temperature affects the coefficient of performance of the heat pumps as well as the total heat demand. All the variables are varied based on the Flex-P2H Scenario. The results from these variations are not presented in a separate section but presented inside the analyses within the relevant parts. Below the importance of varying these variables are explained:

[5] As a result of 2050 scenario analysis of CE Delft (Naber et al., 2016) it is expected that approximately 20% of the heat demand will be satisfied by the thermal storage in the Netherlands. In 2050, this potential would be close to the value of 50% which is the value assumed in Imperial College study (Strbac et al., 2018), when the demand response measures are also added. For this scenario, it is assumed that in 2030, half of this potential is available as 25%.

[6] Maximum hours a household thermal storage can shift the load is stated as 3 hours in (Eames et al., 2014), 4 hours in (Patteeuw et al., 2013) and 5 hours in (Sijm et al., 2017). For this scenario, the maximum value will be used.

**Percentage of Flexible Load:** The aim of the sensitivity analysis for % flexible load for households is to identify the value of increasing P2H load flexibility from the household side. In the base Flex-P2H Scenario it was determined that 25% of the household heat load is expected to be controllable in 2030. However, this percentage depends on factors such as development of thermal energy storage, demand response technologies, behavior of the consumers and policy barriers. The aim is to identify the benefits that are provided by the change of this variable and investigate the implications if the flexibility potential is not fully available. Therefore, this variable is changed for the values 0%, 50%, 75%, and 100%.

**Max. hours to shift:** The effects of maximum hours to shift the household P2H load is important for the decision making of the households. In the Flex-P2H scenario, based on the research from Chapter 3, it was assumed that households that have thermal energy storage are capable of shifting the heat demand 5 hours. The literature research in Chapter 2 revealed that without a storage, it is possible to shift the heat load one hour within the comfort zone. This number can be increased to two hours in case there is high-level insulation (Hedegaard & Balyk, 2013). With a higher capacity neighborhood scale storage, the maximum hours to shift the load increases up to 24 hours (Abhat, 1980). Therefore, this variable represents different investment choices for households. It also impacts the level of flexibility provided by households. By varying the maximum hours to shift, it is possible to compare the situations with and without storage as well as the importance of the size of the storage.

**Weather Conditions:** Weather conditions is an important factor that affects the efficiency of the heat pump technologies. The COP value decreases with the decreasing outside temperature. Usually, the coefficient of performance for a heat pump varies in between 3 and 5 also depending on its type and can decrease until 1.9 in -5 C (Haller, Haberl, Carbonell, Philippen, & Frank, 2014). This increases the heat demand as well as the times it is more efficient to use natural gas. The extreme weather conditions have important effects on the heating cost savings for the households. Heat pump load profile for the year 1984 which was a long cold winter with low average temperatures is used for this analysis. The heat demand for a relatively colder winter is raised from 5.86 TWh to 7.09 Twh based on the increase of the load of an individual household which is provided in FlexNet project heat pump profiles. The model is run again with the new heat pump load profile to obtain the electricity prices. A relation between temperature and the COP of the heat pump is also used to represent the change in the efficiency. The heating costs for the households are compared with the 2012 weather data set.

Rest of the scenario variables are kept constant and not varied in the scope of this research. However, it is important to reflect on the potential effects of these choices on the model results. As it was also discussed in Chapter 3, the P2H demand highly depends on the development of alternative options such as biomass, green gas, geothermal energy or residual heat from industry in the heat networks. This dependence creates some degree of uncertainty for the P2H demand for households and industry. For household P2H demand, the estimation from the National Energy Outlook is used for this research. This amount considers the expected developments in the competitive technologies as well. This number can be considered as less uncertain compared to industry. The literature research in Chapter 3 reveals that the pace of the efficient technology development for the high and medium heat demand is an important determinant of the rate of the electrification of the industry. 33 TWh can be considered as an optimistic assumption and the flexibility potential provided by the industry might be overestimated.

Another choice that has impacts on the results is the VRE generation capacity in the scenarios. The VRE capacity that is used for the scenarios is based on the latest Climate Agreement Report. In all scenarios the VRE capacity is assumed to be the same. However, No-P2H Scenario excludes 38.86 TWh power-to-heat load that is included in the other two scenarios. This might create an overcapacity of VREs for No-P2H Scenario. As no electrification is expected in No-P2H Scenario, less VRE capacity might be expected. The investment for renewable generation also depends on the government policies and subsidies apart from the market conditions. The details about the expected VRE capacity in case there is no electrification from the heat side, is left out for this study. However, the effect of this assumption on the results is discussed later.

Gas prices and CO2 prices are the same for all of the scenarios. The effect of the gas prices are observed more in details regarding the structure of the energy taxes. This analysis is performed outside of the model. Therefore, these variables are not changed in the model. The changes in the number of electric vehicles and the controllable load is not the focus of this research. As a result those variables are fixed for all scenarios as well.

## 4.5 Indicators for the Analysis

The above-mentioned scenarios will be compared based on the relevant indicators. The quantitative indicators derived from the model outcomes are the result of higher-level policy goals. The triple-A goals of the energy system is defined as "Availability, affordability and acceptability" which refers to the security of supply, low end-user prices and environmental and social acceptability, respectively (de Vries, Correljé, & Knops, 2018). Based on these higher level policy goals, specific indicators are determined for the comparison of the scenarios. Some of them are separated for the Netherlands or for all the EU countries in the model. Even though the purpose of this study is to observe the effects in the Netherlands, sometimes it is also reasonable to check indicators for the overall system including all the countries. This is explained more detailed below for specific indicators.

The indicators also differ based on the actors and their interests in the energy system. Investors in the generation side would like to obtain revenues from their investments and decrease their operating costs. Generators usually recover their investment costs during peak hours. For VRE generators, curtailment is an obstacle against increasing operating profits. Most of the time, end-consumers care about the reliable supply of energy and reducing their energy bill. Sometimes, the interests of these two actors might contradict. An example is the additional cost component renewable surcharges can be an extra burden for end-consumers while it is increasing the revenues of the generators.

**System costs**: Energy should be affordable for end-users and should be produced in the least costly way for the generators. Therefore, this is a common indicator for both of the actors. System costs can be defined as the total costs to supply electricity at a given load and a given level of security of supply (OECD, Nuclear Energy Agency). In this research, system costs include the power generation costs, heating costs of industry from hybrid boiler and heating costs for households. The last two components are added later to the model output. Systems costs both reflect the production and the heating part of the consumption side. Providing flexibility decreases the system costs by presenting alternative options to follow the highly variable residual load. The conventional way of providing flexibility is ramping up and down the power plants. In this case, the system cost of short-term balancing between supply and demand (high ramp-up / down and startup / minimum load costs, increasing imports) increases. Sector coupling is expected to decrease these costs. The amount of the change can be smaller in the overall system costs for EU as it includes all the EU countries and the scenario variables are only varied for the Netherlands.

**End-user heating costs and savings**: Heating costs are affected by the price of energy. The benefits of the provided flexibility for the end-users can be measured by the difference in the heating costs compared to before and after the availability of the flexibility options. For this study, only the heating costs are used and the electricity and natural gas consumption for other purposes (e.g. other electric home appliances, cooking) are not included in the costs. In addition, the energy prices do not include all the cost components which are explained in details in Section 3.4. The basic price components are supply costs, network costs, and taxes and levies (energy taxes, ODE, VAT). For this research, both for households and industry, only the effects of the energy taxes and levies and how they change the preference between the two sources are investigated. Therefore, all the heating costs are calculated by using the electricity and natural gas prices including the supply costs, and energy taxes and levies (energy taxes, ODE, VAT). The fixed part of the costs (network costs, fixed supply costs) are not included in the calculations. For households, the fixed supply and network costs for electricity will be paid in any case as electricity is used independent of the heating technology. There can be savings from the natural gas grid connection which is 13% of the total natural gas bill. For industry structure of network costs is more complicated and based on the capacity contracted as explained in Section 3.4. There are different exemptions (e.g. based on the operational hours of the technology). Even though the network costs are not included in the calculations, the possible effects are briefly discussed in Chapter 6. All the heating costs are annual.

**CO2 emissions**: Environmental impacts are important as much as economic concerns. CO2 emissions are the tonne of CO2 / year emitted. It includes the emissions from the power system and heat sector. If the heat demand is satisfied by electricity options in the model, the model output already includes the emissions from the heat sector. If the heat demand is not satisfied by electricity, the emissions from the natural gas are added later both for households and industry. One disadvantage of CO2 emissions NL is the possibility that the emission is transferred to another country. Even though the emissions of the Netherlands are low, the import amount might be increased and the CO2 emissions are moved to another country.

**VRE Curtailment:** VRE curtailment is another indicator for the analysis of the results. Curtailment of the renewable sources is the reduction in the delivery of energy or the scheduled capacity, usually involuntarily. It might be due to excess generation, transmission congestion or interconnection issues. In this case, production needs to be either reduced or stopped completely. Two implications of the curtailment are lack of integration of VREs implying the waste of green energy and the loss of income for wind and solar generators. Wind and solar generators usually are concerned about the economic impacts of the curtailment. It can be unfavorable for generators but good for the system. Curtailment of VRE is the last resort of flexibility after storage and demand response possibilities are explored. There might be times that curtailment is an economical solution and can actually result in system benefits. It helps to reduce net ramp rates or decreases start-up costs due to shutting down a large conventional plant and having to start it again in a few hours (Klinge Jacobsen and Schröder, 2012). Less curtailment does not have to be a positive indicator all the time by itself and it should be considered with other indicators. A decrease in the curtailment implies that the utilization from the renewable sources increases. This implies decreasing CO2 emissions and system costs as the production from conventional power plants are replaced with zero marginal cost VREs. The other way around, there can be less curtailment but a large amount of investments might be required for power generation or inter-connectors. The COMPETES model chooses the most cost-optimal option among the flexibility supply options. This indicator is still important from the point of view of VRE integration as this is also one of the purposes of sector coupling. However, it should be considered with the other indicators which are mentioned above.

**VRE Generation revenues:** VRE generation revenues are the operating revenues for solar and wind farm generators per MWh produced. Maximizing their operating profits is important for the generators. This indicator is also connected to the curtailment amount. Curtailment decreases the operational profits by ceasing production. Increasing flexibility in the power system increases the VRE utilization by lowering the curtailment amount which means increasing operational profits for generators.

**Residual peak load:** is the peak load after the renewable generation is deducted from the total load. Decrease of the peak residual load implies a better correlation between the VREs and the load. It is also important to avoid grid congestion. In a flexible scenario, it is desirable that the load matches with excess production times from VREs more often. This can be better observed in a residual load duration curve. A downwards shift in peak load, an upwards shift in off-peak load and a flatter curve will indicate that peak demand is moved to off-peak hours.

**The correlation between renewable generation and power demand:** This indicator provides insights on the match between the intermittent supply and power demand. Correlation is the statistical association referring to the degree which variables are linearly related to each other. For this indicator the renewable generation is the sum of wind and solar generation. The total demand includes the conventional electric load, load from electric vehicles, heat pumps and hybrid boiler.

One last indicator regarding the power system flexibility is the **system ramps**. It is defined as the difference between the residual loads of two consecutive times (MW/hour). This variation can either be positive or negative. Ramp-ups and ramp-downs are major indicators of the flexibility (ramping) needs of the power sector as a result of the variation of the residual power load (Sijm et al., 2017).

**Total Up and Down Ramp:** is the sum of the positive (ramp up) or negative ramps (ramp down) throughout the year. The sum of the ramp up and down values makes zero. This indicator provides an insight into the amount of changes in the residual load throughout the year.

**Average Up and Down Ramp:** is another useful indicator in terms of the power system. It is more meaningful to have an indicator which is per unit of time. Net Up and Down Ramp is calculated by dividing the total positive or negative ramp by the number of hours they occur (GW/ hours). The ramp up and down indicates the flexibility need of the power sector because of the variation of the residual load.

Table 14 summarizes all the indicators and shows the actor that is most interested. Some indicators are relevant for generators while some are for consumers in the system. Rest of the indicators are system level not specific to a certain actor.

Table 14: Indicators for Analysis

| Indicator | Actor |
|---|---|
| System costs for NL (MEuro) | System |
| System costs for EU (MEuro) | System |
| Generation revenues of wind and solar technologies (MEuro) | Generators |
| End-user heating costs and savings (Billion Euro) | Consumers |
| $CO_2$ emissions NL (Mtonne $CO_2$ / year) | System |
| $CO_2$ emissions EU (Mtonne $CO_2$ / year) | System |
| VRE Curtailment (GWh) | System |
| Annual residual peak load (GWh) | System |
| Total Up and Down Ramp (TWh) | System |
| Average Up and Down Ramp (GW/#hours) | System |

# 5 Analysis of the Model Results

The following analysis of the scenario and the sensitivity runs address the sub-research questions. Each analysis is explained with the necessary background information, the methodology used and the interpretation of the results.

## 5.1 Analysis 1: Effects of Increasing Sector Coupling - Need for Flexibility

This analysis compares the No-P2H and InFlex-P2H scenarios to understand the implications of the increasing sector coupling between power and heat sectors. The InFlex-P2H scenario includes 33 TWh heat demand from the industry which is not flexible and satisfied by electricity. The hybrid option is deactivated. In the same scenario, 5.86 TWh of household heat pump load is also included. The time-shifting option is also deactivated for this part of the load. The analysis aims to highlight the increasing need for flexibility in case the power-to-heat demand is completely inflexible. In this case, it is expected that the electrification of the heat sector creates a need for more flexibility instead of being an alternative flexibility supply. The flexibility provided from the conventional power plants, imports, VRE curtailment or flexible load from the electric vehicles can become the solution for the increasing ramp needs. To compare the two scenarios the basic indicators that are explained in Section 4.5 are used. The sources to satisfy the ramp needs and the generation mix for the two scenarios are also compared. The ramp needs are identified before the VRE curtailment to also observe how much of the ramp need is satisfied by curtailment. The summary of Analysis 1 is seen in Table 15.

Table 15: Summary of Analysis 1

| Analysis | Objective | Outputs from the Model | Indicators |
|---|---|---|---|
| Comparison No-P2H and InFlex-P2H Scenarios | Gain initial insights on the main research question and the need for flexibility due to increasing sector coupling | - Generation costs for EU,NL<br>- VRE Curtailment<br>- VRE Generation Revenues<br>- CO2 Emissions for EU | System costs NL, EU<br>VRE Curtailment<br>VRE Generation Revenues<br>Residual Peak Load<br>Correlation VRE and total demand<br>CO2 Emissions NL, EU<br>Total Ramp<br>Net Up and Down Ramp |

The model outputs from the No-P2H and InFlex-P2H Scenarios are presented in Table 16. As explained earlier, system costs include the costs for generation, net imports and the costs from the heat sector. The model output costs only include the costs from the power sector but not the heat sector unless the demand is satisfied by electricity. Therefore, the costs from the heat side (industry and households) are added to No-P2H Scenario. It is observed that there is 1.7 % decrease in system costs NL in InFlex-P2H Scenario. Even though there is a decrease in the system costs according to its definition, the break down of the components reveal different implications. The only reason of the cost decrease is the decrease in the household natural gas consumption. Using electricity decreases the energy required due to high efficiency of the heat pumps. All the other cost components; industry heating costs, the power system generation costs and the import costs increase. Increase in the import costs signal more dependency on the outer sources. System costs for EU decreases 0.15%, a very small decrease.

Table 16: Indicators No-P2H and InFlex-P2H Scenarios

| | No-P2H | InFlex-P2H | Change |
|---|---|---|---|
| System Costs NL (MEuros) | 1637.6 | 1609.7 | 1.7% decrease |
| System Costs EU (MEuros) | 53085.95126 | 53002.3 | 0.15% decrease |
| VRE Curtailment (GWh) | 556 | 97.4 | 82.4 % decrease |
| VRE Generation Revenues (MEuros) | Wind onshore: 870<br>Wind offshore: 1665<br>Solar PV: 821<br>In total: 3356 | Wind onshore: 1082<br>Wind offshore: 2063<br>Solar PV: 943<br>In total: 4088 | 21.8% increase |
| Residual Peak Load (GWh) | 17 | 22 | 29.4% increase |
| Correlation between VRE and Demand | 0.263 | 0.327 | 24% increase |
| CO2 Emissions EU (Mtone / year) | 348.9 | 354.5 | 1.6% increase |
| CO2 Emissions NL (Mtonne / year) | 30.6 | 22.1 | 27% decrease |
| Total Up and Down Ramp NL (TWh) | 6.97 | 9.57 | 12% increase |
| Average Up and Down Ramp (GW/hours) | UP: 1.62<br>DOWN: 1.57 | UP: 1.9<br>DOWN: 1.7 | |

The next indicator in Table 16 is VRE curtailment. VRE curtailment decreases 82.4%. One reason for this high decrease can be due to the assumption related to VRE capacity. No-P2H Scenario assumes the same renewable generation capacity with InFlex-P2H Scenario where a substantial amount of electrical load is added. In a scenario where there is no power-to-heat demand is expected, renewable capacity might have been less. This assumption might cause the overestimation of the decrease in VRE curtailment. The correlation between VRE generation and the total power demand also increases from 0.263 to 0.327 in InFlex-P2H Scenario. Even though for both scenarios the correlation is not really high, there is an increase compared to No-P2H Scenario. VRE generation and total demand tend to match more in InFlex-P2H Scenario. It is also observed that the revenues for the wind and solar generators increase 21.8% due to decreasing curtailment and increasing off-peak prices which can be seen in Figure 17. When all these indicators are evaluated together, it can be concluded that VRE utilization increases even if the P2H demand is inflexible. The residual load and price duration curves in Figures 16 and 17 also support the decrease in the VRE curtailment and the increase in the VRE generation revenues.

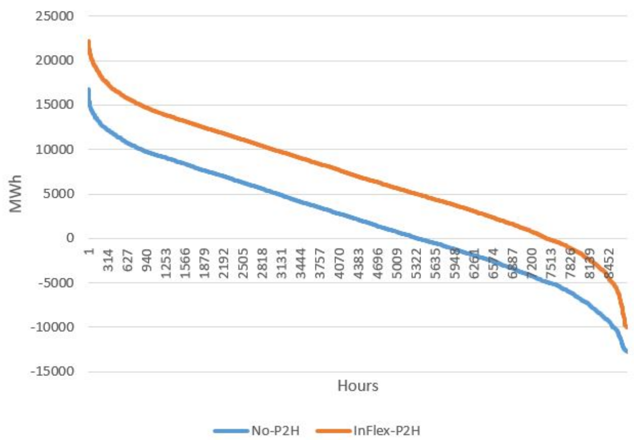



Figure 16: Residual Load Curve No-P2H and InFlex-P2H

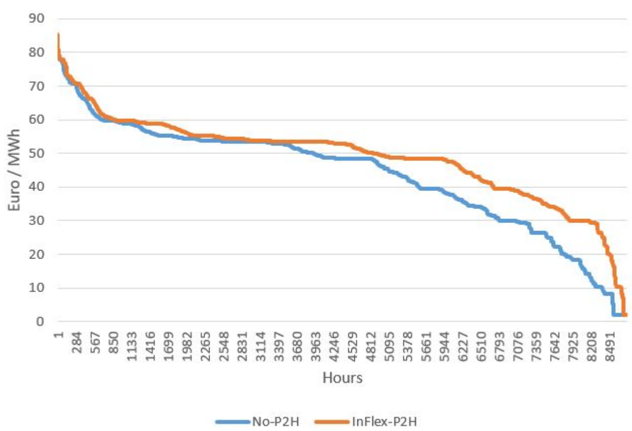



Figure 17: Price Duration Curve No-P2H and InFlex-P2H

Figure 18 reveals how much the generation mix changed to satisfy the 38.86 TWh electrical load increase. The figure presents the supply and demand side of the system balance for the whole year. At the demand side of No-P2H Scenario, in addition to conventional electric load, there is the inflexible part of the electric vehicle demand, grid to vehicle amount and the exports. At the demand side of the InFlex-P2H Scenario, it is observed that the exports decrease. At the supply side of No-P2H Scenario, both onshore and offshore wind energy and gas are the main electricity supplies. The major sources of supply are still the same in the InFlex-P2H Scenario. The important difference is increasing imports and gas usage. Other sources of supply are the same between the two scenarios. Even though there is a slight decrease in the system cost, the increase in the imports imply a dependency to outer sources. The net imports increase 66% in InFlex-P2H Scenario.

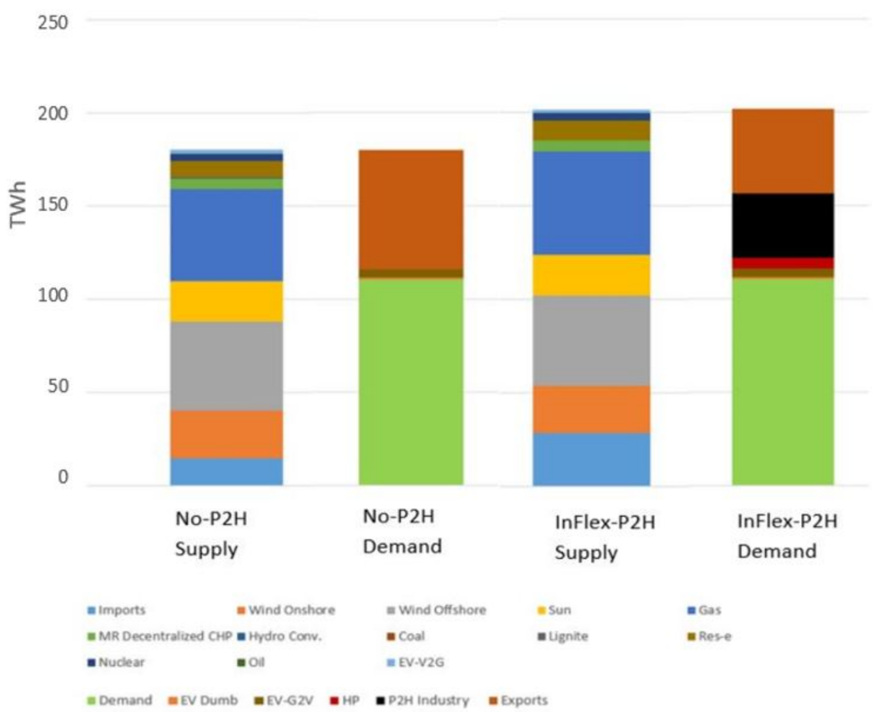



Figure 18: Supply and Demand Balance: No-P2H and InFlex-P2H Scenarios

One of the other indicators in the Table 16 is the residual peak load. Residual peak load increases from 17 GWh to 22 GWh. This is an expected result as a substantial amount of inflexible power-to-heat load is added in InFlex-P2H Scenario. CO2 emissions for the Netherlands decreases 27% when the inflexible power-to-heat demand is added. The decrease can be explained by the decrease in the usage of natural gas for heating. The heat demand that used to be satisfied by natural gas for households and industry in No-P2H Scenario is satisfied by electricity in InFlex-P2H Scenario. The decrease in the curtailment and increase in imports also supports the decrease in CO2 emissions for NL. On the other hand, the emissions for the EU increases 1.6%. The possible reason for this increase might be the transfer of the emissions to other countries due to increasing imports.

The total ramp and the average up and down ramp needs reveal the increasing need for flexibility. The total up and down ramp are very similar so only one of them is presented in Table 16. Total ramp increases from 6.97 TWh to 9.57 TWh. The average up and down ramp also increases in InFlex-P2H Scenario. Figure 19 presents the sources that provide the necessary ramp-up needs. Ramp up and down graphs behaves similarly. In No-P2H Scenario, most of the ramp need is supplied by net imports. This is followed by the ramp that is provided by flexible electric vehicle load. This means, either vehicle to grid amount is increased or grid to vehicle is decreased to satisfy to increasing load in between two consecutive hours. Other most used sources to meet the ramp-up needs are curtailment, gas (CCGT and CHP plants, derived gas) and other renewables (biomass, hydro), respectively. In InFlex-P2H Scenario, the ramp needs that are provided by gas and VRE curtailment decrease. The increase in the ramp needs is compensated by the ramp changes in net imports and flexible electric vehicle load.

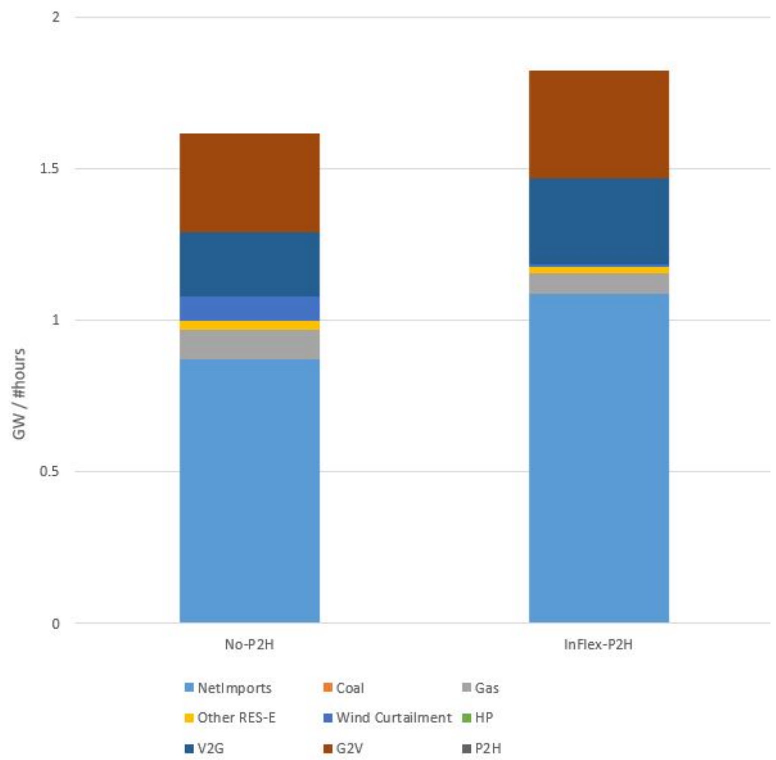



Figure 19: Supply of Flexibility: No-P2H and InFlex-P2H Scenarios

The major findings of this brief analysis reveal that the increasing power-to-heat demand for 2030 (33TWh from industry, 5.86 TWh from households) has important effects on the power system. There is a limited decrease in the system costs for the Netherlands due electrification of the heat sector. System cost decrease might be limited as the additional electric load from heat sector is not flexible. The decrease in the household heating costs is the reason for the decrease in the system costs NL. The residual peak load increases as a result of the increase in the electrical load. This also causes increases in the imports which implies more dependency to outer sources. One important benefit that is observed is the increase in VRE integration. VRE curtailment decreases and the VRE generation revenues increase. In the EU level, the implications are less significant. The system costs stay almost the same and there is a slight increase observed in CO2 emissions which might be caused by the increased imports in NL. According to the average and total ramp indicators, the need for flexibility in the power system increases for the Netherlands. Some part of the increasing ramp need is satisfied by the smart charging of the electric vehicles while the rest is mostly satisfied by the increasing imports. Some part of the gas and VRE curtailment options in No-P2H is also replaced by the smart charging and net imports in InFlex-P2H Scenario. Smart charging of the EVs is the only demand response option in InFlex-P2H Scenario. In the case of increasing demand, it gains importance to satisfy the ramp up and down needs.

## 5.2 Analysis 2: Effect of Additional Supply of Flexibility- Thermal Storage

This analysis compares the two scenarios InFlex-P2H and Flex-P2H which are described in Section 4.4 to answer the research question *"What are the effects of the heat demand flexibility on power sector and end-users?"* InFlex-P2H Scenario includes the inflexible load for household heat pumps, industry hybrid boiler and flexible load for the electric vehicles. Flex-P2H Scenario assumes that 25% of the heat demand is flexible due to the usage of thermal energy storage and the load of heat pumps can be shifted 5 hours in time. The percentage of 25% was found as the potential flexible heat load for 2030 based on the research in Chapter 3. The electric vehicle load is assumed to be 70% flexible for both of the scenarios. The aim of the analysis is to investigate the value of the potential provided by the heat demand flexibility including shifting the load (households) and switching the sources between electricity and natural gas (industry). A brief reflection from the perspective of the end-users is also provided at the end of the analysis. The summary of Analysis 2 is seen in Table 17.

Table 17: Summary Analysis 2

| Analysis | Objective | Outputs from the Model | Indicators |
|---|---|---|---|
| Comparison InFlex-P2H and Flex-P2H Scenarios | Answer RQ 1 | - Generation costs for EU<br>- VRE Curtailment<br>- VRE Generation Revenues<br>- CO2 Emissions for EU | System costs NL, EU<br>VRE Curtailment<br>VRE Generation Revenues<br>Residual Peak Load<br>Correlation VRE and total demand<br>CO2 Emissions NL, EU<br>Total Ramp<br>Net Up and Down Ramp<br>End-user heating costs and savings |

The comparison of the scenarios by using the relevant indicators can be seen in Table 18. One of the most important result to consider for the comparison of the indicators is the electrical load difference between two scenarios due to usage of hybrid boilers. When this option is available 81% of the time natural gas is used due to cheaper prices. This decreases the heat demand that is satisfied by electricity from 33 TWh to almost 6 TWh.

Both in the EU and in the Netherlands system cost decreases are observed indicating the financial value of the heat demand flexibility. The system costs for EU decrease 2.6% while the decrease is 18.4 % for the Netherlands. The example calculation of system costs for the Netherlands for both scenarios can be seen in Appendix F. VRE curtailment decreases 10% but there is also 6% decrease in the VRE generation revenues. The reason for this can be observed in Figure 21 with the decreasing electricity prices. Lower electricity prices are observed in Flex-P2H Scenario as a result of decreased electrical load.

The next indicator in Table 18 is the residual peak load decrease of 18.1%. The option to switch to natural gas and the time shift for the households contributes to the decrease of the peak load. Residual load duration and the price duration curves are also the indicators of the changes in the power system. Figures 20 and 21 present the residual load and price duration curves for the two scenarios, respectively. The total load for both scenarios includes

Table 18: Indicators InFlex-P2H and Flex-P2H Scenarios

| | InFlex-P2H | Flex-P2H | Change |
|---|---|---|---|
| System Costs NL (MEuros) | 1609.7 | 1312.8 | 18.4% decrease |
| System Costs EU (MEuros) | 53002.3 | 51100 | 2.6% decrease |
| VRE Curtailment (GWh) | 97.4 | 87.5 | 10.1% decrease |
| VRE Generation Revenues (MEuros) | Wind onshore: 1082<br>Wind offshore: 2063<br>Solar PV: 943<br>In Total: 4088 | Wind onshore: 1010<br>Wind offshore: 1924<br>Solar PV: 909<br>In Total: 3843 | 6% decrease |
| Annual Residual Peak Load (GWh) | 22 | 18 | 18.1 % decrease |
| Correlation between VRE and Demand | 0.327 | 0.553 | 69% increase |
| CO2 Emissions EU (Mtonne / year)) | 354.5 | 342.9 | 3.2% decrease |
| CO2 Emissions NL (Mtonne / year) | 22.1 | 21.8 | 1.3% decrease |
| Total Up and Down Ramp (TWh) | 9.57 | 9.59 | - |
| Average Up and Down Ramp | UP: 1.9<br>DOWN: 1.7 | UP: 1.82<br>DOWN: 1.6 | |

the conventional electric load, heat pump load, electric vehicle load and the load of the hybrid boiler from the industry. The residual load is calculated by subtracting the VRE generation (wind and solar). This already includes the curtailment (after curtailment).

The residual load curves in Figure 20 show that the heat demand flexibility contributes to a decrease in the peak demand during peak hours. On the other hand, there is no increase in demand during mid-load and off-peak hours as it would be expected as a result of demand response. The reason for this can be explained by the high natural gas usage by the hybrid boiler. Even during the mid-load and off-peak hours, natural gas is usually cheaper than electricity. In this case, natural gas is preferred and electricity consumption is decreased. It is seen that the difference between the two residual load curves keeps decreasing towards off-peak hours. However, the demand response options are not enough to increase the off-peak load. From the industry side this is due to high preference of gas usage. From the household side, the flexible part of the heat load might not be enough to increase off-peak load.

In Figure 21, a decrease in the electricity prices is observed in the peak load (First 1200 hours) and mid-load (between 1200 and 7200 hours) times in Flex-P2H Scenario (Sijm et al., 2017). In addition, there are periods that the difference between the prices are higher than the rest of the graph (1225-20141 ,3673-4897, 5101-7141 hours). The decrease in the prices in these load times can be explained again by natural gas replacing substantial part of the heat demand from industry and decreasing the electrical load. Only during the off-peak load times, the prices are almost the same. The flexibility provided by the heat side does not increase the off-peak prices. The heat demand from industry is mostly satisfied by natural gas (81%) and the demand shift from the household side is not enough to change the prices.

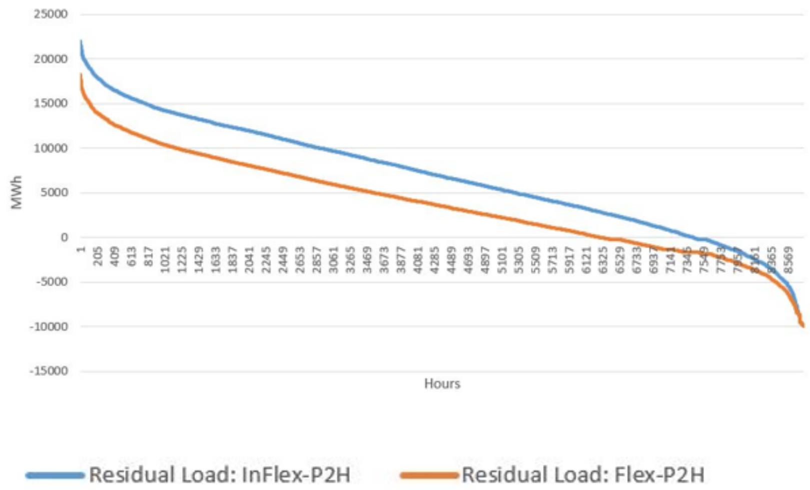



Figure 20: Residual Load Duration Curve: No-P2H and InFlex-P2H Scenarios

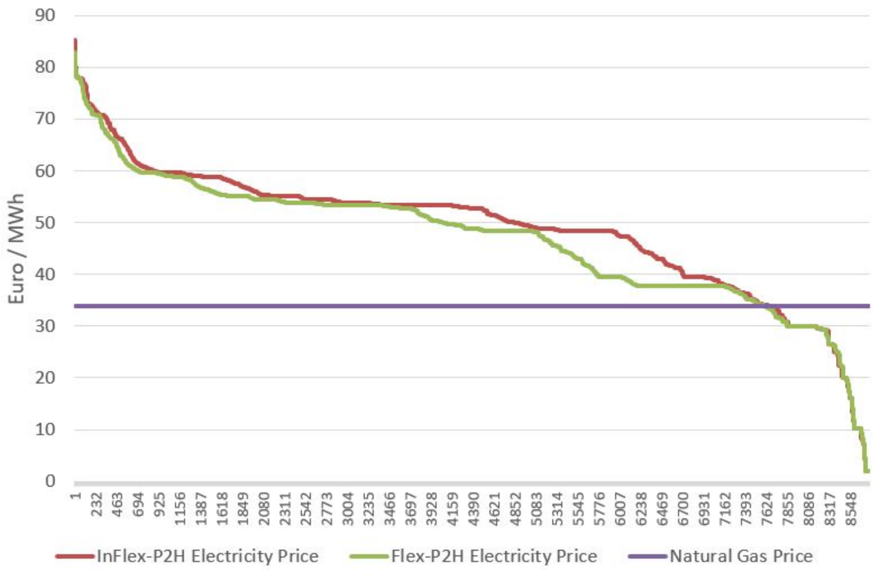



Figure 21: Price Duration Curve: No-P2H and InFlex-P2H Scenarios

The next indicator in Table 18, the correlation between the VRE supply and the total demand, increases in Flex-P2H Scenario. This can be explained by the response of both types of consumers to the changes in energy prices. Industrial end-users decide when to use electricity based on gas versus electricity prices while households can shift the heat demand in time based on the changes in electricity prices over time. Hourly power demand tends to follow a pattern more in line with VRE generation as a result of these responses. Another indicator is the CO2 emissions. There is a decrease in CO2 emissions both in the EU and the Netherlands. There is 1.3% decrease of CO2 emissions for the Netherlands and 3.2% decrease for the EU. The decrease is limited since natural gas is preferred over electricity most of the time for the hybrid boiler due to cheaper gas prices.

The total ramp and average ramp up and down needs for the power system decrease slightly in the Flex-P2H Scenario. This change is due to the decreased electrical load in Flex-P2H Scenario. The decreased heat demand from the industry is satisfied by natural gas instead of electricity. The sources to satisfy the net ramp-up needs are seen in Figure 22. It is observed that flexibility provided by the heat sector mostly replaces imports, natural gas, other renewables and the controllable electric vehicle load.

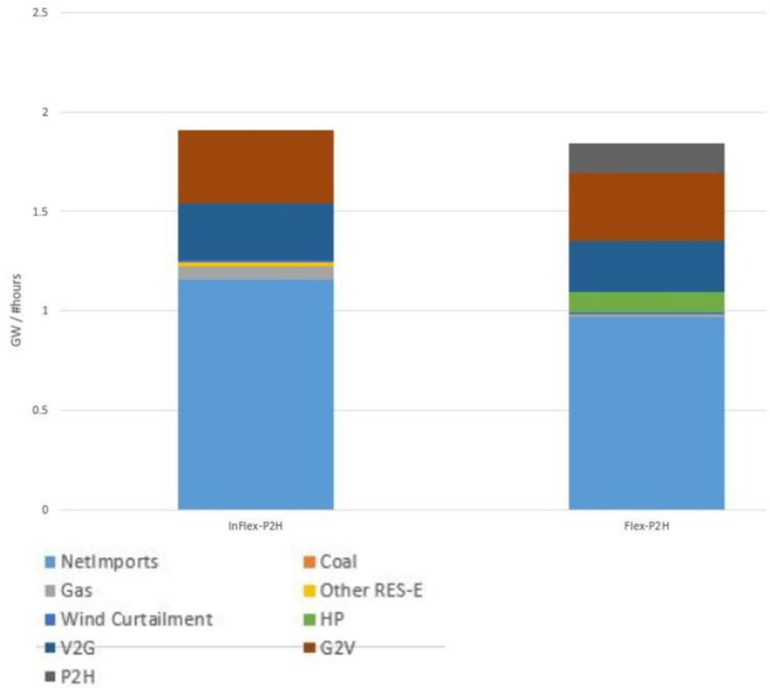



Figure 22: Supply of Flexibility: InFlex-P2H Scenario and Flex-P2H Scenario

The generation mix of the two scenarios can be seen in Figure 23. The balance is yearly and it is the sum of all the supply and demand sources. In Figure 23, on the supply side as a result of decreasing demand, imports decrease. On the demand side conventional electric load, electric vehicle and heat pump loads are the same for both of the scenarios. The only difference is the less power-to-heat demand from the industry as explained before. That part of the demand is replaced by exports. The most important difference between the two scenarios is the decrease in the net imports in Flex-P2H Scenario. There are no substantial changes in the usage of the other supply sources.

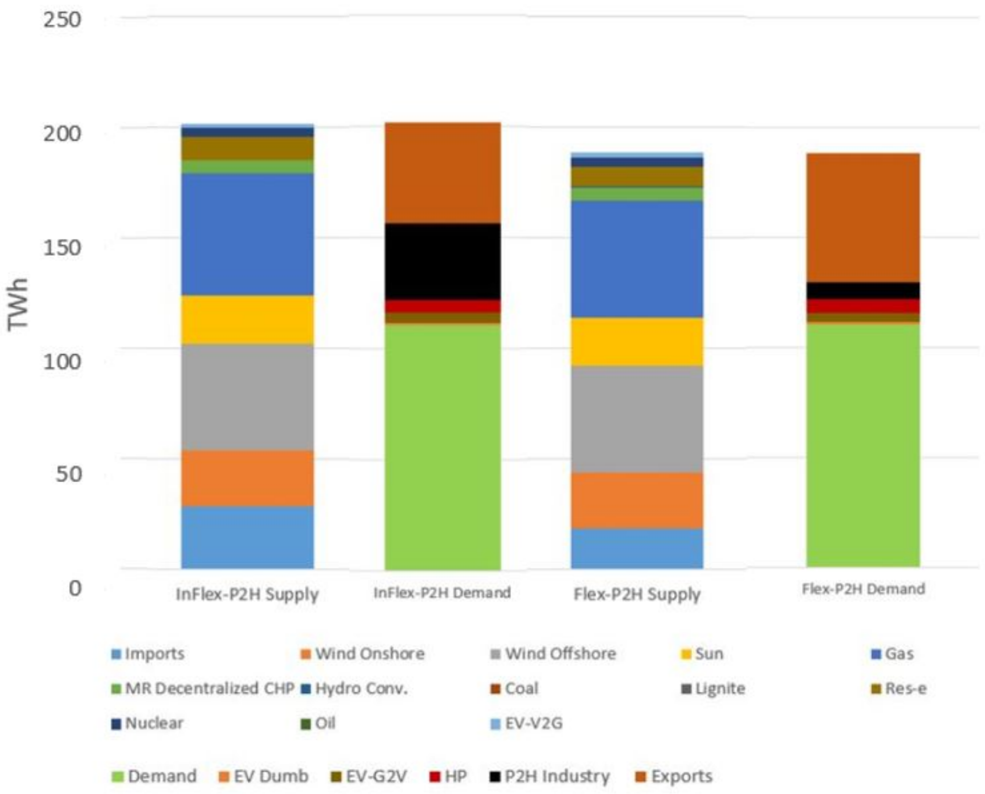



Figure 23: Supply and Demand Balance: InFlex-P2H Scenario and Flex-P2H Scenario

So far an overview of the changes in the power system has been presented. The following part of the analysis focuses on the perspective of the end-users: households and industrial consumers.

**Households:**

In Figure 24, the household heat pump load for 24 hours is compared between InFlex-P2H Scenario and Flex-P2H Scenario. These hours are chosen from the first day of January. The electricity prices for two scenarios are seen as one line in the graph as they are almost the same. From the perspective of households, 5 hours of shifting would be only possible via thermal energy storage. It can be interpreted that during the first two hours, heat from the thermal energy storage is used due to the high electricity prices. The following hours, there is a decrease in the electricity prices and the storage is charged to compensate for the previous two hours. From 3 to 15 hours, electricity prices are the same. However, there is still a shift observed. The model chooses to shift the load, as this does not make any change in terms of the household costs and the objective function. However, this behavior might cause an unnecessary increase in the load. The model objective function includes a penalty to avoid this unnecessary shift to a certain extent. During the low price period, storage is charged once more between hours 13 and 15. This amount is used between hours 15 and 16. Starting from 16 till 20 hours the electricity prices increase. Starting from 17 for four hours heat from the storage is used. After hour 21 prices start to decrease and again the storage is charged. Most of the time, if in the previous hours the storage was discharged, the next suitable hour charging is done one at a time for all the used load previously. This is the case for the first two hours and also for the interval 17-21 hours. The load for the interval 17-21 hours is compensated at 22 hours. As the prices during 23 and 24 hours are still the same, the load could have been compensated during those hours as well. This situation might also cause increases in the peak load when compared with the inflexible load profile.

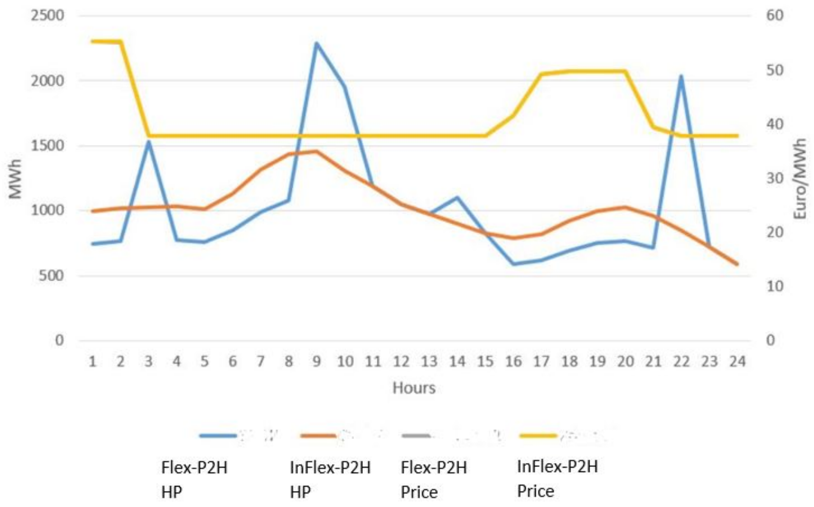



Figure 24: 24 hours heat pump profile for households

In addition to the load profile and the peaks, the economic benefits of the shifting for households is important. In the model cost of storage is not included so a household level analysis is made regarding the benefits gained from heat demand flexibility (shifting P2H demand in time) and whether it would be enough to cover the costs of thermal storage. Heating costs of households which have the storage (households that have a flexible demand profile) and the households without storage (inflexible demand which can not be shifted in time) are compared. The difference gives the savings that the households can achieve in their energy bills annually. The aim is to calculate the heating cost difference between the two types of households and the percentage it constitutes in the overall heating costs. Therefore, it is more reasonable to evaluate the numbers comparatively for the two types of households. Thermal energy storage, which operates in a cost-efficient manner in terms of the electricity prices, can help households to reduce their heating bills. This is a motivation for the households to either use decentralized heat storage or be involved in a central neighborhood scale storage. The savings from the heating costs can be used to determine the payback period of thermal energy storage for a household.

In this analysis, it was assumed that based on the research in Chapter 3, 25% of the households have thermal energy storage in the form of a small tank water storage system or connected to a centralized smart electric thermal storage which is capable of shifting the load maximum 5 hours. InFlex-P2H Scenario profile in Figure 24 is used to represent the households without thermal energy storage while Flex-P2H Scenario profile is used for the households that have thermal energy storage. Both types of households have the same total annual consumption but a different profile. The consumption of a single household is calculated by dividing the total heat pump load for all households by the number of households that have power-to-heat technologies in 2030, which is assumed to be total of 4.9 million households. This number was decided based on the research in Chapter 3. The electricity prices from Flex-P2H Scenario are used as there is only a slight difference between the prices of both Flex-P2H and InFlex-P2H Scenarios. These prices from the model output are modified to represent the household electricity prices. The model electricity prices are modified in a way that consumer taxes are also included based on Table 10 in Chapter 3. The annual electricity costs for a single household due to the usage of heat pumps is calculated as 603 euros annually when the heat pump load is inflexible. When the same calculation is done for the households with thermal storage (flexible load), it is found that a single household saves 150 euros annually compared to a house without thermal energy storage. This is **25 %** of the annual heating costs of a household without thermal energy storage.

Max hours to shift the flexible heat demand was chosen as five hours in this scenario. It was already found out in Chapter 2 that within the comfort limits, it is possible to shift the heat load 1 hour. This number can be increased one more hour in case there is high-level insulation. In this research, the data profile was formed with the assumption that the houses have the highest level of insulation. The variable maximum hours to shift the load is changed as 2 hours in Flex-P2H Scenario to see whether the difference is significant when there is thermal energy storage. The overall consumption is the same for both of the households but only the consumption hours differ. When the same analysis is conducted with a maximum of 2 hours shifting for households, the household savings decrease to 120 euros annually which is **20 %** of the total heating costs when the demand is inflexible. It should be noted that the purpose of this comparison is to identify the potential of the 2 hours shifting in case a household already has a high level of insulation and has information about the prices. This also reveals how much additional value the thermal storage can provide. The purpose is not to reflect on how much savings insulation provides. This requires another type of data set as the data set used for this analysis already assumes high-level insulation. When the storage has a capability of shifting the load for 23 hours the savings were 250 euros annually which is 41% of the annual heating costs. However, it is not possible to shift the load for this duration only by using an individual storage. A neighborhood size, centralized storage is necessary.

The analysis from the model results shows that there is only 5% difference between the amount of heating cost savings that can be achieved via shifting the load by thermal storage (5 hours) and high-level insulation (2 hours). For an existing household which is connected to the natural gas grid, increasing the insulation measures, installation of heat pumps and integration of thermal energy storage (e.g. a heat pump buffer) is quite costly. However, most of the newly built households are already constructed with high-level insulation and with heat pumps as the heating source (without a connection to the gas grid). In this study, all the houses that use the heat pumps are assumed to have high insulation. In this case, these houses with high insulation can already save 20% within the comfort limits by adjusting their consumption based on the electricity prices. In case they decide to invest in thermal energy storage which is capable of shifting the heat demand 5 hours, the savings increase to 25%. The value of this extra investment depends on the investment costs of thermal energy storage. The storage cost is strongly related to its size.

To gain some insights whether it would be worth for those households to make the extra investment to save 5% more from their annual heating costs, a heat pump with a buffer storage tank can be taken as an example. A German manufacturer and supplier of eco-friendly heating systems, Solarbayer GmbH offers buffer storage tanks in the standard sizes 500, 800, 1000, 1500, 2200, 2500, 3000 and 5000 liters. This type of storage is recommended for the integration of biomass boilers and heat pumps. A 5000 L buffer heat storage tank with double installation is able to shift the heat demand as much as the identified hours in Flex-P2H Scenario. Such a buffer tank costs 4500 euros. With 150 euros annual savings this cost is covered at least 30 years (without including the interest rate) which does not seem to be a viable option. Smaller buffer water tanks such as 3000 L costs relatively less 2940 euros with a lower capacity to keep the heat approximately 3 hours which will provide savings in between 20% and 25%.

It was observed that only with insulation already 20% is saved annually. In this case, individual storage buffers provide slightly more benefits than heat demand shifting that is provided by insulation. Instead of investing in individual storage buffers, usage of collective storage within the neighborhood scale which can defer the heat load the same amount or even more can be more economical. In this case, the costs can be shared between different actors within the neighborhood. In addition, for collective storage projects, utility companies or DSOs might also provide incentives for households in return of decreasing the peak load for certain hours. Involvement of more actors can make the case more economical. As the storage size increases, the cost of the storage per volume decreases. In heat networks, a neighborhood size storage of 300m3 of water costs about 470 Euro/m3 while for 12 000 m3 to costs would decrease to 120 Euro/m3. Pit thermal stores (seasonal storage) have a cost of 30 Euro/m3, with 75 000 m3 volume of water (Eames et al., 2014). More cost savings can be achieved with a higher capacity storage compared to the 5 hours that is used in this study. The costs would be shared within the actors who are going to benefit from the shift of heat load in time such as households, utilities, and DSOs.

**Industry:**

In this section, the impacts on the industrial end-users is presented. For industrial end-consumers, in InFlex-P2H Scenario, there is no option to switch between natural gas and electricity. That demand is only satisfied by electricity. In this case, the heating costs are 1.6 billion euros for all industry. In Flex-P2H Scenario, the option to switch to natural gas is activated. In this case, the heating costs decrease to 1.3 billion euros when the hybrid boiler is used, which means a 19% decrease. Figure 28 shows the operation of the hybrid boiler for 4 days. It can be seen that natural gas is preferred over electricity during the times that it is cheaper (7-16 hours) and (22-34 hours). Throughout the whole year, it is more cost-efficient to use electricity for 1613 (18.4 %) hours and more cost-efficient to use natural gas for 7147 (81.5%) hours. A more detailed end-user side analysis focusing on the electricity and natural gas prices is presented in Analysis 4.

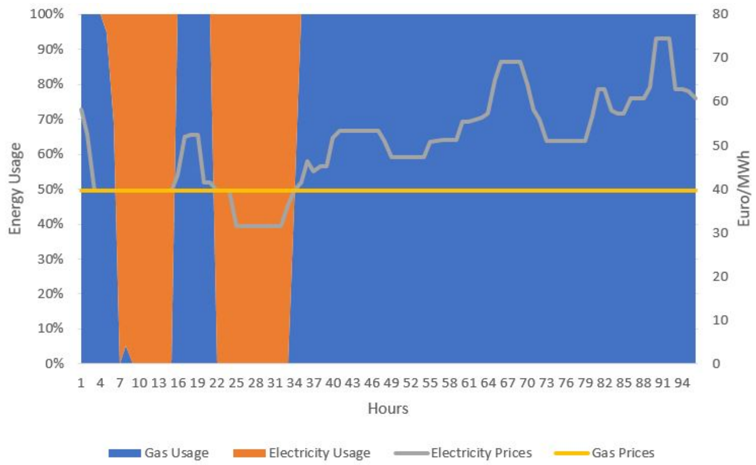



Figure 25: 4 days operation of Hybrid Boiler

Analysis 2 investigated the effects of the heat demand flexibility, first on the power system and then on the different end-users: households and industry. The hybrid boiler option and the thermal storage for households provide significant cost decreases in the Flex-P2H Scenario. From the generators perspective even though the curtailment decreases, the revenues from VREs do not increase. This is due to the high natural gas usage by the industry. As the price of the natural gas is lower compared to electricity, 81% of the year it is preferred by the hybrid boiler. In this case, electricity is used less to satisfy the power-to-heat demand from the industry which results in decrease of electricity prices. There is a decrease in the annual residual peak load. However, the off-peak load does not increase in the residual load curve as it was expected as a result of heat demand flexibility. This is again due to the high usage of natural gas from the industry side and the inadequacy of the demand response from the household side. $CO_2$ emissions decrease both in the Netherlands and in EU. The total and average ramp needs are similar for the two scenarios. Flexibility from the heat side replaces the flexibility provided by net imports, gas and demand response from electric vehicles. The generation mix between the two scenarios does not differ substantially apart from the net imports which decrease in Flex-P2H Scenario.

The next section of the analysis focuses on the end-users perspective. Households can shift the heat pump load in time. In terms of financial benefits, it is found out that a heat pump buffer tank which can shift the load for 5 hours provides 25% heating cost savings compared to a household with inflexible load. The heating cost savings are also compared with high-level insulation which can provide 2 hours shifting. It was found out that 20% savings are already possible only with 2 hours shifting. This makes an investment for a hot water tank thermal energy storage less attractive. A simple calculation with an example brand reveals that the investment costs are higher relative to savings and the payback period is not reasonable. From the perspective of industrial end-consumers, using a hybrid boiler decreases the heating costs by 19%. Natural gas is preferred over electricity 81% of the time. This substantial natural gas usage also limits the $CO_2$ emissions decrease to 3.2% for the EU and 1.3% for the Netherlands.

## 5.3 Analysis 3: Unlocked Flexibility Potential

The aim of this analysis is to observe the system-wise benefits of the increasing share of the flexible heat demand. This analysis complements the previous research question and provides an answer to the second one: *What are the implications if the flexibility potential is not fully unlocked?*. The term unlocked represents the percentage of the household heat load that is not flexible due to any kind of barriers such as regulatory, behavioral or technological.

A sensitivity analysis is conducted for the flexible heat demand parameter of the model based on the Flex-P2H Scenario. This scenario already included 25% flexible heat from the household side and 5 hours of maximum shifting. Flexible load parameter is changed for the values: 0%, 50%, 75%, 100%. Different than Analysis 1 which considers both flexibility options from industry and households, this part of the analysis only examines the household heat demand flexibility by changing the flexibility percentage. Hybrid boiler option is available for the industry in all the cases. Table 19 presents a summary of Analysis 3.

Table 19: Analysis 3 Summary

| Analysis | Objective | Outputs from the Model | Indicators |
|---|---|---|---|
| Flex-P2H Scenario - % Flexible Load Sensitivity Analysis | Answer RQ 1 and 2 | - System costs<br>- Curtailment<br>- CO2 emissions | - System costs EU, NL<br>- Residual peak electricity load<br>- VRE curtailment<br>- VRE Generation Profits<br>- CO2 emissions EU<br>- Total Benefits |

Figure 26 presents the residual load curves for different percentages of heat demand flexibility. All scenarios are very similar throughout the entire year with almost no visible changes. Due to the increased flexibility of the household demand, it was expected that the shift in the heat demand would help to decrease the load in peak hours (a downward move in the residual load curve) and increase during off-peak hours (an upwards move in the residual load curve). As a result, a flatter residual load curve would be formed. However, a significant change in the residual load curves is not observed for the entire year. The decreases in the systems costs and CO2 emissions are also limited. On average, the system costs decrease 0.01% for EU and 2% for the Netherlands while CO2 emissions for the EU decrease 0.04%. The reason for the small changes could be the fact that the household heat pump load constitutes a very small segment of the total load. Out of 128.7 TWh, 5.86 TWh is the load for heat pumps which is 4.5% of the overall demand. And the part of the load that can be shifted is actually lower depending on the percentage. For the heat pumps, this analysis only considers households but in the system description in Chapter 3, an additional power-to-heat load from the service sector is also mentioned. In Chapter 3 Table 4, the upper limit for P2H demand for 2030 is 33.1 PJ (9.17 TWh) including the demand from the service sector. Inclusion of the power-to-heat demand from the service sector can cause more substantial effects.

In terms of the size of the demand, the industry has higher potential to have more significant effects on the residual load curves as observed in the previous analysis, the comparison between InFlex-P2H and Flex-P2H Scenarios. Electrical load shedding from the industry (switching between natural gas and electricity) provides cost decreases compared to the inflexible electrification of the industry. The household level flexibility does not provide the same amount of cost and peak load decreases. This might indicate that household level flexibility can be more beneficial for the distribution network scale to prevent congestion during peak hours. Distribution network is not included COMPETES.

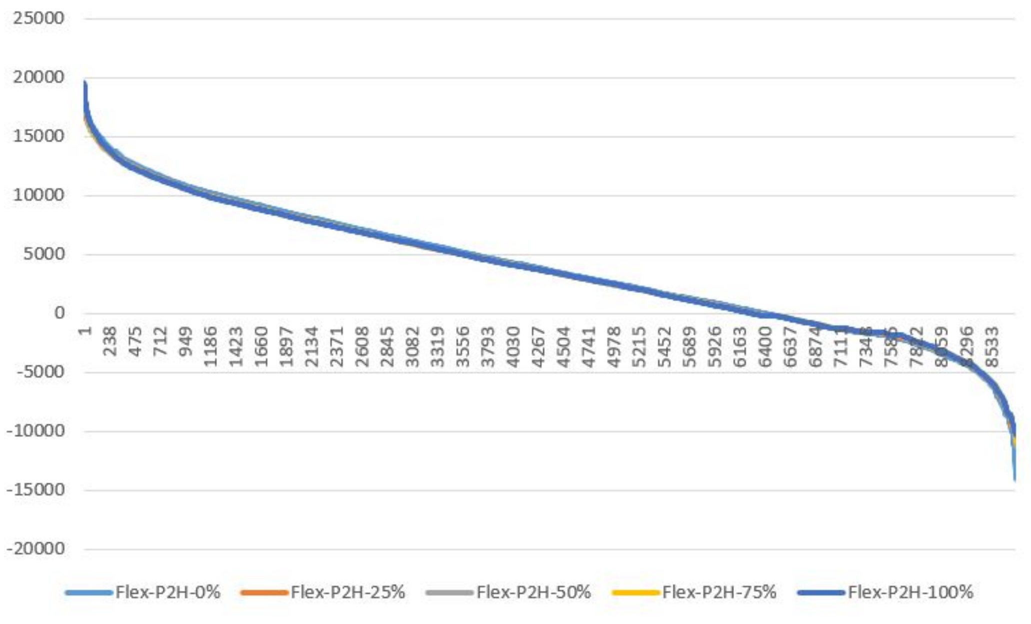



Figure 26: Residual Load Duration Curves of the Different Household Flexibility Levels

Figure 27 aims to provide an overview of the indicators and their change with the heat demand flexibility of the households. The changes in the system costs both for EU and the Netherlands, peak electricity load, VRE curtailment, CO2 emissions for EU and VRE generation profits for the Netherlands are included in the graph. System costs for EU line is not directly visible as it follows the same pattern with CO2 emissions line. The values are normalized to fit all the indicators on the same scale in the graph. Based on the values of these indicators, total benefits are calculated. The total benefit is defined as being directly proportional to the decrease in these indicators (increase in case of VRE generation profits). The normalized values of the indicators are summed and multiplied by the weight of a certain indicator. The weight of the indicator represents its importance. For this analysis, systems costs, CO2 emissions, peak electrical load, VRE generation profits are all weighted the same except the curtailment which is weighted half of the previous indicators. As it was explained in Section 4.5, curtailment affects other indicators such as CO2 emissions and system costs as well as VRE generation profits. Therefore, it is weighted less but still included to observe its relation with other indicators. It should be noted that the total benefits function serves as a collective indicator to provide an overview and summary of all other indicators. It does not aim to present a final decision on the benefits of the heat demand flexibility. The changes in the individual indicators are more important.

The most visible effect of increasing heat demand flexibility is the decrease in the curtailment. It is followed by the decrease in system costs for NL. The system costs and CO2 emissions for the EU follow a slightly decreasing pattern which is less visible compared to other indicators in the graph. The residual peak electricity load first decreases then increases and it is almost stabilized in the end. The reason for the first increase can be the unnecessary shifts of the model when the model is indifferent for shifting the load under the same electricity prices.

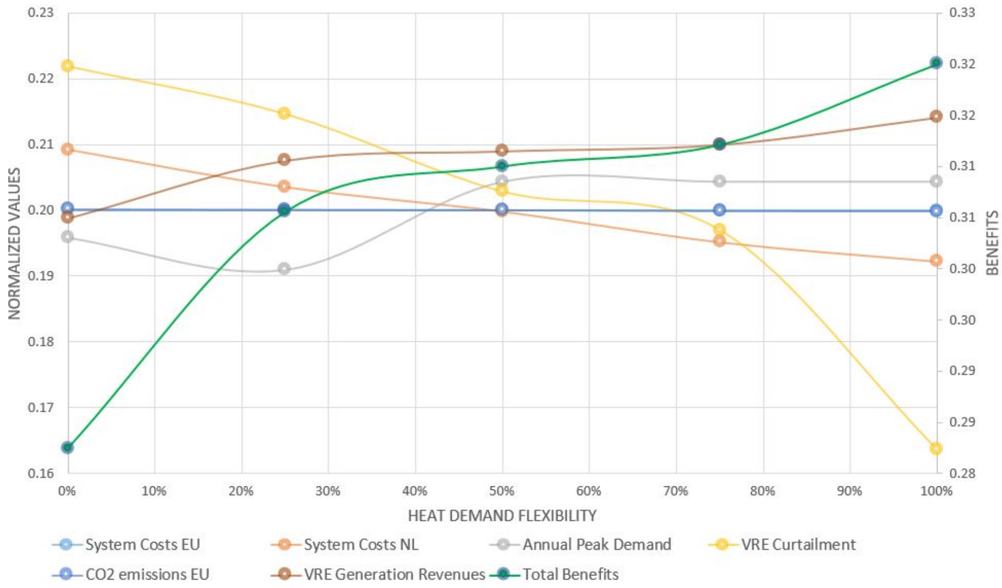



Figure 27: System Benefits from Increased Flexibility

VRE generation revenues keep increasing in small increments and have a higher increase in the final interval. As the curtailment decreases, it can be expected that the VRE revenues increase.

Except for residual peak electricity load, all the indicators are improved (at a different pace) as the flexible percentage of the heat demand increases. The benefits captured differ in each interval of the flexible heat demand. It can be checked whether an interval where most of the system benefits are captured and where the benefits start to decrease exists or not. Table 20 provides an overview of the changes in the indicators.

Table 20: Heat Demand Flexibility: Changes of the Indicators

| Flexible Demand Percentage | 0%-25% | 25%-50% | 50%-75% | 75%-100% |
|---|---|---|---|---|
| System Costs EU Decrease | 0.01% | 0.01% | 0.01% | 0.01% |
| System Costs NL Decrease | 2.72% | 1.82% | 1.60% | 1.51% |
| Annual Residual Peak Load Decrease | 2.48% | 0.00% | 0.00% | 0.00% |
| VRE Curtailment Decrease | 5.49% | 3.27% | 2.89% | 10.95% |
| CO2 Emissions EU Decrease | 0.05% | 0.03% | 0.09% | 0.02% |
| VRE Generation Profits Increase | 4.43% | 1.68% | 1.48% | 6.00% |

The system costs for EU is quite stable for all the intervals. From the overall system cost decrease for NL, most of the benefits are captured within the initial increase from 0% to 25%. The decrease in the system costs for NL keeps decreasing with the increasing flexible heat demand percentage. In the case of the curtailment, upto 75% flexible demand benefits are nearly the same. Most of the benefits are obtained from the increase from 75% to 100%. The most benefits from the VRE generation revenues are also captured in the last interval from 75% to 100%. CO2 emission reductions for EU do not follow a noticeable pattern in terms of the benefits that are captured. An increase during 50%-75% and a decrease in 75%-100% is observed which can be related with the changes in the VRE curtailment at the same intervals.

It is observed that there is not a clear pattern for the change in the indicators except the system costs.

When all these indicators are combined to obtain overall benefits, a total benefit function from increasing the heat demand flexibility can be seen as the green curve in Figure 27. There is not a steady increase for the overall benefits. Overall the first (0%-25%) and the last (75%-100%) improvements catch the most benefits. Since most of the cost decrease for EU and NL are during the initial improvements and all of the indicators are improving, the total benefits show the most increase from 0% to 25% interval. Due to the decrease in VRE curtailment, increasing VRE generation revenues and decreasing system costs from 75% to 100% interval; the total benefits also tend to increase more in the last interval. Between 25% and 50% the increase of total benefits is relatively less due to the increase in the annual residual peak load despite other indicators are positive. The total benefits function aims to provide an overview of the all indicators. Some of the indicators are connected to each other such as system costs, VRE curtailment, CO2 emissions, VRE generation revenues. Therefore, the individual changes of the indicators are also presented.

This analysis investigated the effects of the increasing heat demand flexibility on the power system. The residual load curves for the entire year show that the effects are not significant enough to make changes. Decrease of the peak load and increase of the off-peak load is not observed in the transmission system level. There is a limited system cost decrease provided for the Netherlands. An important benefit is the decrease in the VRE curtailment and the increase in the VRE generation revenues. The benefits captured by the changes in the indicators differ. In terms of the cost decrease, most of the benefits are captured in the initial increase within 0%-25% range and the benefits continue decreasing with the additional improvements. For VRE generation revenues and curtailment most benefits are obtained in the last 75%-100% interval. CO2 emissions do not follow a clear pattern. There is neither a clear indication that there is a point that all the benefits are captured mostly nor a trend that all the indicators start to decrease or increase. The only generalization that can be made is for the costs which improve the most during the the first 0%-25% improvement interval.

## 5.4 Analysis 4: Distortions on the End Costumers

The output of the COMPETES model is optimal for the power system. However, there are some extra price components for the end-users that are not included in the model. The addition of these components might create distortions and make the results "sub-optimal" for the end users. These kind of distortions are barriers against sector coupling from the end-user side. Lack of a positive business case for end-users would cause avoidance of electricity based solutions despite the technology developments. To achieve the benefits from the optimal power system results, it is important that end-users have incentives. One of the sources of the above-mentioned distortion is taxes, levies and grid charges on top of the wholesale electricity prices for households and industry. Background information related to the consumer prices is provided in Section 3.4. This analysis aims to investigate the deviation of the end-users from the optimal results from the model due to the inclusion of extra costs on top of the electricity and natural gas and to gain insights about the taxes and levies as a potential barrier for the usage of electricity in P2H technologies. As a result, the following research question is answered: *What are the effects of the price distortions as a barrier against sector coupling ?*

The effect of these potential barriers is observed based on the outcomes of Flex-P2H Scenario, 50% flexible household heat demand. For this part of the analysis, only the variable component, energy taxes and levies are considered including VAT and ODE components as well. The network costs should be treated separately since they are fixed costs and paid monthly or yearly. Network costs for power grid have to be paid in any case for households as they have to be connected to the power grid. If the end-consumers switch to all-electric heating technologies they can save from being disconnected from the natural gas grid. However, this is not the case for hybrid technologies. In this study, it is assumed that heat pumps for households do not require an upgrade in the connection to the power grid.

The electricity prices are the output of the model and do not include the additional components for end-users that are mentioned in Section 3.4. There is only a single price for electricity and natural gas for everybody in the energy system which makes it difficult to see the distortion for different end-users. Therefore, this is a post analysis based on the results of the COMPETES model and the other cost components are added later. To determine the effects of the taxes, electricity, and gas prices are compared as well as the heating costs of the end-users. The prices that are compared also contain the efficiency of the technologies based on the below formula. They can be referred to as the cost of one unit of heat by using electricity or natural gas for a specific technology. Even if the electricity prices are higher than natural gas, due to difference in efficiency, cost of obtaining one unit of heat from electricity might be cheaper.

$$HeatPrice = \frac{ElectricityPrice}{(\eta)_{electric}} + \frac{NaturalGasPrice}{(\eta)_{gas}}$$

To calculate the heating costs, for industry, the ETS CO2 prices are included in the natural gas price according to the formula below. As household heating is not involved in the CO2 market, the natural gas prices for household heating do not include the CO2 prices. CO2 price is already included in the natural gas pries in the model while the marginal costs for the power sector are calculated. However, it is interesting to see the implications if households were also involved in a CO2 market as this might provide more incentives to use power-to-heat technologies for households. Therefore, calculations with and without CO2 costs are made for the households as well.

$$NaturalGas(Euro/MW) = WholesalePrice(Euro/MW) + (Emission(tonne/MW) * CO2price(euro/tonne)$$

Table 21 presents the summary of Analysis 4.

Table 21: Analysis 3 Summary

| Analysis | Objective | Outputs from the Model | Indicators |
|---|---|---|---|
| Flex-P2H-50% Scenario Outputs | Answer RQ 3 | - Electricity Prices<br>- Industry optimal gas and electricity consumption | - % hours electricity price is higher<br>- % hours the model choice is suboptimal (for industry)<br>- Heating costs (for industry and households) |

Firstly, the electricity prices from the model output are compared with the natural gas prices to form a base for the later analysis. Wholesale electricity prices are lower than the wholesale natural gas prices including CO2 costs and taxes 3011 hours a year (34% of the year) and 347 (4% of the year) excluding CO2 prices and taxes. Even without any kind of additional taxes, it is not very frequent that the electricity prices are lower than the natural gas prices.

For industrial end-users, cost of one unit of heat is calculated based on the efficiency of the hybrid boiler. For households, this is calculated by using the coefficient of performance of the heat pumps which changes according to the temperature.

**Industry**

Based on the cost of one unit heat, it is observed that 1613 hours in a year (18% of the year), it is cheaper to use electricity for a hybrid boiler. This number is still before the addition of the taxes. For the small industrial consumers whose consumption is within the tax category 3 according to the classification in the Table 10, after the addition of the relevant taxes the number of hours that using electricity is cheaper is only 208 hours (2% of the year). For industrial consumers with higher consumption above 10 million m3 natural gas and 10 million kWh of electricity which are in tax category 4, the hours electricity usage is preferred to the natural gas is 2645 hours (30% of the year). The reason behind this increase is that for category 4 natural gas taxes are slightly higher than electricity taxes as it can be seen in Table 10. When the modified electricity and natural gas prices are very close to each other, the addition of the taxes makes natural gas prices slightly more expensive than electricity. The decision after the taxes are added is different 1405 hours from the model decision for the tax category 3. This implies that 16% of the year the model decision is sub-optimal for category 3 consumers. All of these hours electricity was chosen to be used by the model. After the addition of the taxes, the decision switches since using natural gas is more effective. For tax category 4, the decision was different 11% of the year (1032 hours) than the model decision. This time after the addition of the taxes, model choices change in favor of the electricity.

Figure 28 shows the operation of the hybrid boiler more in details for 4 days. The prices in the graph include the efficiency of the electric and natural gas boilers. Without the taxes included, electricity and gas usage is optimal based on the provided natural gas prices and model output electricity prices. On the other hand, Figure 29 presents the case after the taxes are added to the previous model results in Figure 28. For category 3, the hours that the decision

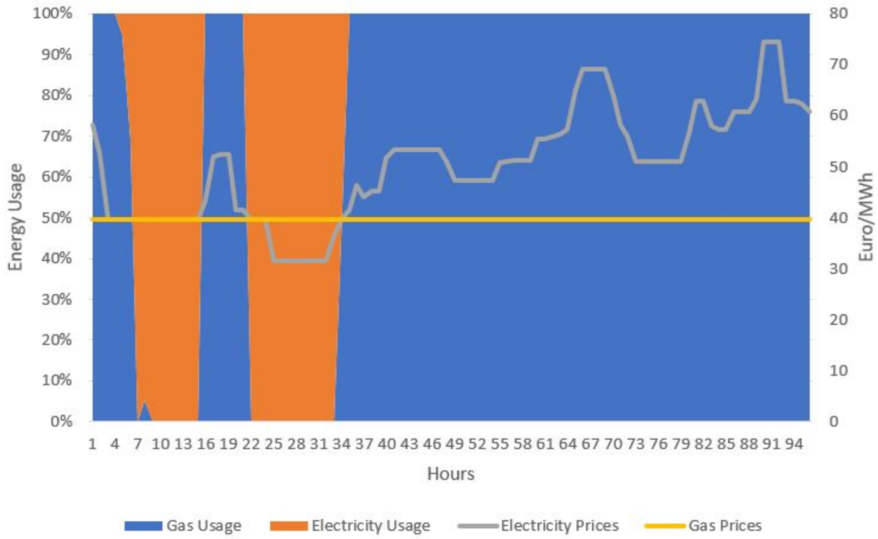


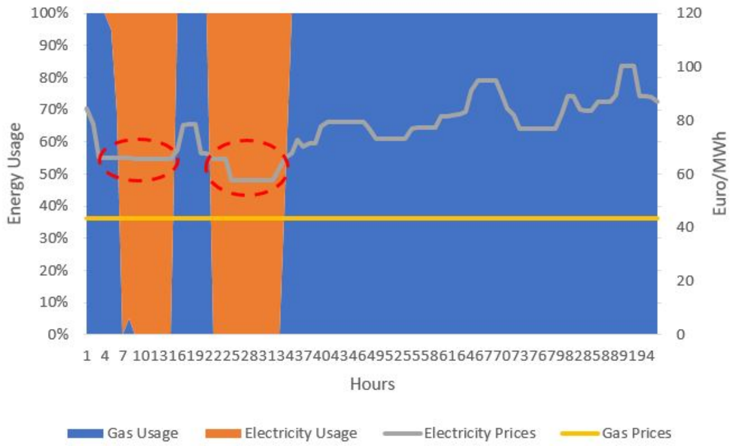

Figure 28: 4 days operation of Hybrid Boiler

is sub-optimal is seen in the areas with red circles. Even though the gas prices are cheaper in those times after the addition of taxes, electricity is preferred according to the previous model decision. For tax category 4, different 4 days are shown in order to observe the difference in the decision. It can be seen that at the point where arrows are located, even though the electricity is cheaper, natural gas is used. Most of the sub-optimal decisions in this category are due to these small price difference between electricity and natural gas. As the difference is too little, the decision is very sensitive. Therefore, it can not be concluded that the taxes in category 4 encourage the usage of power-to-heat technologies.

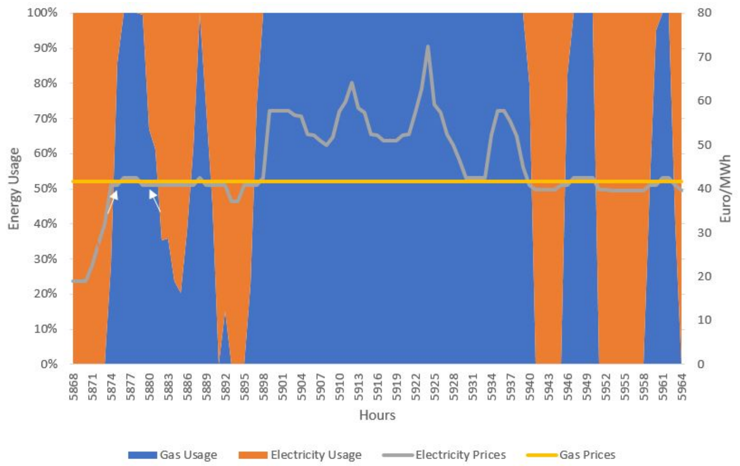
Table 22 shows the heating costs for the both category of industrial users. Without the inclusion of the taxes, the overall heating costs is less for both type of consumers. After the addition of the taxes, based on the new decision, the heating costs increase 19% for tax category 3 consumers and increase 8% for tax category 4 consumers. It is also seen that using natural gas boiler is cheaper for category 3 consumers. For category 4 consumers, hybrid boiler is a cheaper option with a small difference compared to natural gas boiler. However, this analysis does not include network costs for industry. It is highly probable that the costs will increase even more in this case and make the natural gas boiler a cheaper option.

Table 22: Heating Costs for Industry

| Heating Costs (Billion euros) | Without Taxes Hybrid Boiler | With Taxes Hybrid Boiler | With Taxes Natural Gas Boiler |
|---|---|---|---|
| Industry Tax Category 3 | 1.35 | 1.60 | 1.55 |
| Industry Tax Category 4 | 1.35 | 1.47 | 1.49 |




(a) Tax Category 3




(b) Tax Category 4

Figure 29: Deviations from the Optimal Decision for Different Tax Categories

**Households**

For households, a similar analysis is conducted to investigate the price distortions. Even though hybrid heat pump is not included in the model, the input hourly heat pump load data for households is used to make decisions in between electricity and natural gas, similar to the decision of the hybrid boiler. To test different conditions, the thermal heat load is calculated based on the input heat pump load profile by using the changing coefficient of performance based on the temperature. The decision to satisfy this heat demand by using gas or electricity is done by comparing the cost of one unit of heat from electricity and natural gas. This decision procedure is done outside of the model with and without adding the taxes. It is important to consider that the choice to use electricity or gas for the households also highly dependent on the coefficient of performance of the heat pump. A regular all electric heat pump for a household usually has a coefficient of performance between 3-4. Electricity is always preferred independent of the addition of the taxes due to the huge efficiency difference between a heat pump and a natural gas boiler, if the coefficient of performance is considered to be 3-4 for the entire year. However, this is not the case normally. The temperature and the relation between COP is tested for an air heat pump and the following data is collected in (Haller et al., 2014) which is seen in Table 23.

Table 23: Temperature and COP Relation

| Temperature (°C) | COP |
|---|---|
| -10 | 1.3 |
| -5 | 1.9 |
| 0 | 2.5 |
| 5 | 2.8 |
| 10 | 3.1 |
| 15 | 3.6 |

The above data is used to represent the relationship between temperature and COP. The average value of the coefficient of performance is used as a constant for the intervals. For example, between 5 °C and 10 °C , 2.95 is used as the COP. At -10 °C and below it is considered as 1.3. This simple adjustment is made not to neglect the effect of the outside temperature on the COP. The decision for the households before and after the addition of the taxes is calculated. Before the addition of the taxes, 88% of the time (7696 hours) using electricity is more cost-efficient. After the addition of the household taxes this decreases to 80% of the year (7181 hours). This decrease is less than expected even though these taxes significantly increase the electricity prices. Also, the heating costs suggest that overall, even after the addition of the taxes, using all-electric heat pumps is cheaper compared to using natural gas boilers.

The heating costs of households are calculated for three cases: the first two calculations assume that there is the possibility to switch in between sources depending on the cheapest one. This can be considered as a hybrid heat pump. Heating costs are calculated with taxes with the possibility to switch between the sources (1). Another calculation is made based on the model input data when only electricity is used to satisfy the heat demand including taxes (2). Finally heating costs are calculated if only natural gas boiler is used (3). The comparison in Table 24 shows heating costs decreases 11% if there is an opportunity to use natural gas instead of satisfying the heat demand all from electricity. This implies that with the current prices hybrid technology is more cost-efficient and might be a good transition technology. Satisfying all of the heat demand from natural gas causes the heating costs to increase to 1.6 billion euros.

Table 24: Heating Costs for Households

| Heating Costs (Billion euros) | Hybrid Heat Pump | All-electric Heat Pump | Natural Gas Boiler |
|---|---|---|---|
| Households | 1.2 | 1.3 | 1.6 |

A sensitivity analysis is conducted to observe the effect of the extreme weather conditions. In an extremely cold weather due to the efficiency drop in the heat pumps, the hours it is more cost-efficient to use natural gas increases. To observe this change, an extreme weather data profile from 1987 is used for households. This year was a relatively cold year for the Netherlands. The data set for 2012 that is used in all the scenarios has an average winter temperature of 4 °C and 522 hours below 0 °C while the average winter temperature in 1987 data is 1.1 °C with 1043 hours below zero °C. As a result of lower temperatures, the electricity consumption from the heat pumps is higher in this data set. The electricity prices used are based on the new model run. The three different cost calculations mentioned above are compared in Table 25.

Table 25: Heating Costs under Normal (2012) and Extreme (1987) Weather Conditions

| Heating Costs (Billion euros) | Year: 2012 | Year: 1987 |
|---|---|---|
| Household Hybrid (1) | 1.27 | 1.41 |
| Household All Electric Heat Pumps (2) | 1.31 | 1.65 |
| Household Natural Gas Boiler (3) | 1.68 | 1.85 |

All the heating costs increase as a result of the increasing heat demand in the 1987 case. The hybrid option is the most cost-efficient option in both weather scenarios. This is followed by the all electric heat pumps. The natural gas boiler is always more costly than the other options independent of the weather. However, in the 1987 weather scenario the heating costs for all electric heat pumps are closer to the natural gas boiler than the 2012 weather scenario. The cost gap with the natural gas boiler is smaller due to the decreasing coefficient of performance. Despite the tax advantage of electricity and the decreasing coefficient of performance, it is more cost-efficient to use hybrid or all electric heat pumps compared to natural gas boiler. The calculation for the hybrid scenario assumes the market prices are closely followed and consumers are directly influenced by the price changes.

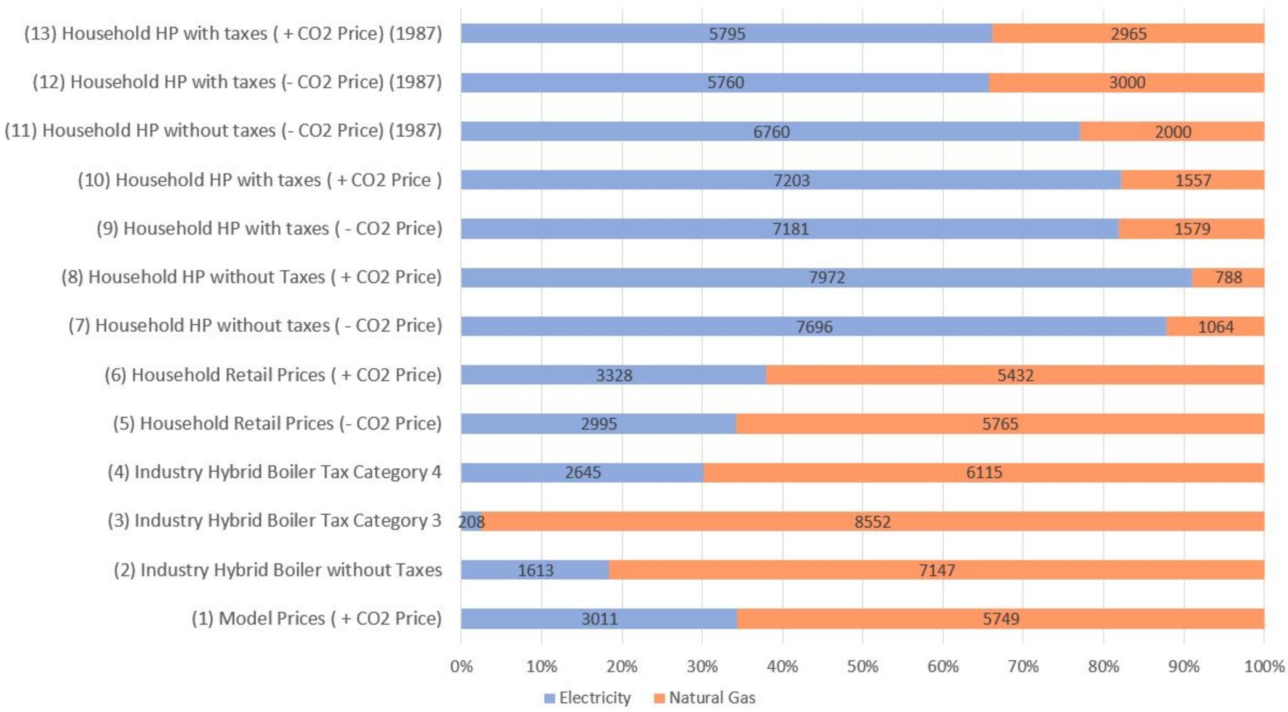



Figure 30: Annual cost-efficient Usage of Natural Gas and Electricity of Heat Pumps and Hybrid Boilers

Figure 30, summarizes the hours of the year when it is more cost-efficient to use electricity or natural gas. The first four cases are related to the industry. Case 1 is the electricity prices from the model output and the natural gas prices with CO2 price. The model prices do not include any efficiency factor for a specific technology. In this case electricity is cheaper than using natural gas 34% of the year. For the all other cases, comparison is made based on the price of one unit of heat considering the technology efficiencies. Case 2 shows the usage of electricity and natural gas for hybrid boiler without any taxes included. In this case, 18% of the time electricity is the cheaper option. In the latter cases, the taxes are added for the industry. In Case 3 (For tax category 3 industrial consumers), the time electricity is cheaper is 2% of the time, 1405 hours less than the case without taxes. In Case 4 (For tax category 4 industrial consumers), 30% of the time electricity is cheaper. This is 1032 hours more than the case without taxes. It is observed that addition of the taxes decreases the number of hours electricity is used for industry category 3 consumers while there is an increase for industry category 4 consumers.

Cases 5-13 are relevant for the households. The coefficient of performance of the heat pump technology is assumed to be changing according to the assumption explained previously based on Table 23. Due to the high efficiency of the heat pumps, it is cost-efficient to use electricity most of the year. The comparison between these cases aims to analyze the effect of the taxes, CO2 price for household heating and weather conditions.

For households inclusion of the taxes decreases the amount of time that is more cost-efficient to use electricity. This is observed in the comparison of Case 7 and 9 (From 88% to 81.9%), in Case 8 and 10 (From 91% to 82.2%) and Case 11 and 12 (From 77% to 66%). The extreme weather conditions also contribute to a decrease in the amount of time that it is more cost-efficient to use electricity. This is observed in Case 9 and 12 (From 91% to 65%) and in Case 10 and 13 (from 91% to 66%). When the retail prices are compared for the households it is observed that the inclusion of CO2 price causes 11% increase in the electricity usage. The addition of the CO2 tax increases the heating costs of natural gas boiler 39% while there is no change for hybrid boiler. However, for a hybrid boiler, inclusion of CO2 price to the natural gas price for household heating does not create substantial changes for the households. In Case 7 and 8 after the addition of CO2 costs, electricity usage increases only 3%. For cases 9 and 10 the increase is 0.2% and for case 12 and 13 it is 0.3%.

Figure 31 presents the cost-efficient usage of electricity and natural gas based on the tax shift proposed in the Climate Agreement Report. This proposal suggests the following changes in the tax scheme for households:

1- An increase in the price of natural gas by 5.5 ct/m3 (0.0056 euro/kwh) (19% increase) and lowering that of electricity by 2.7 ct/kWh (27% reduction) (0.027 euro/kWh) as a first step.

2- An increase in the price of natural gas 20 ct/m3 (0.02 euro/kwh) (67% increase) and lowering that of electricity 7.34 ct/kWh (0.0734 euro/kWh) (74% decrease).

The first suggestion is thought as a modest contribution and more is needed for a substantial achievement. Calculations show that the second shift is expected to decrease the payback period of label B insulation from 25 years to 20 years and percentage of homes with a hybrid heat pump increases from 20% to 60% in 7 years (Dodion & Melotte, 2018).

In Figure 31, for the households after the proposed tax shift, it is more cost-efficient to use electricity almost all the year. The remaining amount of time in which natural gas is more cost-efficient is less compared to the current situation. For small industry (Category 3 industry consumers) the first shift is still not very effective and still 59% of the time natural gas is more cost-efficient in that case. For the second tax shift, it is not possible to lower the electricity prices more since some prices go negative. Therefore, only natural gas price is increased. With a higher increase in the natural gas prices in the tax shift 2, 93% of the hours it is more cost-efficient to use electricity. For industry category 4 consumers, the current taxes were already changing the usage in favor of electricity. However, the heating costs for the hybrid boiler and

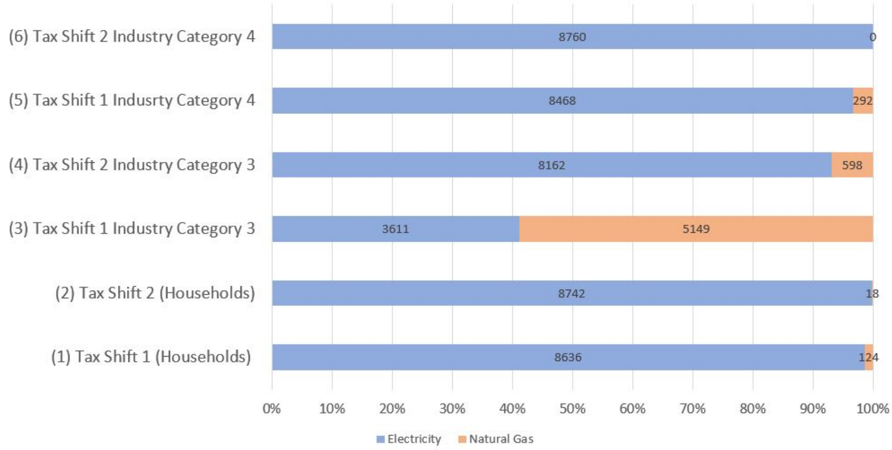



Figure 31: Annual cost-efficient Usage of Natural Gas and Electricity of Heat Pumps and Hybrid Boilers

natural gas were closer to each other. It is probable that the inclusion of network costs can change the situation in favor of the natural gas boiler. So a tax shift would also guarantee the positive business case more for these consumers. With the first shift the hours it is more cost-efficient to use electricity increases to 97%. After the first shift it is no longer possible to decrease the electricity prices so for the second shift only natural gas prices are increased. If the natural gas tax increase is applied as suggested in shift 2, electricity is cheaper to use over the entire year.

Table 26 shows that the tax shift 1 decrease the heating costs 32.5% for the hybrid heat pumps and 34.7% for all-electric heat pumps. Tax shift 2 decrease the heating costs by 54% for the hybrid heat pumps and 55% for the all-electric heat pumps. For category 3 industrial consumers, the first tax shift decreases the heating costs 1.25% and the second shift decreases 50%. For category 4 industrial consumers the first tax shift decreases the heating costs 42.1% while the second shift decreases 45%. The natural gas boiler costs increase for all the end-users. For households, after the tax shift all electric technologies are slightly less costly compared to hybrid heat pumps. For industry category 3 consumers hybrid boiler becomes a cheaper option. For large industrial consumers the cost gap between hybrid boiler and natural gas boiler increases from 0.2 billion euros to 0.85 billion euros providing more heating cost savings which might be enough to cover the increased network costs.

It is important to note that the efficiency of the technology that is used affects the heating costs and savings. From Figure 30, it is observed that in the case of hybrid boiler, using electricity is cost-efficient only a limited amount of time. Addition of the taxes makes the situation worse for small industrial consumers while it is the opposite for large industrial consumers. When the same calculation for heat pumps and households is made, due to the high efficiency of heat pumps, it is observed that even though there are higher amount of taxes for electricity, heat pumps would contribute to the decreasing the heating costs. The situation is the same in a relatively cold weather scenario. Power to heat technology that is used for industry and households are different in terms of energy efficiency. This is one of the reasons of the difference between the end-users. If a hybrid boiler technology is used for households, the tax structure might pose a greater barrier for the usage of electricity.

[7] HHP: Hybrid heat pump, HP:Heat pump, NG: Natural gas

Table 26: Heating Costs for Different Consumers after Tax Shift

| Billion euros | 2012- Current Tax Structure | Tax Shift 1 | Tax Shift 2 |
|---|---|---|---|
| Households HHP [7] | 1.27 | 0.857 | 0.587 |
| Households HP | 1.31 | 0.855 | 0.585 |
| Household NG | 1.68 | 2.05 | 2.62 |
| Industry Category 3 HB | 1.6 | 1.58 | 0.79 |
| Industry Category 3 NG | 1.55 | 1.7 | 2.27 |
| Industry Category 4 HB | 1.47 | 0.85 | 0.8 |
| Industry Category 4 NG | 1.49 | 1.7 | 2.2 |

This section presented an analysis to evaluate the energy taxes and levies as a barrier against the usage of power-to-heat technologies. Before the addition of the energy taxes for the year 2030, wholesale electricity prices are already more expensive than the natural gas most of the time which is not encouraging for P2H technologies from the beginning. The addition of the taxes creates different price distortions for different end-users and might discourage the usage of electricity. For this analysis different efficiencies of the technologies are considered in the comparisons depending on the technology that the end-consumer is using. For industry two different tax categories were defined. A small industry (Tax category 3) is negatively affected from the addition of the taxes. Considering the efficiency of the hybrid boiler, using electricity is cheaper only 2% of the time for these consumers. For larger industries (Tax Category 4), surprisingly an opposite effect is observed. The times that electricity usage is cheaper is 30%.

For the households the situation is more in favor of the usage of electricity due to the high coefficient of performance of the heat pumps. Number of hours it is more cost-efficient to use natural gas is limited with and without the taxes. Without taxes 87% of the time using electricity is more cost-efficient while this is 81% after the addition of the taxes. A relatively cold winter can decrease these percentages more to 65.7%. However, in both cases when the heating costs are compared it is found out that under the assumption of perfect price information, the most cost-efficient option is switching in between natural gas and electricity which implies a hybrid heat pump option for the households. Using a natural gas boiler all the time is the most costly option even in the extreme weather conditions. Using electricity with all-electric heat pumps is between these two options.

A comparison with and without CO2 costs for household heating is also included in the cases. Addition of ETS CO2 prices (41.81 euro/ton CO2) to retail prices increases the hours that electricity is cheaper than natural gas to 11%. The heating costs of a natural gas boiler increases by 39% and this can provide an incentive to consider other heating alternatives. However, this addition does not affect the operational hours of hybrid heat pump significantly which implies a shift in electricity prices is also needed.

In the final part of the analysis, the suggested tax shift of the Climate Agreement Report is tested on the defined consumer types. It is observed that for the small industry (Tax Category 3) even the first tax shift is not encouraging enough. A more ambitious shift such as the second one is able to turn the case more positive for these consumers. For the large industry and households both of the suggested tax shifts encourage the usage of electricity almost all the year. The shift also causes substantial decreases in the heating costs both for households and industry.

## 5.5 Summary of the Analysis

This chapter presented four different analyses providing answers to the three sub-research questions as well as the main research question of this study.

Analysis 1: Effects of Increasing Sector Coupling, provides an initial overview for the main research question *"What are the flexibility implications of the increasing sector coupling between heat and power sectors?"* and outlines the increasing flexibility needs. The analysis reveals that increasing coupling between heat and power sectors slightly decrease the system costs for the NL and almost makes no changes for the EU. Even though there is a slight decrease in the system costs due to operational savings from the heat sector, the imports increase to satisfy the additional 39 TWh electric load. In addition, the ramp needs of the power system increase and the ramp sources change. The ramp needs provided by gas and VRE curtailment decrease while the increasing ramp needs are satisfied by cross-border power trade and another demand response option, smart charging of EVs. One positive effect is observed from the side of VRE generators. There is an increase in the revenues due to the decrease in VRE curtailment. In addition, VRE generation and the total demand becomes more correlated. Overall, the inclusion of this extra demand provides emission and system cost reduction benefits for the Netherlands to a certain extent but at the same time increases the dependency to outer sources and increases the need for flexibility. Analysis 2: Effect of Additional Supply of Flexibility and Analysis 3: Unlocked Flexibility Potential investigate whether the heat demand flexibility provided by the industry and households, has the potential to provide more system cost reductions and satisfy the increasing ramp needs.

*1) What are the effects of the heat demand flexibility on power sector and end-users?*

P2H demand flexibility is provided by two different sources in this study. Industrial end-users have the possibility to switch between electricity and natural gas by using a hybrid boiler while households that have electric heat pumps can shift the P2H demand by means of thermal storage or insulation. These new flexibility options from the heat side provide cost decreases both for the Netherlands and EU compared to the case where P2H demand is completely inflexible. There is also a decrease in the peak load. However, it is observed that both demand response options do not facilitate the increase of the off-peak load in the residual load curve. The main reason for this is the high natural gas usage (81% of the year) from the industry side. Even though there is a large potential in terms of the size of the demand from the industry, an increase in the off-peak load is not observed due to high natural gas usage. Electricity prices decrease due to the decrease of the electric load in Flex-P2H Scenario. This causes a decrease in the VRE generator revenues despite the decrease in the VRE curtailment. $CO_2$ emissions both for the Netherlands and the EU decreases. As a new flexibility option, the flexibility from the heat sector also replaces some part of the smart charging to provide the ramp up needs. The supply and demand balance reveals that net imports decrease which implies more independence from outer sources.

When the hybrid boiler option from the industry is available and only the household P2H demand flexibility increases, the system cost savings are not substantial. In addition, the changes are not enough to create visible effects on the residual load and price duration curves. There is not a significant change in the annual residual peak demand as well. In terms of smoothing the electrical load profile, no significant contribution from the household level flexibility is observed. CO2 emission decreases are limited for the Netherlands and the EU. On the other hand, the household level flexibility decreases VRE curtailment and increases VRE generator revenues implying a contribution to VRE integration. In the end, the effect of the flexibility from the household side is limited on the power system compared to the industry.

To evaluate the value of the heat demand flexibility from the end-users side heat cost savings as defined in Section 4.5 and the cost-efficient operational times of electricity and natural gas during a year are used. Using thermal energy storage which is capable of shifting the heat load 5 hours provides 25% annual heating cost savings for the households. It was identified that the payback period of a hot water tank storage which serves as a buffer for heat pumps is not reasonable with the identified amount of cost savings. In addition, it was found out that high level insulation which can shift the heat load 2 hours provides 20% savings, 5% less than the thermal energy storage option. For industrial end-users which have the hybrid technology, natural gas is preferred over electricity most of the time throughout the year. Depending on the tax amount that the user needs to pay, hybrid boiler can be more or less cost-efficient to use. For small industry consumers using hybrid boiler increases the costs 3%. For large industries using the hybrid boiler decreases the costs 1.3%. This is the case without the inclusion of the network costs. The preference over natural gas from the industry side also limits the possibilities for more VRE integration and the reduction of the CO2 emissions which is only 3% for EU and 1% for the Netherlands.

The next question investigates the implications if the flexibility potential is not unlocked fully.

*2) What are the implications if the flexibility potential is not fully unlocked?*

The flexible percentage of the household load represents the part of the load that can be shifted in time for households. This is possible by using thermal energy storage or demand response technologies. However, there are certain barriers such as cost and regulations in front of the large-scale adaption of them. Therefore, not all of the household P2H load is available to respond to the changes in the power system and the flexibility potential might not be fully unlocked. To answer this research question, the analysis is conducted from the household perspective as the COMPETES model allows to change the related variable. However, it is also a question to what degree this is important. It can also be possible that after a certain point there are no benefits from the increasing household level flexibility. The research from Chapter 3 indicated that in 2030, the flexible percentage of the heat demand from households is expected to be around 25%. This percentage is used in Flex-P2H Scenario. As the heat demand flexibility from the household side keeps increasing, the VRE utilization increases with the decreasing VRE curtailment and increasing VRE generator revenues. System costs and CO2 emission decreases are limited. The increase of the flexible household P2H load from 0% - 25% (the initial increase) is more valuable in terms of system cost reduction while the later improvements are still valuable for the increase in the VRE utilization. This suggests that it is not possible to find a break-even point that all the indicators offer the most benefits. In addition, a point where all the benefits start to decrease at the same time is also not found. Unlocking additional potential of flexibility keeps bringing more benefits for different indicators that are used in this study. If the percentage of the household P2H load that is flexible is kept only at 25%, most of the system cost benefits would be captured but a higher potential for more utilization from VREs is missed which can be captured during the last intervals.

One of the factors that might prevent the potential to be fully unlocked is the price structures of electricity and natural gas. These prices affect the positive business case for the end-users. The following research question investigates the effect of price distortions on the end-users.

*3) What are the effects of price distortions as a barrier against sector coupling ?*

It was found out that when both electricity and natural gas taxes are included in the model prices, the usage of electricity as a heating source decreases for households and small industrial consumers. On the other hand for large industrial consumers, the magnitude of the taxes are less and the tax for electricity is slightly less than natural gas. The addition of the taxes increases the electricity usage and therefore it can be considered as less important as a barrier against sector coupling.

For the households, addition of the taxes decrease the hours in which it is more cost-efficient to use electricity by 6%. Due to the high efficiency of heat pumps, the distortion is limited. However, the efficiency of the heat pumps are highly affected by the weather conditions. During relatively cold weather conditions the advantage of using electricity over natural gas decreases. As a result, electricity is used 26% less compared to the normal weather conditions. When the coefficient of performance is lower, also the taxes have more effect in decreasing the electricity usage. The comparison between the case with and without taxes for the extreme weather conditions reveals that the use electricity decreases 11% after the addition of the taxes. The taxes and relatively cold weather conditions favor the usage of natural gas. Despite this fact, the operational costs of a natural gas boiler is the highest compared to the other options. If there is the opportunity to switch between natural gas and electricity (hybrid heat pump), heating costs are less than the case in which electricity or natural gas is used all the time. This is valid under the assumption that the consumers have perfect information on prices and change their behavior accordingly. The all electric heat pumps are in between the two options. In relatively cold weather conditions, the gap between natural gas boiler and heat pumps is less but still not enough to make the natural gas boiler cheaper. The results imply that with the electricity prices in 2030 and the tax structure of today, getting rid of the natural gas completely is not reasonable and natural gas still preserves its position as an important source for household heating.

The current prices with the taxes included still allow consumers to save from their energy bills if they use electricity. However, as it is also suggested in the Climate Agreement Report, the increase in the energy savings will help to decrease the payback period for the households that are faced with high capital investments for heat pumps and insulation. The tax shift that is proposed in the Climate Agreement Report guarantees that for a household, using electricity is cheaper almost the entire year. Increasing energy savings (up to 55%) by means of a tax shift would decrease the investment cost barrier for households. For households another option to discourage the natural gas usage is the inclusion of $CO_2$ prices for the household heating. If ETS $CO_2$ price that industry is exposed to is included in the natural gas prices for households heating, the hours that the retail electricity price is cheaper increases by 11%. The heating costs by natural gas boiler also increases by 39%. This is a disincentive for households that use only natural gas as heating source. However, this addition does not create significant effects for the operation of a hybrid heat pump. The hours that is more cost-efficient to use electricity increases slightly. To increase the cost savings due to the usage of a hybrid boiler, a decrease in the electricity tax is also necessary.

For the industry, the tax structure is a barrier for the small industry consumers whose consumption is less than large industry. These small businesses pay relatively more taxes due to higher tax rates at lower energy use levels. Using natural gas is a more cost-efficient option for them. The number of hours in which it is more cost-efficient to use electricity decreases by 16% after the addition of the taxes. For the large industry it was found out that the current tax structure increases the electricity usage by 11.7% and does not impose a barrier compared to the situation without taxes.

The efficiency of the technology that is used has an important effect on the positive business case of the electrification of the heat sector. The hybrid boiler is not a positive business case for the industry with the current electricity and natural gas price structure. Contrary to households, the operational cost savings are not high. For small industry, using a natural gas boiler is in fact a better option and decreases the annual heating costs 3%. For large industry, using hybrid boiler is only 1.3% cheaper than a natural gas boiler. The difference is very small and can be easily changed by the inclusion of the network costs. The first suggested tax shift in Climate Agreement Report which decreases the electricity taxes 27 euro/MWh and increases the natural gas taxes 5.6 euro/MWh, is not enough to favor the usage of electricity for small industry. A more ambitious shift which decreases the electricity taxes 73.4 euro/MWh and increases the natural gas taxes 20 euro/MWh makes the business case positive. For the large industry both tax shifts create a positive business case for the hybrid boiler and has potential to balance the effects of the network costs.

# 6 Discussion of the Results

This chapter provides a discussion of the analysis of the model results from Chapter 5 combined with the real system description from Chapter 3 and the model description from Chapter 4. The answers provided to the sub-research questions in Chapter 5 are synthesized to answer the main research question: *"What are the flexibility implications of the increasing sector coupling between heat and power?"*

The increasing coupling between heat and power sectors has different implications for the power system and for the two end-users included in this study: households and industry. The previous chapter presented a systems view together with the perspective from the households and industry side. The discussion in this section is presented from these three perspectives, namely, power sector, household and industry, respectively.

## 6.1 Power System

The expected P2H load in 2030 which is around 39 TWh creates an increase in the need for flexibility in the power system. The need for flexibility can be caused by the uncertainty of the residual load (forecast errors), the variability of the residual load due to the increase in power generation from VREs or by the increase in the total load resulting from the increase in electric vehicles (EVs), heat pumps and other additional electrification sources. The increase in electricity production from VRE power sources is usually the main driver of the increase in the demand for flexibility while hourly variation in the consumer loads from EVs or heat pumps are secondary causes (Sijm et al., 2017). If the additional load is mostly satisfied by VRE power sources, this additional electrification has an important impact on the demand for flexibility. In this research, VRE generation capacity is assumed to be constant in all of the scenarios. Therefore, the increasing power load from the electrification of the heat sector is evaluated as the main source of the increasing flexibility needs. The results revealed that there is a 2.6 TWh increase in the total up and down needs and on average 0.28 GW/hour increase in up and 0.13 GW/hours increase in down ramp needs. Ramps in the cross border power trade and controllable load from the electric vehicles gain importance to satisfy these increasing ramp needs.

One of the other power system indicators that change due to the additional P2H load is the system costs. System costs in this study include costs of power generation, heat sector, and net imports. Even though there is a small decrease in the system costs due to savings from the heat sector side, the extra electrical load increases the generation costs from the power sector and net imports which implies an increase in the dependency to the outer sources. An important benefit of the coupling is the increase in VRE utilization. This shows that the additional P2H demand is satisfied by the VREs to a certain extent. However, the increasing imports and increasing conventional power generation costs imply that still extra sources are needed to satisfy this additional P2H demand. Flexibility of this additional P2H load can facilitate a more cost-effective coupling and decarbonization of the heat sector. In this case, this additional power load can also be a supply of flexibility.

In this research, the heat demand-side flexibility is provided by the households and industry. As a new flexibility option, the flexibility from the heat sector replaces some part of the smart charging to provide the ramp needs. The ramp needs satisfied by the imports also decrease. The heat demand flexibility also decreases the system costs by 18.4% compared to the scenario where the P2H demand is inflexible. While the generation costs are almost the same, an important part of the cost savings is from the operational savings from the hybrid boiler and heat pumps. A substantial part of the reduction is also from the decrease in the net imports which also implies more independence from the outer sources.

Among the two alternatives, load shedding provided by the industry has a higher potential than the households to decrease the residual peak load as the size of the potential heat demand that is determined for this study is substantially larger in the industry. However, the hybrid boiler from the industry fails to increase the off-peak load in the residual load curve which would normally be expected as a result of demand response options. One reason for this is the current price structure of electricity and natural gas prices. With the expected prices in 2030, 81% of the year natural gas is more cost-efficient to use for a hybrid boiler in the model. Therefore, natural gas is preferred even during the off-peak price hours of electricity. This high preference for natural gas has also impacts on the other actors. The decrease in the electricity load due to high usage of natural gas decreases the electricity prices in the Flex-P2H Scenario. As a result, a decrease in the VRE generation revenues is observed compared to InFlex-P2H Scenario.

The demand response from the household side does not change the residual load graph significantly. The reason behind this can be explained by the choice related to the two of the scenario variables described in Chapter 4: size and the flexible percentage of the P2H demand from households. The size of the demand for 2030 is determined as 5.86 TWh based on the expectations of National Energy Outlook and other scenario studies in Chapter 3. This is 4.5% of the overall electricity demand for 2030. In addition, the non-residential sector was excluded from the built-environment side. If this part is also included, the P2H demand from the built-environment can increase up to 9 TWh for 2030 as mentioned in Chapter 3. Inclusion of the non-residential heat demand can cause higher impacts on the power system. Even though there are no significant changes observed in the residual load curve, the individual P2H load graph for the households presents decreases in the peak loads. It is possible that with the help of household level demand response, distribution network performance can be enhanced and expansion costs can be decreased. In addition, as the flows in the distribution networks and the interactions between the grid and the consumers increase via electric vehicles and rooftop PVs, it is important that distribution networks are more active and flexible to prevent congestion. Demand response would also be important to manage these congestions. This effect is not observed in this study as the COMPETES model does not include distribution networks. The Liander bottom-up network model ANDES which was used in FlexNet studies evaluates the impact of the adoption of electric vehicles and heat pumps on the Liander regional distribution grid. It was identified that in 2030 about 8% (±3000) of the distribution transformers and 9% (about 40) of the substation transformers will be overloaded. Beyond 2030, the occurrence of grid overloads is more significant and can be avoided by the right investment strategies or demand response (Sijm et al., 2017).

The demand response from the household side results some changes in the power system indicators such as system costs, VRE curtailment, VRE generation profits and CO2 emissions. All the indicators vary to a different extent with the increasing percentage of the household P2H load that is flexible. The largest systems cost decrease occurs in the initial increase of the household flexibility level which is 0% to 25%. This increase was assumed to happen until 2030 in Flex-P2H Scenario. This implies that the development of the demand response and the related investments until 2030 are important and will provide the most of the system costs reductions. As more heat load becomes controllable (25%-100%), the rate of the systems cost reduction decreases. The VRE generation profits increase and VRE curtailment decrease in the last increase interval of household flexibility (75%-100%). This implies that unlocking the full potential is important as different benefits are observed in different increase intervals for household P2H load flexibility.

## 6.2 Households

The flexibility implications for the households differ between the new and existing households. In 2030, it is expected that there will be nearly 8.575 million households, 717 000 of which are new buildings. Most of these are planned to be constructed without connection to the natural gas grid. Climate Agreement Report estimates that 25% of the new households are expected to be connected to a heat network, 56% to have all electric heat pumps and 19% to have hybrid heat pumps. Among the existing households, 45% is expected to be connected to a heat network, 37% to have hybrid heat pumps and only 18% to have all-electric heat pumps.

For the existing households investing in a heat pump is quite costly. As most of these houses lack sufficient insulation, the costs for insulation is also added to the heat pump costs. An all-electric heat pump costs between 10 000 and 19 000 euros without including the insulation expenses (van Ende, 2017). To enable demand response, a decentralized thermal storage in the form of a buffer water tank which costs 4500 euros is considered in this study. All of these elements create substantial extra costs for a household. Zero on the meter (nul op de meter) is a Dutch national project initiated by the government which aims to renovate existing households as an energy neutral one. This includes insulation, providing new technologies such as new smart heating installations, insulated rooftops equipped with solar panels and heat pumps. A full zero net energy renovation including all the elements can cost up to 40.000-45.000 €. These investments are not usually made by individual household owners but in collaboration with housing associations. Tenants pay their energy bills to the housing association instead of the utility company. In return, there will be energy savings from the energy bill both in the form of reduced consumption and disconnection from the natural gas grid. The fixed supply and network costs for the natural gas grid is approximately 12% of the total annual energy bill which is not going to be paid any more in case of disconnection from the natural gas grid. The savings from the energy bill are used to cover the investment costs (Bouwmeester, 2015). It is less likely for an existing household to make all the investments mentioned above unless costs are shared with other actors or incentives are provided.

Compared to all-electric heat pumps, the hybrid heat pump option which costs between 4,000 and 8,000 euros is more affordable for the households. Hybrid heat pumps are also able to make use of the existing natural gas infrastructure. According to the Climate Agreement Report, installing hybrid heat pumps is a relatively inexpensive method for CO2 reduction in already existing houses. The situation will be even more favorable if production costs between natural gas and green gas (via subsidies) are equalized. The ambition is to produce 70 PJ (19.44 TWh) green gas by 2030 of which a significant part can be used in the built-environment. The analysis in Chapter 5 revealed that annual heating costs for a hybrid boiler are the least compared to all-electric and natural gas boiler options. Lower operational and investment costs of the hybrid heat pumps offer shorter payback period times compared to all-electric ones. Hybrid heat pumps are promising as a transition technology in 2030 and they can be more attractive than the alternatives electric heat pumps and district heating for the existing households.

High coefficient of performance of the heat pumps is one of the important factors that provides energy savings. The coefficient of performance of the heat pumps are sensitive to weather conditions and decrease in relatively cold weathers. A sensitivity analysis for the extreme weather conditions based on the year 1984 revealed that decreasing temperatures increase the heating costs up to 26%. However, it is still cheaper to use hybrid or all-electric heat pumps compared to natural gas boiler. This strengthens the position of the heat pumps as a power-to-heat technology option for the households. The assumptions made for the temperature and COP relationship affects the results of the analysis. This relationship depends on the type of the heat pump and might be different for specific brands. In addition a linear relationship between COP and temperature is assumed in this study and the average values of COP for the temperature intervals. This simplistic assumption can be changed and a non-linear function can be used to represent the relationship between two variables. The calculations related to increasing heating costs can be more precise in this case.

It was found out that for households in 2030 with the current tax structure, 18% of the year natural gas is still more cost-efficient to use and this percentage increases to 34% in the extreme weather conditions. This shows that there is still the potential to increase energy savings by decreasing the times that natural gas is used. Such an increase in the energy savings would also decrease the payback period for the heat pumps and would encourage the households to invest in the technology. The structure of the electricity and natural gas prices is important to achieve this goal. The proposed tax shift by the Climate Agreement Report aims to adjust the taxes in favor of electricity. With the proposed tax shifts, it is more cost-efficient to use electricity almost all year and energy savings increase up to 55%. In the meantime, it can be expected that as the technology becomes more mature the investment costs also decrease. A comparison with and without CO2 costs for household heating is also tested in terms of how much it can discourage the usage of the natural gas for households. The addition of the ETS CO2 price which is assumed to be 40 euro/tonne in 2030 increase the annual heating costs of the natural gas boiler 39% which is an important first step to discourage the natural gas usage for household heating. For the households with hybrid heat pumps, the addition does not create significant differences in the operational hours for electricity and natural gas. To increase the savings even more and encourage the electricity usage a tax decrease is also required for the electricity.

The above discussion reflects the perspective of the existing households. On the other hand, most of the new households are already built with high-level insulation and equipped with heat pumps. For an owner of such a household, a decentralized thermal energy storage will be an extra investment. In the analysis, the potential of a thermal storage system that can shift the load for 5 hours is compared with a 2 hour shift that can be provided by an already existing high-level insulation. It is found out that there is only 5% difference between the amount of savings that can be achieved via shifting the load by thermal storage (5 hours) and high-level insulation (2 hours). For the households which already have insulation and heat pumps, it is unlikely that they choose to do this extra individual investment. Instead of a residential based decentralized storage system, using a centralized storage which can defer the heat load same amount or even more can be more economical. In this case, the costs for thermal energy storage can be shared between different actors. A utility-based storage or community energy storage system are the other storage options. Community energy storage is defined as an intermediate solution between residential energy storage and utility-scale distributed energy storage and can be integrated with flexible demand technologies such as heat pumps and electric vehicles. Such storage can facilitate local balancing, energy costs reduction, reliable supply of energy and social cohesion and community engagement(Koirala, Oost, & Windt, 2018). Utilization of this storage will involve other actors as well such as housing corporations, energy suppliers, aggregators, distribution system operators, balance responsible parties, local market operators, technology providers, and municipalities. The system operator is interested in peak shaving and ancillary services, households want to obtain low-cost energy and aggregators want to maximize the value of flexibility. For these collective storage projects, utility companies, DSOs or aggregators provide incentives for households in return of decreasing the peak load for certain hours (Koirala et al., 2018). The related costs such as capital costs, operation, and maintenance costs, replacement costs can be allocated between the actors that are involved in return of the benefits such as peak decrease, grid reinforcement deferral, emission reductions, grid support services, and energy costs reduction (Sardi, Mithulananthan, Gallagher, & Hung, 2017). Such storage systems are usually capable of shifting the load more than 5 hours. The analysis showed that a 23 hours shift can help to achieve energy savings up to 41% annually. In the end, more savings and shared expenses between the actors will make thermal energy storage more attractive option for the households.

An important assumption behind the identified benefits is that the market prices are followed closely by the consumers. It is not likely for households to operate the devices such as heat pumps, electric vehicles or storage by themselves in order to gain operational cost savings. In a study with the participation of different consumers, it was found out that even though consumers received feedback about their energy consumption via smart displays in their home, most of them continued their everyday routine and did not prefer to change their consumption (Nilsson et al., 2014). This is mainly due to the unwillingness of consumers to change their routine, lack of time, motivation and information about the possible benefits. In many demand response programs, consumers are notified to change their consumption or the consumption is automatically controlled. To participate in a demand response program, usually, financial motivations are found to be more important than the environmental concerns (Balcombe, Rigby, & Azapagic, 2014). The savings from the electricity bills are sometimes not enough to guarantee to recover the investment in demand response technologies or to compensate for the change of routine of the consumers (Boisvert & Neenan, 2003). Therefore, many demand response programs offer a different kind of extra incentives such as a credit on the customer's utility bill, check issued for performing actions, reduced kWh rates for overall power or capacity payments (Siemens, 2011). One of the new roles emerging related to demand response is an aggregator, a third party who is in control of the different amount of devices from end-users including electric vehicles, heat pumps, and storage. As defined by Carreiro, Jorge, Antunes (2017), they "offer the opportunity to exploit the flexibility potential of small end-users and promote their access to the retail electricity market by selling load flexibility (to utility companies) and benefiting from rewards or lower energy bills" (Carreiro, Jorge, & Antunes, 2017). The aggregator may combine the flexibility from many devices to shift a considerable amount of electrical load and has an important role in reducing the total operational costs for a household.

The demand response programs and roles such as aggregators are relatively new to the power system and more time is required to discover the best method that provides benefits to all actors involved. In the end, to achieve a significant impact on the transmission or distribution networks, the size of the controllable load is important. The most important factor that determines the flexibility potential from the household side is the engagement of the consumers in these demand response programs. Providing enough information related to the benefits is the key to encourage them more. It is important to inform consumers about the role of the aggregator, the benefits that can be achieved and the operational consequences of the programs. One such example is the standardization for the heat pumps with Smart-Grid (SG-ready) label in Germany. The label is specifically designed for heat pumps and tried out with 370 heat pumps and 19 manufacturers. This label defines four different operational modes for the heat pumps. In these modes there is a maximum hour limit that the heat pump can be switched off. The device can be operated in an energy efficient mode by a controller by using a thermal storage. The change can be either in the form of a recommendation or an order depending on the operational mode (Fischer, Wolf, & Triebel, 2017). A standardization like this might convey the information about the operational schedule and the consequences in a very basic way to the consumer at the time of the purchase of the product. The potential of these demand response programs also depends on technical, operational and regulatory issues that still needs to be resolved. Investments in the ICT technology is needed such as real-time communication systems, remote sensing, software development and measures against cyber-security risks.

## 6.3 Industry

The flexibility from the industry is provided by the hybrid boiler technology which can switch between electricity and natural gas. The lower efficiency of the hybrid boilers compared the heat pumps make them more vulnerable to the electricity and natural gas prices. The analysis revealed that with the current price structure, using a hybrid boiler has a disadvantage over natural gas boiler regarding the operational costs. The evaluation includes two different industry categories, small and large, which are subjected to different energy taxes. Small scale industries have microscale manufacturing and production such as paper, pen, water bottles, tissues. The large industry is composed of chemicals, refining, food and processing, construction materials and the energy-intensive part such as the production of basic metals.

For small industrial consumers, taxes decrease the operational hours of electricity by 16%. For these consumers using a natural gas boiler is a cheaper option. For large industry, the electricity tax is not the main barrier against electrification as it is already slightly lower than taxes for natural gas. For these consumers, operational costs of the hybrid boiler are slightly less than a natural gas boiler. The energy tax shift that is proposed by the Climate Agreement Report is also tested for industrial consumers. With the shift of the taxes, it is more cost efficient to use electricity almost all year and the heating costs are decreased up to 50% for small industry and up to 45% for large industry. So far, these costs only include supply costs and energy taxes and levies for different type of industrial consumers. The addition of the network costs can make the business case worse for both type of consumers with the current tax structure. As it was explained in Section 3.4, the network costs for the industry is based on a contracted transmission capacity (kW contracted) and measured maximum capacity (kW max). Contracted capacity is the expected maximum power required by a consumer during the year (euro/kW/year). Measured maximum capacity KW-max is the maximum power used by a terminal in a month or week (euro/kW/month (or per week)). This tariff structure is against the electrification and the demand control in the industry. To be able to adopt power-to-heat technologies, companies need to switch to larger connections and increase their kW contracted capacity. The operational hours of electricity are the problem for the hybrid boiler. It is not possible to utilize from some network cost exemptions if the operational hours for electricity are more than 600 hours. However, these hours are not enough to cover the increased network costs. It was estimated that if electricity boiler is operating below 5700 hours, it is not possible to have positive returns (Joost de Wolff et al., 2018). Tax shift is one way to increase the operating hours and cover the network costs. To achieve substantial energy savings, adjustments to the network costs are also required. Some of the improvement suggestions involve tariffs according to available space on the network which uses green, orange and red codes according to the availability. Another option is making distinctions for specific technologies. In Germany, there are already some exemptions from network charges for certain technologies (Bayer, 2015).

Apart from the price structure, another important factor is the technology efficiency. The technology efficiency affects the business case of the power-to-heat technologies and the degree they are affected by the energy taxes. Households are not affected by the natural gas and electricity prices as much as hybrid boiler technology due to the high efficiency of the heat pumps. The lower efficiency of the hybrid boilers makes them more vulnerable to electricity and natural gas prices. Currently, the hybrid boiler is one of the commercially available and mature power-to-heat technology options for the industry. Other power-to-heat technologies with higher efficiencies are still in the research and development phase especially for the high and medium temperature heat demand. This part has the most potential for electrification of the industry compared to low-temperature heat demand. Even though heat pumps and hybrid boilers are already available for the low-temperature part, it is practical to use the residual heat from the other processes for this part. For the medium and high-temperature parts, the technology options are still not commercially available. High-temperature heat demand is mostly satisfied by fossil-fuel powered furnaces. Electric furnaces are under research and development phase. For the medium temperature, currently, hybrid boilers are ready to be used but without a positive business case. The high temperatures in the industry make the research and development process more challenging in terms of reaching high efficiencies. Industrial heat pumps have a lower COP compared to the ones that are used in the built environment.

In terms of providing flexibility, hybrid options stand out for the industry as well, similar to households. Hybrid technologies are considered as the transition technology for 2030. They have the potential for demand response in the form of load shedding and they can play a balancing role by switching between the sources. In the long term, they can be good decarbonization options when combined with a H2 (renewable gas) or green gas boiler. All-electric technologies can increase the burden on the power system if the load is inflexible.

## 6.4 Effect of Model Limitations and Assumptions

In this section, results of the analysis are discussed considering the assumptions and the model limitations provided in Chapter 4.

- The conclusions depend on the scenario choices that are made to represent the P2H demand for industry and households in 2030. In this study, it is identified that a hybrid boiler option from the industry provides a flexibility supply and a more cost-efficient coupling supported by residual peak load decreases. This conclusion depends on the available heat demand potential for hybrid boilers from the industry. In this study, it is assumed that this potential is 33 TWh which is approximately 27% of the expected P2H demand from industry. This demand is highly uncertain as it depends on the technology developments and the policies that provide incentives for electrification of the industry. The pace of the research and development for high-efficiency technologies might switch some part of this demand to full-electric technologies. In this case, a fixed increase in the electrical load would be observed without the option to switch between natural gas and electricity. This can decrease the identified power systems benefits from this study.

For the households, the review of the scenario studies in Chapter 3 reveals that the P2H load highly depends on the development of the competitive options such as biomass, solar thermal energy, geothermal energy, residual heat from industry and availability of green gas which can be injected to the natural gas grid directly to replace it. Depending on the availability, green gas has the potential to satisfy 8 to 12 TWh of household heat demand per year with a price of 0.7 to 1.5 euro/m3. Some scenario studies in Chapter 3 expect lower P2H demand for households and favor other competitive options. This implies lower impacts than this study concludes for 2030.

- COMPETES model does not include hybrid heat pump technologies for households. The aggregated household heat pump load is input and the optimal decision to use electricity and natural gas is not decided in the model. To analyze the decision of the households a decision mechanism outside the model was used similar to the hybrid boiler. Cost of one unit of heat was determined based on the electricity, natural gas prices, energy taxes and the heat pump COP which changes based on the temperature. Lack of this option in the model excludes one heat demand-side flexibility option for the households which can complement load shifting. A hybrid heat pump option from the household side can have more effects on the residual load curve by decreasing the peak load and increasing the off-peak load.

- System costs in this study do not include the investment costs for the optimal generation and transmission capacity as the investment module of COMPETES is not used. In addition, the investments for power-to-heat technologies, demand response technologies, and thermal energy storage are not included in the current version of the model. These costs are discussed to complement the model results but not presented together with the system costs. Exclusion of these components can result in overestimation of the system cost decreases.

- The thermal storage is not explicitly included in the model. It is represented by the variable, maximum hours to shift the load. The assumption that is made to match the maximum hours to shift and the storage type determines the results of the analysis related to the hot water heat tank. The maximum hours that this storage is able to shift the P2H load can change based on specific technical properties of the heat storage. Parameters such as the efficiency of the storage or losses are not included. When these parameters are also included the benefits for households might be lower than what is identified in this study. The payback period is also simply identified based on the savings and excludes the interest rate. The analysis provides initial insights related to the potential of the heat demand shifting from the perspective of the households. Inclusion of the above mentioned details can affect the findings.

- An important assumption related to the renewable generation capacity for the Scenarios No-P2H and InFlex-P2H is the VRE capacity. In both scenarios it was assumed that the renewable capacity is the same. However, if there is no additional electric load expected from the heat sector such as in InFlex-P2H Scenario, it is possible that the renewable capacity that is installed is smaller. The investment for renewable generation also depends on the government policies and subsidies apart from the market conditions. Effect of these factors were neglected and the renewable capacity was assumed to be the same in both scenarios. This assumption causes higher VRE curtailments in No-P2H Scenario as there is an overcapacity of VRE generation according to the total power demand. Therefore, the curtailment is significantly higher in No-P2H Scenario compared to InFlex-P2H Scenario. This assumption might cause an overestimation of the benefits from VRE integration when comparing the two scenarios.

- The database that is used for this study does not include the electrification from electric vehicles and heat pumps for the other countries in the model. Many countries in the model also face an increasing electrification in the transport and heat sectors but this demand is only included for the Netherlands. This assumption might cause underestimation of the EU system costs and emissions. It might also affect the trade flows between countries and as a result the system costs for NL.

- The cost savings of end-users in this study is only calculated for heating costs but not for the overall energy bill including other types of energy consumption (e.g. household appliances). The overall energy bill also includes the network costs and fixed supply costs. These costs are not included in the heating cost calculations for the households and industry as this research mainly focuses on the price distortions caused by the energy taxes and levies, the variable component of the energy and natural gas prices. In Chapter 3, it is identified that for households, the fixed supply and network costs compose approximately 25% of the total electricity bill while for natural gas this is approximately 12% of the total natural gas bill. For households, the fixed supply and network costs for electricity will be always paid as electricity is used independent of the heating technology so it does not contribute to the savings of switching from natural gas to electricity. In case of disconnecting from the natural gas grid there will be savings from the fixed natural gas costs, 13% of the overall natural gas bill. The exclusion of 25% electricity fixed network and supply costs might cause an overestimation of the overall cost savings for households (not just heating). On the other hand, with the same logic, the exclusion of the same costs for the natural gas consumption might cause an underestimation of the savings as disconnecting from the natural gas will bring monthly savings. Therefore, these two effects might balance each other in the end. For industry the structure of the network costs is more complex based on the capacity requirements and on operational hours for some exemptions. Therefore, it is briefly introduced and reflected but not analyzed in details in this study.

# 7 Conclusion and Further Research

This research investigated the implications of the increasing coupling between heat and power sectors from the perspective of power system and two end-users: households and industry. The chapter summarizes the main findings of the research and discusses them considering the current policy agenda. In the end, suggestions on model development and further research areas that can strengthen the provided analysis are presented. Below the main conclusions of the research are summarized:

**1)** Increasing coupling between power and heat sectors creates a need for more flexibility. If the extra power-to-heat load is not controllable, the power generation costs and net imports increase. To gain more benefits from this coupling the additional P2H load should be responsive to the needs of the power system. Heat demand flexibility helps decreasing system costs, CO2 emissions, net imports and VRE curtailment. As a new flexibility option, the flexibility from the heat sector replaces some part of the smart charging to provide the ramp needs.

**2)** The shifting of the household P2H demand in time has minimal effects on decreasing the peak and increasing the off-peak load. Effects on the other power system indicators such as the system cost and CO2 emission decrease are limited as well. This might imply that higher electrification rates for households are necessary in 2030 to create more substantial effects. Heat demand from the industry has a larger potential to decrease the peak load in the transmission level while households can be more important in the distribution level.

**3)** The most important benefit of the household level flexibility is the increase in the VRE integration. The largest system cost decrease is obtained when the percentage of controllable household P2H load is increased from 0% to 25%. There is not a specific interval that all the benefits are captured from the indicators that are determined for this study; namely, systems cost, CO2 emissions, VRE generation revenues, VRE curtailment, annual residual peak load.

**4)** The obtained heating cost savings by means of shifting the P2H demand in time is promising for households but may not be enough to change the consumer behaviors on a large scale. Extra incentives and well-provided information are needed for households to participate in demand response programs. Aggregator as a new actor in the power system is definitely important to provide optimal savings for the consumers.

**5)** The small difference in heating cost savings (5%) between 2 hours and 5 hours load shifting reveals that for a household that already has insulation and heat pump, it is not reasonable to invest in a decentralized thermal storage. A larger size utility or community scale storage can be a better option as it will increase the savings from the heating costs more and reduce the initial costs by allocating them between various actors such as system operator and the aggregators.

**6)** Heat pumps provide operational savings for households compared to natural gas boilers even with the energy taxes and under the extreme weather conditions due to their high coefficient of performance. However, current tax structure prevents obtaining more energy savings for the households to cover the investments in shorter time. This makes the investment costs for the heat pumps an important barrier for the existing households. The tax shift suggested in the Climate Agreement Report increases the annual heating cost savings for a household that uses heat pumps up to 55%. More savings imply a shorter payback period which encourages consumers for the adoption of the heat pump technologies.The addition of ETS CO2 prices to natural gas prices for household heating increases the heating costs by 39% for a natural gas boiler. However, it does not increase the operational hours of electricity for a hybrid boiler. This implies that to achieve more cost savings for shorter payback periods, a modification of the electricity prices is also needed.

**7)** Industry has a potential for providing flexibility to the power system from hybrid power-to-heat applications. To unlock this potential two factors are important: technology research and development and tariff structure (network tariffs for electricity and tax tariffs for electricity and natural gas). These two factors should progress simultaneously to make a positive case for power-to-heat in 2030 for the industry.

**8)** Small industrial consumers are affected negatively by the high electricity taxes while for the large industry these taxes do not discourage the usage of electricity. The efficiency of the power-to-heat technologies also determines the degree that the end consumer is affected by these taxes. The industry is influenced more than the households as hybrid boiler technology has lower efficiency compared to heat pumps.

**9)** With the current price structure, the businesses case is not positive for hybrid boilers in industry. As a result, not all the flexibility benefits that hybrid boiler can provide is revealed. Using natural a gas boiler is a cheaper option for small industry while the operational costs are really close to each other for the large industry. Addition of the network costs will turn the situation more against the usage of electricity. While a tax shift can switch the operational times to electricity for a hybrid boiler almost all the year, to achieve more energy savings a reform in the network costs should be implemented together with the tax shift.

**10)** Even though the aim is to become natural gas free towards 2050, natural gas is still a cost-efficient option in 2030 without any policy interventions. Hybrid technologies stand out as an attractive transition pathway both for industry and households. They are also promising options for decarbonization as they can be used together with renewable and green gas.

Climate Agreement, a package of policy measures that aims to bring 49% of emission reductions for the Netherlands by 2030 compared to 1990, presents the most recent policy agenda for the Netherlands. One of the important policy instrument that is on the agenda right now is the tax shift from electricity to natural gas. The commodity prices are the result of market interactions but subsidies and taxes can be used to stimulate the desired consumer behavior. It is important to carefully design these instruments in order to avoid inefficiencies and distortions in the market. The two-step tax shift that was discussed in the Climate Agreement Report helps to reduce the barriers against power-to-heat technologies for the end-users. However, there are concerns that it will increase the energy costs for the low-income houses that are connected to the natural gas grid and cannot afford heat pump technologies. Possible solutions for this include reducing income tax, increasing rent allowance or other benefits to compensate for the increase in the energy bill for these houses. The Ministry of Economic Affairs is currently calculating the effects of the tax shift on the purchasing rate for heat pump technologies. The tax shift percentages are subject to adjustments according to these calculations. It is expected that with the tax shift, the heat pumps are going to be used more widely and as a result, the investment costs will decrease for the existing households (Pieters, 2018).

There are also subsidies provided for sustainable energy investments. Dutch Sustainable Energy Investment Grant (ISDE) is a program launched by the Dutch government to encourage the adoption of sustainable heating technologies such as heat pumps, solar boiler, biomass boiler or pellet stoves. For 2018 the Ministry of Economic Affairs and Climate Policy has allocated 100 million euros for this subsidy scheme. The subsidy is for businesses and households and partially compensates the initial investments depending on the device and its energy performance. The amount of subsidy varies between 1000 to 2500 euro depending on the technical parameters of the heat pump (Rijksdienst voor Ondernemend Nederland). In addition, government considers including hybrid boilers under the renewable subsidy scheme SDE ++ which is the widened version of the SDE renewable energy subsidy scheme. The new version will focus on CO2-reducing technologies and provide incentives through an operating grant (financing the running costs). There are concerns that a production subsidy might lead to disruption of the electricity market and possibly additional emissions since the option fosters the production even when there is no renewable energy.

Without additional policy instruments, it is unlikely that the identified potential benefits of sector coupling will be unlocked as there are important barriers both for households and industry. Different type of policy measures is on the agenda of the Dutch government to encourage the end-users. There is substantial flexibility potential from the industry side which does not have a positive business case in 2030 with the current policies. For the industry, the tax shift needs to be supported by a reform in the network costs. The effects of the household demand flexibility are minimal on the transmission system. The effects might be more valuable for the distribution system. For households, one of the key policy measures is to increase the energy savings by a tax shift from electricity to natural gas. There are already subsidy schemes provided for sustainable heating technologies. With the increase in energy savings due to the tax shift, the remaining amount that households need to pay will decrease. In the process of designing policy instruments, the involvement of various actors is important to make the transition more cost-efficient. The negotiators include environmental organizations, municipalities, housing corporations, energy companies, construction companies, banks and trade unions.

Finally, some suggestions for further research points that can follow up this study are explained below.

- A network constrained power system model (COMPETES) is used in this thesis to answer the research questions. As it is mentioned in Chapter 4, the heat part of the model is still developing. An improvement for the model is the inclusion of a hybrid heat pump for the households. This can be done in a similar operational logic for the hybrid boilers that are already in the model. The hourly thermal energy profile for household heating can be provided as an input to the model, similar to industry heat demand. The hourly temperature data for a year can also be provided as input to determine the changing COP of the heat pump. This relationship depends on the type of heat pump (air/ground) and can be identified from the technical parameters. A hybrid heat pump switches in between the two energy sources which are the most efficient. The switch in between can be again based on the price of one unit of heat which is calculated by the efficiency of the gas boiler and the changing coefficient of performance of the heat pump. Heat pump and gas boiler modes can be used separately and together as well depending on the efficiency.

- Investment module of the COMPETES is not used for this study. It is found out that increasing power-to-heat demand requires more flexibility in the power system. However, this can only provide benefits to a certain extent according to the already existing generation portfolio. At some point, the increasing electrical load might also require generation and transmission capacity investments. Investment module of the COMPETES model can be used to identify the optimal generation and transmission capacity needs for the power system. In the analysis, the total system costs do not include the investment costs for the scenarios. The system costs can be recalculated including the optimal investment costs for all of the scenarios. As a substantial amount of electrical load is added in InFlex-P2H Scenario from the industry side, extra investments might be required for this scenario compared to others. It is also expected that the heat demand flexibility that is provided will contribute to more efficient use of transmission and generation assets and result in lower needs for investment for Flex-P2H Scenario. After the inclusion of these costs, the system costs savings can change in between the scenarios. For all of the scenarios, the model is able to satisfy the provided electrical load which implies that there will not be significant investment requirements.

- This research focuses on the scenarios for 2030 and does not includes any cases for 2050. With the 2030 database, it is observed that even without the taxes electricity prices are lower than the natural gas prices only a limited amount. The model output electricity prices can differ in 2050 which supports a more favorable condition for P2H technologies. In addition, for 2030 it is found out that the power system benefits from the household side are limited. The increasing power-to-heat demand in 2050 can reveal more significant effects.

- The 5TWh heat pump load only includes the demand for households. The effects on the residual load curve and the decrease in the peak load are less than expected. If the service sector is also included the power-to-heat load for 2030 can increase up to 9 TWh for built-environment as mentioned in Chapter 3. Inclusion of this part of the heat demand can cause more significant effects on the power system. The demand profile for service sector is different than households. Buildings such as industrial/company halls, shops and offices are used between 7 a.m. and 7p.m and they are heated to 19 °C during these hours. After 7 pm the average temperature drops to 13 °C (van Ende, 2018). A profile based on these basic requirements can be included.

- The network costs for industry are not included in the heating cost calculations. The energy savings gained by switching to P2H technologies can be compared with the increase in the network costs to understand the financial effects of the network costs more in detail. The analysis showed that even without considering the network costs the business case for hybrid boilers is not positive. Inclusion of these costs are important as a barrier. The capacity contracted determines the network cost to be paid by the large industrial consumers. P2H technologies usually increase this amount. A comparison can be made between energy savings from using hybrid boiler (instead of natural gas boiler) and the increased network costs (kW contract and kW max) to see whether energy savings are enough to cover the increased network costs.

# Appendix A

The sources and some additional explanation for the heat demand per energy carrier and year from Table 4 is provided below:

(Natural) Gas 2015 and 2030: National Energy Outlook (ECN, 2017) and Monitoring Warmte (Menkveld et al., 2017).
*Numbers are according to the assumption that there are extra measures for reduction of natural gas. Natural gas that is used also includes cooking.

(Natural) Gas 2050: CE Delft (Naber et al., 2016), Berenschot (den Ouden et al., 2017) and Ecofys (van Melle, Menkveld, Lohuis, de Smidt, & Terlouw, 2015)

Heat (2015): National Energy Outlook (ECN, 2017)

Heat(2030): National Energy Outlook (ECN, 2017) , Climate Agreement Report (Dodion & Melotte, 2018)

Heat (2050): CE Delft (Naber et al., 2016), KIVI study (Persoon, Luitjens, Boonstra, & van Moerkerken, 2017)

*The values for electricity exclude ambient heat.

Electricity (2015): Monitoring Heat (Menkveld et al., 2017). Electricity for households include heat pumps, heating boilers, electric radiators, underground heating. For service sector it is only heat pumps.

Electricity (2030): National Energy Outlook. Expectation of 14 PJ increase in heat pumps is added to 2015 number for households which makes 21.1 PJ For service sector 3.9 - 12 PJ increase of electricity demand is expected.(ECN, 2017)

Electricity (2050): CE Delft. The electricity demand for heating for households vary between 14 and 72 PJ (Naber et al., 2016). Same amount is assumed for the service sector.

# Appendix B

Table 27 shows the summary of the scenarios under different conditions from (Naber et al., 2016). The green cells represent the scenario variables that are changed for that particular scenario.

Table 27: Scenario Studies for Heat-Demand in Built Environment in 2050 (Naber et al., 2016)

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 |
|---|---|---|---|---|---|---|---|---|
| Available Green Gas | 1.5 bcm (45 PJ) | 1 bcm (30 PJ) | 1.5 bcm | No limit (can be imported) | 1.5 bcm | 1.5 bcm | 1.5 bcm | 1.5 bcm |
| Green Gas Price | 0.7 euro / m3 | 0.7 euro / m3 | 1.5 euro / m3 | 0.7 euro / m3 | 0.7 euro / m3 | 0.7 euro/m3 | 0.7 euro/m3 | 0.7 euro/m3 |
| Insulation | Cost optimally determined | Cost optimally determined | Cost optimally determined | Cost optimally determined | At least level C | Cost optimally determined | Cost optimally determined | Cost optimally determined |
| HR Boilers | Available | Available | Available | Available | Available | Available | Not Available | Available |
| Residual Heat | Well available | Well available | Well available | Well available | Well available | No residual heat | Well available | Well available |
| Electricity Price | 0.07 euro/kwh | 0.07 euro/kwh | 0.07 euro/kwh | 0.07 euro/kwh | 0.07euro/kwh | 0.07euro/kwh | 0.07euro/kwh | 0.12euro/kwh |
| Heat Demand Per Technology | | | | | | | | |
| * Demand Heat Pump | 4.1 PJ (1%) | 7 PJ (2%) | 2 PJ (0.5 %) | 0 PJ (0%) | 7 PJ (2.1 %) | 3 PJ (0.8 %) | 3 PJ (0.8 %) | 2 PJ (0.6 %) |
| * Demand Hybrid Heat Pump | 46 PJ (12 %) | 38 PJ (10.6 %) | 77 PJ (21.2 %) | 88 PJ (%22.7) | 32 PJ (9.8 %) | 52 PJ (14.7 %) | 78 PJ (21.4%) | 28 PJ (8.4 %) |
| Penetration per Technology [% # households] | | | | | | | | |
| * Heat Pump | 2 % | - | - | 0 % | - | 2.5 % | 1.3 % | |
| * Hybrid Heat Pump | 10% | - | - | 22.6 % | - | 11.5 % | 17% | |
| Electrcity | 29 PJ | 33 PJ | 27 PJ | 7 PJ | - | 36 PJ | 26 PJ | - |

The last row in Table 27, "electricity" is the energy carrier to cover the final heat demand excluding ambient heat. According to the table, the amount of available green gas affects the electrification of heat demand significantly. As long as it is available, it is the first preference and all of it is used. The percentage of demand that is satisfied by the electric technologies are close to the percentage of households that use the technologies. The penetration rate of hybrid heat pumps varies between 10% and 22.6%. The penetration of all-electric heat pumps vary between 0% and 2.5% and is lower compared to FlexNet study market penetration rate for 2050 in Table 5.

For these scenarios the following assumptions are made:

1) In 2050, individual heating options using gas are all switched from natural gas to biogas.
2) Individual all-electric options, heat network are used when all available green gas is exhausted and no residual heat or geothermal energy is available locally.

3) The heat network includes geothermal, district CHP and residual heat options.
4) The energy demand consists of the demand for space heating, hot tap water, co-firing with gas, cooling, ventilation, auxiliary energy and energy for equipment and lighting.
5) The heat demand can be reduced by insulation measures, but also by means of solar water heaters and solar PV (for electric pumps). The amount of these savings are determined by the model.

# Appendix C

The sources and some additional explanation for the heat demand per energy carrier and year from Table is provided below:

Total Energy Demand (2015): National Energy Outlook (ECN, 2017). Includes final energy use for heat, final electricity usage and non-energetic use

Total Energy Demand (2030) and (2050): Berenschot (den Ouden et al., 2017)

Total Heat Demand (2015): Monitoring Warmte (Menkveld et al., 2017)

Total Heat Demand (2030):Berenschot (den Ouden et al., 2017) (10%- 20% decrease in heat demand)

Total Heat Demand (2050): McKinsey (Roelofsen et al., 2017), Berenschot (den Ouden et al., 2017): Depending on the high and low economic development

Heat from Electricity (2015): Monitoring Heat (Menkveld et al., 2017) indicates it is unknown.

Heat from Electricity (2030): Berenschot (den Ouden et al., 2017), National Energy Outlook (ECN, 2017)

Heat from Electricity (2050): McKinsey (Roelofsen et al., 2017)

# Appendix D

Below the explanation for the values in Table 11 is provided:

[1]- FlexNet R2030. [2]- FlexNet A2030. [3]- Based on Climate Agreement Report [4] All three numbers from CE Delft Scenario Study under different conditions. [5] Ratio of Heat from Electricity to Total Heat Demand from Table 5.

- The total heat demand and the P2H Demand are from Table 4 and 7.

Built-environment 2030:

- For built-environment the share of households that are expected to be connected to heat networks or use all-electric or hybrid heat pumps and the number of expected households to be built are obtained from Climate Agreement Proposal.

- Penetration P2H Technologies: Technology options include heat pumps (air, ground) and hybrid heat pumps. Three different percentages for the penetration of technologies were obtained from two different studies. Climate Agreement Draft Report suggests that among the new households 25% will be connected to heat network, 56% will have all electric heat pumps and 19% will have hybrid heat pumps. It is expected to have 717 000 new buildings by the end of 2030. This makes 537 750 households with heat pumps (hybrid and others). Starting from 2021 to 2030, among the existing households 45% is expected to be connected to heat network, 18% all electric, 37% hybrid (Page 93 of the report). According to CBS data in 2018 there were 7 857 914 private households in Netherlands. This makes 4 321 853 households with heat pumps (hybrid and others). Overall in 2030, 8 574 914 households exist with the new constructed ones (7 857 914 + 717 000). This number might slightly decrease when the number of demolished households are also considered. CBS forecasts 8 487 000 households for the year 2030 and also provides a 95% interval of 7 859 000 - 9 199 000. For the calculations number of households are considered as 8 574 914. Among all houses, 4 859 603 households have either hybrid or all electric heat pumps. Penetration rate is found as 56% for all type of heat pumps.

- Technology Mix: Based on the shares provided by the Draft Climate Agreement Analysis among the households that already adopted the heat pump technologies 37% (1 815 945 /4 859 603) uses all electric technologies while 63% (3 043 658 /4 859 603) uses hybrid heat pumps. It is assumed that houses are well isolated. In FlexNet scenario it was assumed that 95% households have all electric heat pumps while only 5% have hybrid heat pumps. Table 28 shows the calculation.

Table 28: 2030 Technology Mix for Households

| | Existing Households | New Households |
|---|---|---|
| Heat Network | 45% (# 3 536 061) | 25% (#179 250) |
| Heat Pumps (all-electric) | 18% (# 1 414 425) | 56% (# 401 520) |
| Hybrid Heat Pumps | 37% (# 2 907 428) | 19% (# 136 230) |
| Total | 100% (#7 857 914) | 100% (#717 000) |

Built-environment 2050:

- There are no predictions for 2050 in Climate Agreement. FlexNet and CE Delft 2050 Scenario studies are used.

Industry 2030:

- Penetration P2H Technologies:In the Climate Agreement Draft report, there is not a specific indication about how much of the heat demand will be electrified in industry. According to Table 7 of the scenario studies, the ratio is between 24% - 32%. However, Climate Agreement Analysis predicts that the 52.5 % of the emission reductions will be due to electrification.

- Technology Mix: For industry most technologies are in the development phase, there are no predictions on the technology mix. In the scenarios of the Climate Agreement Draft Analysis 33 TWh of heat demand is used for an analysis by hybrid boilers.

# Appendix E

Table 29: COMPETES Generation Technologies

| Fuel | Types | Abbreviation |
|---|---|---|
| Gas | Gas turbine | GT |
| | Combined cycle | NGCC |
| | Combined heat and power | Gas CHP |
| | Carbon capture and storage | Gas CCS |
| Derived Gas | Internal combustion | DGas IC |
| | Combined heat and power | DGas CHP |
| Coke oven gas | Internal combustion | CGas IC |
| Coal | Pulverized coal | Coal PC |
| | Integrated gasification combined cycle | Coal IGCC |
| | Carbon capture and storage | Coal CCS |
| | Combined heat and power | Coal CHP |
| Lignite | Pulverized coal | Lignite PC |
| | Combined heat and power | Lignite CHP |
| Oil | Oil | |
| Nuclear | Nuclear | |
| Biomass | Co-firing | |
| | Standalone | |
| Waste | Standalone | |
| Geo | Geothermal power | |
| Solar | Photovoltaic solar power | |
| | Concentrated solar power | |
| Wind | Onshore | |
| | Offshore | |
| Hydro | Conventional | |
| | Pump storage | |

# Appendix F

Table 30: Systems Cost NL Calculation for InFlex-P2H and Flex-P2H Scenarios

| Million euros | InFlex-P2H | Flex-P2H |
|---|---:|---:|
| Biomass | 82.83 | 82.66 |
| GasCCGT | 404.15 | 339.15 |
| GasCHP | 1069.65 | 1026.25 |
| DerivedGasCHP | 4.79 | 4.79 |
| DerivedGasIC | 127.26 | 127.39 |
| Hydro | 0.10 | 0.10 |
| Nuclear | 41.19 | 41.24 |
| Waste | 284.32 | 244.74 |
| WindOnshore | 37.90 | 37.90 |
| WindOffshore | 96.66 | 96.65 |
| NetImports | -539.09 | -1693.16 |
| NaturalGasIndustryHeat | | 1005.11 |
| Total | 1609.76 | 1312.82 |

Industry heat demand is satisfied by natural gas for 7098 hours. The price of the natural gas is 33.80556841 euros / Mwh. Hourly heat demand is 3767.123 MWh and if this amount is satisfied by natural gas it is 4431.909412 MWh. There is 1 billion extra cost from the industry heat demand.

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