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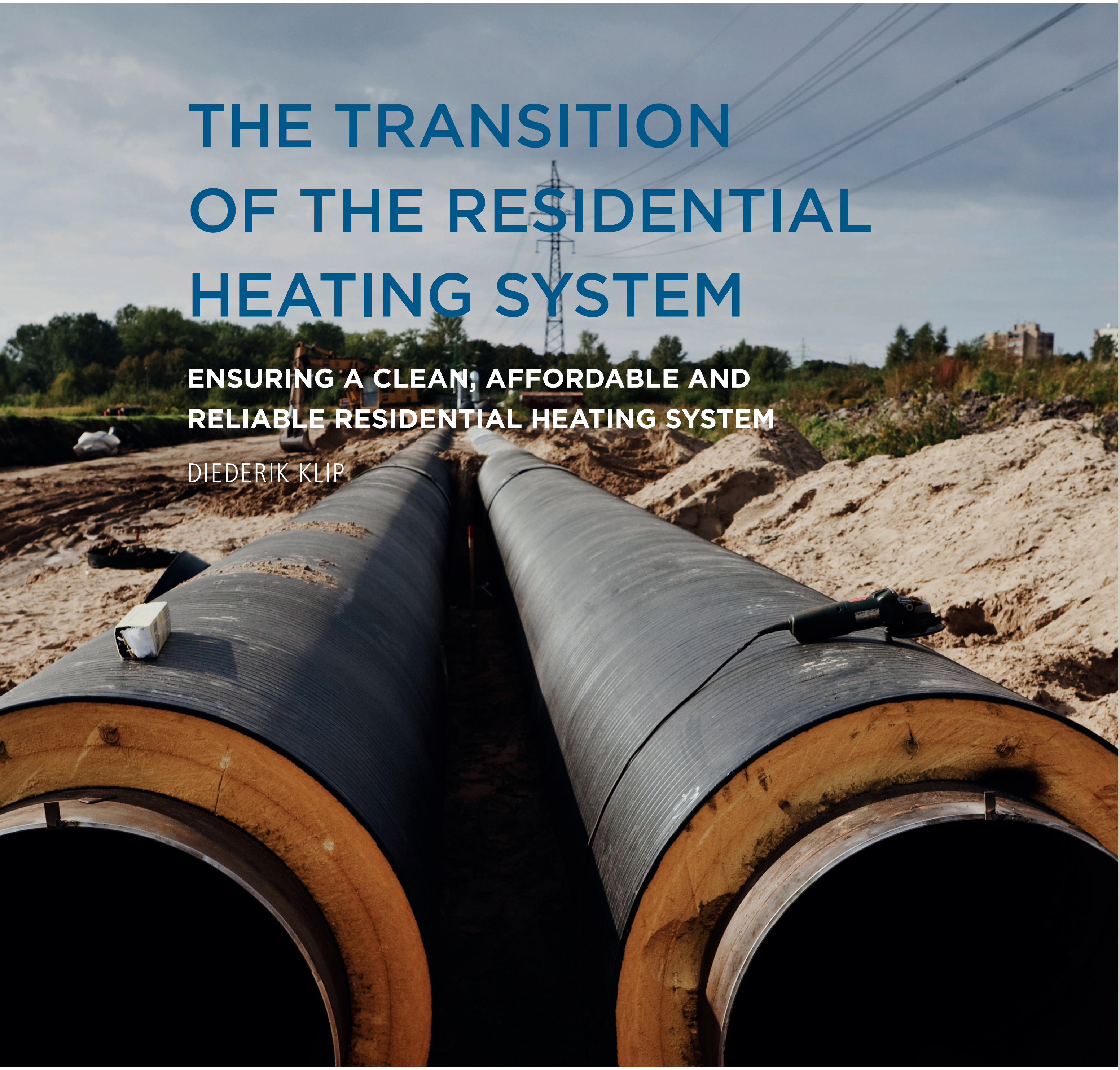

THE TRANSITION OF THE RESIDENTIAL HEATING SYSTEM

ENSURING A CLEAN, AFFORDABLE AND RELIABLE RESIDENTIAL HEATING SYSTEM

DIEDERIK KLIP

CIEP PAPER 2017 | 01

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AUTHOR
Diederik Klip

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Tom Johnson

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Studio Maartje de Sonnaville

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ADDRESS
Clingendael 12, 2597 VH The Hague, The Netherlands
P.O. Box 93080, 2509 AB The Hague, The Netherlands

TELEPHONE
+31 70 374 67 00

EMAIL
ciep@clingendaelenergy.com

WEBSITE
www.clingendaelenergy.com

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LIST OF ABBREVIATIONS

ASHP	Air Source Heat Pump
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
DSM	Demand-Side Management
DSO(s)	Distribution System Operator(s)
EV	Electric Vehicles
HCS	Heat-Cold-Storage
HP	Heat Pump
H-gas	High-calorific gas
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
ICT	Information and Communications Technology
L-gas	Low-calorific gas
RES-E	Renewable Energy Sources for Electricity
SMR	Steam Methane Reforming
TES	Thermal Energy Storage
TSO	Transmission System Operator

Units

kW	Kilowatt
MW	Megawatt
GW	Gigawatt
kWh	Kilowatt Hour
MWh	Megawatt Hour
GWh	Gigawatt Hour
TWh	Terawatt Hour

EXECUTIVE SUMMARY

Stakeholders and policy-makers alike increasingly recognise the magnitude of the looming challenge to decarbonise the residential heating system, which represents approximately 15% of Dutch final energy consumption. This paper considers three alternative heating options which could reduce emissions in the run-up to 2050, and eventually have the potential to become fully carbon neutral, namely: all-electric heat pumps, district heating and hybrid heat pumps.

Looking at the current transition efforts being undertaken in the Netherlands, it appears that there are no mechanisms in place to steer stakeholders, such as end users, housing corporations, homeowners, market parties, energy network companies and project developers, toward achieving demonstrable CO_2 emission reductions from a supply chain perspective. Further, it seems that the reliability and affordability of alternative heating options are not actively considered, and that the trade-off in terms of societal cost between these two aspects is, as yet, insufficiently recognised.

The main problem is that stakeholders do not take account of the whole supply chain of alternative heating options, but only consider the costs with which they are directly confronted, such as for heating equipment or building energy efficiency measures, hereby limiting their ‘system boundary’ to a small part of the supply chain. This paper provides a qualitative analysis of the supply chains of the three alternative heating options. Its key findings are that:

- The potential shift of CO_2 emissions from the residential sector to electricity and district heating systems is not sufficiently recognised. As a result, the costs associated with decarbonising the respective alternative heating supply chains are opaque, which prevents these costs from being adequately compared.
- Energy infrastructure costs are not consistently incorporated into the economic assessment of stakeholders. Potential electricity infrastructure costs to meet peak demand from all-electric heat pump systems are implicitly socialized, leaving end users, project developers and housing corporations alike with little incentive to consider these costs. By contrast, the current regulated pricing regime for district heating, albeit under revision, explicitly incorporates infrastructure costs. Conversely, the potential avoided or at least deferred infrastructure costs

associated with hybrid heat pump systems are not adequately valued. Finally, stakeholders disregard the potential cost associated with (partially) removing the existing gas infrastructure, which may lead to premature depreciation or double infrastructure.

- The production side of the energy economy will need to be reconfigured toward more production capacity in the electricity and district heating systems. Particularly for all-electric heating, an increase in electricity peak demand requires sufficient flexible generation capacity to guarantee a reliable supply of electricity at all times. Likewise, large investments will be required to shift towards more district heating production. Finally, the fact that the security of supply of hybrid heat pumps is underpinned by the flexibility of the gas system is not sufficiently recognised.

The consequences of the lack of a supply chain perspective are twofold. First, it inhibits stakeholders from identifying and exploiting synergies arising from the interplay of the supply chain components. Second, the lack of a supply chain perspective means that stakeholders are not able to make an adequate assessment of *which* alternative heating options are to be implemented *where* and *when*. This can result in the adoption of sub-optimal solutions from a supply chain perspective and thus higher societal costs. Even if they are unable to perceive them, end users are ultimately exposed to these costs, be it in the form of higher grid tariffs, higher electricity prices (due to tighter electricity market conditions), or higher levies on electricity and gas bills (to finance the support scheme for renewable energy). Excessive costs could eventually erode public support for the transition, and jeopardise its effectiveness in reducing CO_2 emissions.

One way of incorporating the supply chain costs into the economic assessment of stakeholders is to make these costs transparent by means of stakeholder coordination at a local level but under the tutelage of the national government to ensure equal treatment of all citizens. To eventually determine what is the most cost optimal heating option for reducing CO_2, while maintaining an acceptable level of reliability, a uniform 'technology neutral' assessment framework might prove useful. Such an assessment framework would also allow for 'upstream' supply chain costs to be incorporated that do not directly accrue to a specific party.

The development of the residential heating system up to 2050 is inherently uncertain, as technological progress will continue to change the relative costs of alternative heating options. Adaptive policy will be crucial to manage this uncertainty. Ultimately, the challenge is to institutionalise a 'technology neutral' approach, enabling affordable CO_2 reductions while maintaining an acceptable level of reliability, and ensuring sufficient flexibility to react to changing relative costs over time.

1 INTRODUCTION

The transition of the residential heating system has recently become a hot topic in the Netherlands. Stakeholders and policy-makers alike increasingly recognise the magnitude of the looming challenge to decarbonise this sector, which represents approximately 15% of Dutch final energy consumption.[1; 2]

Residential heat demand in the Netherlands is mainly met by highly efficient gas-fired condensing boilers, which are a very reliable as well as affordable heating option for end users.[3] In fact, the Dutch gas-based heating system is already relatively CO_2-efficient compared to some countries, where more carbon-intensive fuels such as heating oil, coal or liquefied petroleum gas are still widely used. Yet to reach the CO_2 reduction targets set out in the Paris Agreement on mitigating climate change, CO_2 emissions from residential heating will need to be substantially reduced, and ultimately virtually eliminated.[4]

This paper considers three alternative heating options which could reduce emissions in the run-up to 2050, and have the potential to become fully carbon neutral, namely: all-electric heat pumps, district heating and hybrid heat pumps.[5]
The anticipated costs of substantially reducing emissions from residential heating for the Netherlands' 7.2 million existing dwellings up to 2050 are enormous. The transition will require investment in new in-house heating technologies, energy efficiency measures to reduce heat demand, new energy infrastructure to transport the energy for heating to end users, and upstream investments in electricity production, district heating and biogas production.

The transition of the residential heating system is further complicated, both by the diversity of the existing building stock, and by the presence of a wide range of relevant stakeholders, each with their own interests and targets. As such, there is no silver bullet or one-size-fits-all solution. Instead, the optimal approaches and

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[1] The horticulture sector is also a major consumer of low-temperature heat to maintain favourable growing conditions inside greenhouses. The sector uses around 105 PJ/year, equal to 5% of final energy consumption.

[2] CBS Statline data and ECN, PBL and CBS. (2015), 'Nationale Energieverkenning 2015.'

[3] ECN and RIGO. (2013), 'Energiebesparing: Een samenspel van woning en bewoner – Analyse van de module Energie WoON 2012.' Commissioned by the Dutch Ministry of the Interior and Kingdom Relations.

[4] Raad voor de leefomgeving en infrastructuur. (2015), 'Rijk zonder CO_2 – Naar een duurzame energievoorziening in 2050.'

[5] In 2015, district heating and electric heating, although growing, only represented 4.5% and 2% of total heat production respectively. See ECN, PBL and CBS. (2015), 'Nationale Energieverkenning 2015.'

technological solutions are likely to differ per neighbourhood.[6] More importantly, stakeholders' objectives, and their approach to determining *which* heating configuration to implement *where* and *when*, can have a substantial effect on the total societal cost of the transition.[7]

This paper argues that the goal of the transition is to reduce CO_2 emissions, achieving a cleaner residential heating system, while balancing two other key objectives, affordability for the end user and reliability of supply. Worryingly, the current debate in the Netherlands has been muddied by secondary considerations, such as 'getting off gas', without due consideration to achieving demonstrable CO_2 reductions, implementing cost-efficient solutions and ensuring the reliability of the energy system as a whole.

Currently, CO_2 emissions associated with residential heating mainly take place within the built environment, when consumers combust natural gas in a boiler to heat their homes. However, with the advent of alternative heating options, CO_2 emissions will increasingly take place within the electricity system or in the district heating system, after which electricity and heat is transported through the energy infrastructure to the end user. To be able to assess the CO_2 intensity of the alternative heating options, and thus steer on the affordability of CO_2 emissions reductions, stakeholders will need to take this shift into account.

At present, we take it for granted that there is always sufficient supply of gas for residential heating. However, when moving to other energy carriers, the production side of the energy economy will need to be reconfigured toward more production capacity in the electricity and district heating systems. Only the gas infrastructure has been dimensioned to cope with the highly seasonal peak demand for residential heating. The existing electricity distribution infrastructure would need considerable investment to cope with the large electricity demand arising from all-electric heat pumps. Failing to ensure sufficient transport capacity could endanger the reliability and functioning of the network. In the case of district heating, new infrastructure will need to be constructed from scratch to deliver heat to end users.

Some stakeholders, such as housing corporations, homeowners and end users, naturally tend to pursue low-cost heating options. However, by limiting their system boundary to the costs they bear directly – such as the cost of in-house heating

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[6] CE Delft. (2016), 'Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving –update 2016, De route naar een klimaatneutraal Nederland.'

[7] Ecofys and ECN. (2015), 'De systeemkosten van warmte voor woningen.' Commissioned by Alliander, Gasunie and TenneT.

technology, the radiator system, or energy efficiency measures to reduce demand – stakeholders often neglect the costs and investments incurred by other parties, including energy infrastructure and other upstream costs in the energy system.

To shed some light on these issues, this paper provides a qualitative analysis of the supply chains of the three alternative heating options. The aim is not to promote the adoption of any single option, but rather to provide insight into how clean, reliable and affordable these alternatives are when the entire supply chain is taken into account. Ultimately, we hope this research can contribute to more rationality in the ongoing debate on the decarbonisation of the residential heating system.

The analysis presented in this paper pertains to the Dutch residential heating system. Some of the findings are however relevant for other countries, especially those that have gas distribution infrastructures, such as the United Kingdom, Belgium and Germany.

2 THE CURRENT GAS-BASED RESIDENTIAL HEATING SUPPLY CHAIN

Following large domestic gas findings in the late 1950s, the Netherlands developed an extensive and highly reliable natural gas transmission and distribution infrastructure, ushering in the transition from coal, town gas and (to a lesser extent) oil-based heating to natural gas-based heating.[8] The shift from coal to gas was a win-win. Apart from being a cleaner, more convenient and more reliable fuel, natural gas also became cheaper once the infrastructure had been realized through extensive public-private coordination.

Gas is relatively less carbon-intensive compared to other heating fuels, such as coal, heating oil and liquefied petroleum gas (LPG). Consequently, the Dutch residential heating system is relatively CO_2-efficient compared to international peers. Some EU countries still use (substantial shares of) heating oil in their residential energy mix, for example: Ireland (37%), Luxembourg (31%), Belgium (31%), Germany (24%), and France (17%), while the average across the EU-28 is 13% (see Appendix A for a graphical overview).[9]

Figure 1 is a schematic depiction of the Dutch gas supply chain for residential heating, consisting of flexible domestic gas production, gas imports, underground gas storage, gas infrastructure and in-house gas boilers. The gas consumed in the residential sector is primarily low-calorific natural gas (L-gas) extracted from the Slochteren field in Groningen. Large industrial consumers mainly consume high-calorific gas (H-gas), which either comes from smaller offshore fields or is imported (see Box 1).

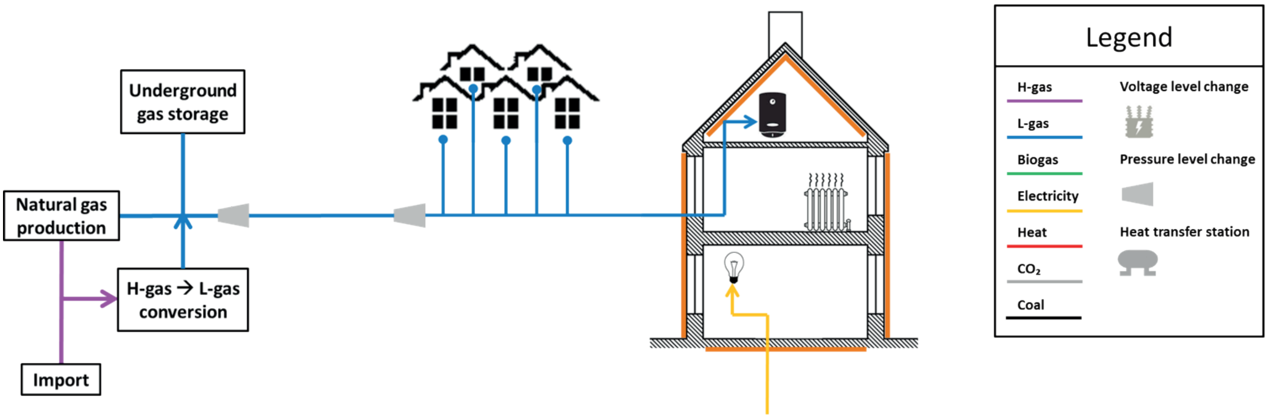

FIGURE 1. SCHEMATIC REPRESENTATION OF THE GAS SUPPLY CHAIN FOR RESIDENTIAL HEATING

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[8] Correljé, Aad, Van der Linde, Coby, and Westerwoudt, Theo. (2003), 'Natural Gas in the Netherlands: From cooperation to competition?' Clingendael International Energy Programme/Oranje Nassau.

[9] Data from Eurostat (2014).

Space heating represents the bulk of residential gas consumption (79%), followed by domestic hot water use (19%), while cooking only represents a small fraction (2%).[10] Average household gas consumption, and thereby its associated CO_2 emissions, decreased by 25% over the period from 2000 to 2015, from 1,911 to 1,432 cubic metres (m^3).[11] This can be attributed to improvements in the level of building energy efficiency, particularly insulation measures, as well as an improvement in the average efficiency of in-house gas boilers.[12]

Despite the decrease in average household gas consumption, the absolute volume of gas consumed for residential heating remains substantial. Figure 2 plots the gas consumption pattern at a distribution network level (LDC level, in blue), which *includes* the residential sector, the horticulture sector and some industrial users, but *excludes* large industrial gas users which are connected to the H-gas network. Industrial H-gas consumption is intentionally omitted to emphasise the magnitude of peak demand for residential gas (see Appendix B for industrial and aggregate gas demand patterns). For comparison, Figure 2 also shows the national electricity consumption pattern in green, which *includes* large industrial electricity users.

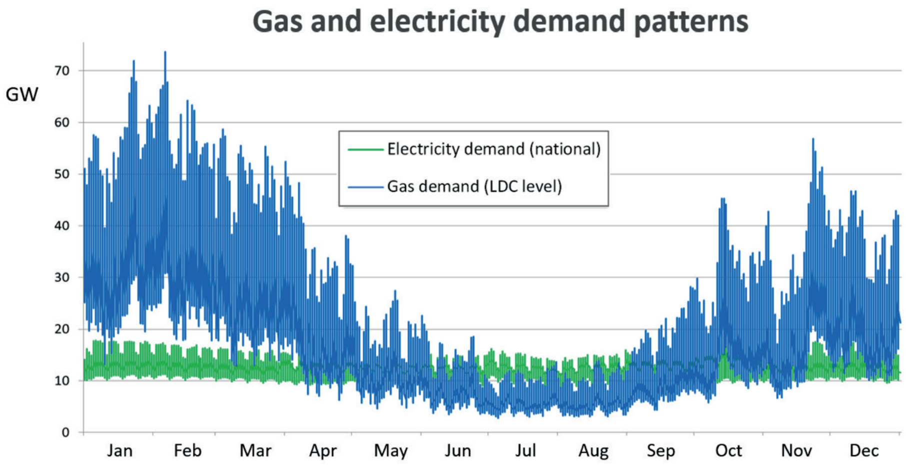

FIGURE 2. NATIONAL HOURLY ELECTRICITY LOAD VALUES FOR THE NETHERLANDS IN GW, AND GAS CONSUMPTION AT LDC (I.E. DISTRIBUTION LEVEL) OFFTAKE POINTS IN GW, IN 2015. SOURCE: CIEP ANALYSIS, DATA OBTAINED FROM ENTSO-E AND GASUNIE TRANSPORT SERVICES.

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[10] Figures from 2010, see Netbeheer Nederland. (2015), 'Energie in cijfers.'

[11] CBS data, extracted from ECN, PBL and CBS. (2015), 'Nationale Energieverkenning 2015.'

[12] The average efficiency of the gas boiler stock has improved due to the adoption of condensing boilers. See ECN and RIGO. (2013), 'Energiebesparing: Een samenspel van woning en bewoner – Analyse van de module Energie WoON 2012.' Commissioned by the Dutch Ministry of the Interior and Kingdom Relations.

What stands out is the high peak demand for gas during winter, mainly for space heating. The Dutch transmission system operator for gas, estimates that the maximum required capacity is approximately 100 GW.[13] In 2015, due to a relatively mild winter, peak demand (only) reached 74 GW. By contrast, national electricity demand fluctuates between 9 GW and 18 GW over the course of a day, but shows only limited seasonal variation.

For energy infrastructure, peak demand, rather than average or total consumption, determines the required capacity to ensure supply can meet demand at all times. At present, only the gas transmission and distribution infrastructure is dimensioned to deliver this high peak demand for heating. By contrast, the electricity grid is only dimensioned to supply the demand for household electric appliances, which is substantially smaller than the demand for heating.

However, infrastructure is only one side of the story. The high peak demand for residential heating needs to be matched by a sufficient supply of gas. The supply side of the gas system provides extraordinary flexibility, through a combination of flexible domestic production, imported H-gas which can be converted to L-gas quality, and underground gas storage to shoulder high peak demand (see Box 1).

Achieving similar levels of system reliability for alternative heating options will require investments in new energy infrastructure, production capacity for heat and electricity, and potentially require forms of energy storage, or other forms of flexibility to bridge periods of scarce production or alleviate infrastructure capacity constraints.

The gas distribution and transmission infrastructure is already in place, and its costs are sunk, making it difficult for alternative heating options to compete on cost. However, when the gas distribution infrastructure needs to be replaced, gas heating and alternative heating options can compete equally on the basis of their infrastructure cost.

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[13] Gasunie Transport Services. (2015), 'Network Development Plan 2015.'

Box 1. Flexibility provided by the Dutch natural gas system

Most of the gas consumed by households is L-gas extracted from the Slochteren field in the Groningen province. In the past, the field's unique geological characteristics allowed it to ramp up production significantly, providing the gas system with considerable flexibility. However, now that the field has reached maturity, its pressure level and – consequently – its potential flexibility have declined. In addition, seismic activity associated with gas production at the Slochteren field has prompted policy-makers to impose an annual production cap of 21.6 billion cubic metres, and to pledge to maintaining a flat production pattern.[14]

In response to the decline in pressure, multiple underground gas storage facilities have been developed to make up for the lost flexibility. At present, underground gas storage is the only energy storage technology, besides oil storage, that can deliver the substantial volumes needed to cope with seasonal fluctuations in residential heat demand.[15] The largest L-gas storage facility in the Netherlands, in Norg, has a maximum storage capacity of 68.4 TWh and a maximum withdrawal capacity of over 39 GW.[16] To put this in perspective, 1 TWh of storage capacity is equivalent to more than 74 million Tesla Powerwall systems of 13.5 kWh.[17]

Besides the Slochteren field, the Netherlands has multiple smaller (offshore) fields with either L-gas or H-gas. As a result of the decline in European gas consumption over the past decade, there is also ample pipeline capacity for imports of H-gas, e.g. from Norway and Russia.[18;19] Moreover, additional (H-gas) supplies could enter the market in the form of liquefied natural gas (LNG) utilising the 'Gate' LNG regasification terminal in Rotterdam.[20] However, the ability to utilise domestic and imported H-gas is constrained by the conversion capacity required to dilute it, by adding inert nitrogen, to obtain the L-gas calorific value.

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[14] Kamp, H.G.J. (2016), 'Kamerbrief - Advies SodM betreft seismiciteit Groningenveld.', 18-04-17.

[15] Underground gas storage facilities store gas during summer, when gas demand and thus prices are relatively low, and withdraw gas during winter, when demand and prices are relatively high. See Clingendael International Energy Programme. (2011), 'Seasonal Flexibility in the North Western European Gas Market - An Outlook for 2015 and 2020.'

[16] Calculated based on NAM data using a calorific value of 35.17 MJ/m^3. See http://www.nam.nl/gas-en-oliewinning/ondergrondse-gasopslag/gasopslag-locaties.html (accessed 30-03-17).

[17] See https://www.tesla.com/powerwall.

[18] Pisca, I. (2016), Outlook for EU Gas Demand and Import Needs to 2025 – CIEP Perspectives On EU Gas Market Fundamentals', Clingendael International Energy Programme.

[19] Franza, L. (2016), 'Outlook for Russian Pipeline Gas Imports Into The EU to 2025 – CIEP Perspectives On EU Gas Market Fundamentals', Clingendael International Energy Programme.

[20] Franza, L. (2016), 'Outlook for LNG Imports Into The EU to 2025 – CIEP Perspectives On EU Gas Market Fundamentals', Clingendael International Energy Programme.

3 ALTERNATIVE HEATING OPTIONS

This paper considers three possible alternatives to gas-based heating in the context of the Dutch residential heating system. These options, schematically depicted in Figure 3, are: all-electric heat pump systems (b), district heating (c) and hybrid heat pump systems (d). These alternative heating options could each help reduce emissions in the run-up to 2050, and have the potential to become fully carbon neutral. The remainder of this chapter will briefly introduce the alternative heating supply chains.

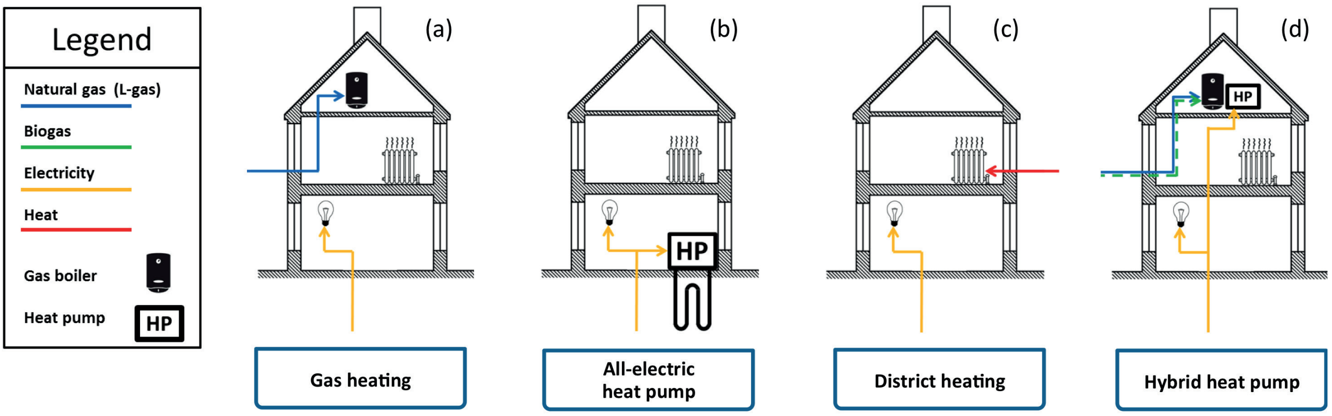

FIGURE 3. SCHEMATIC REPRESENTATION OF THE CURRENT GAS-BASED HEATING SYSTEM (A), WHICH IS AT PRESENT THE DOMINANT OPTION FOR RESIDENTIAL HEATING IN THE NETHERLANDS, AND THREE ALTERNATIVE HEATING OPTIONS: ALL-ELECTRIC HEAT PUMP SYSTEM (B), DISTRICT HEATING (C) AND HYBRID HEAT PUMP SYSTEM (D).

ALL-ELECTRIC HEAT PUMPS

All-electric heat pump systems use electricity to drive a vapour compression cycle, extracting heat from an external environment, such as the outside air or an underground loop or aquifer, and releasing it to the heating system of the building. All-electric pumps can serve both space heating and domestic hot water needs; cooking uses electricity, as no gas infrastructure is present.

The efficiency of heat pumps is expressed as the 'coefficient of performance' (COP), which varies from 2 to 6, meaning 1 kWh of electricity yields 2 to 6 kWh of heat. There are several types of heat pumps, discussed in more detail in Box 2, which vary in both conversion efficiency and investment cost. The efficiency of the heat pump determines the peak demand for electricity.

Figure 4 shows the all-electric heat pump supply chain, including the production of electricity, the infrastructure that transports electricity to residential end users, the in-house heat pump system, and building energy efficiency measures (in orange).

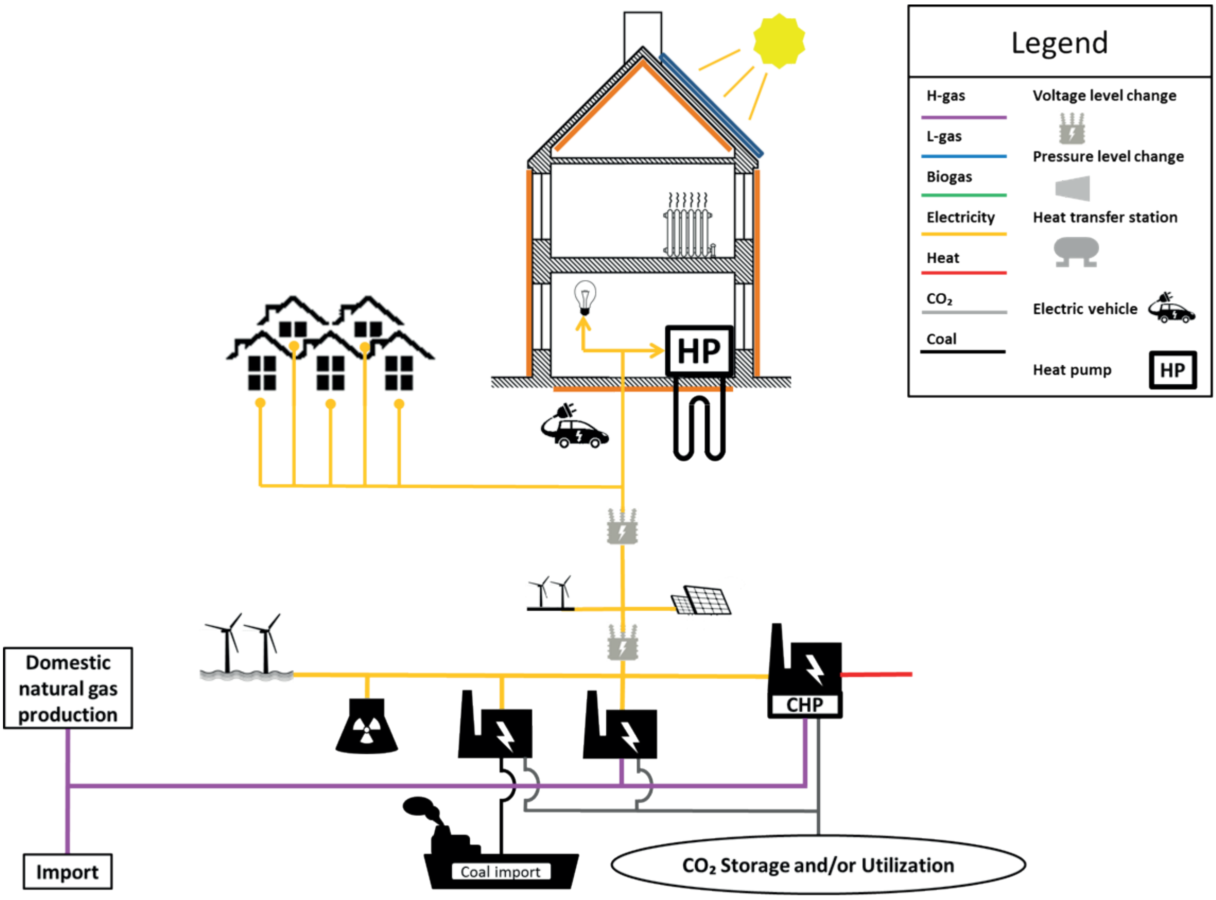

FIGURE 4. SCHEMATIC REPRESENTATION OF THE ALL-ELECTRIC HEATING SUPPLY CHAIN. SOURCE: CIEP

To function correctly, ensure comfort and reduce operating costs, heat pumps require energy efficiency measures to be implemented in the building. This makes them attractive for new build homes, which have a high level of energy efficiency. However, installing comprehensive insulation in existing dwellings can be expensive (and intrusive) for inhabitants. Where implemented, energy efficiency reduces heat losses and thus (peak) demand for electricity.

Box 2. Types of all-electric heat pump systems

The COP of a heat pump depends on the temperature gradient it needs to bridge, i.e. the difference between the heat source, which differs per heat pump type, and the desired in-house temperature for space heating and domestic hot water. This paper differentiates between three types of heat pumps.

Air source heat pumps (ASHPs) derive heat from the ambient air. They are the cheapest type of heat pump, but also the least efficient. The colder the ambient air, the lower the efficiency of the heat pump, and the higher the potential level of peak electricity demand.

Horizontal ground source heat pumps (GSHPs) derive heat from the ground by circulating a working fluid in a loop, buried horizontally at a depth of one to two metres. These systems are inherently more efficient than ASHPs, as ground temperature is much more stable than air temperature throughout the year, fluctuating between 10°C (winter) and 14°C (summer).[21] However, GSHPs are more expensive than ASHPs, and it may not always be practical to install a GSHP, for example for flats or other multi-storey buildings.

Vertical GSHPs, also known as Heat-Cold-Storage (HCS) systems or water source heat pumps, use water-bearing ground layers in the subsurface at a depth of 100-150 metres, as a thermal reservoir. HCS systems are often sized to service multiple houses, or even an entire neighbourhood, and thus require a collective heating infrastructure.[22] HCS systems exchange heat with the subsurface, either through a 'closed loop' heat exchanger, or through the direct exchange of water in a so-called 'open system.' In summer, the heat pump operates in air conditioning mode, extracting heat from the building and storing it in the subsurface. During winter the system reverses, extracting heat from the subsurface to supply the heat demand.[23] To avoid excessive cooling of the subsurface, the addition and subtraction of heat from the subsurface by the HCS must be in balance over the course of the year.[24] Since HCS systems tap into a hot water source during winter, which has been stored during summer, they have a higher efficiency than ASHP or GSHP systems. However, the need to drill boreholes of up to 100-150 metres makes these systems expensive to install, and not every location's subsurface is equally suitable for accommodating HCS systems.[25]

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[21] Ground Source Heat Pump Association. (2007), 'Domestic Ground Source Heat Pumps: Design and installation of closed-loop systems.' See http://www.gshp.org.uk/documents/CE82-DomesticGroundSourceHeatPumps.pdf (accessed 28-03-17)

[22] Taskforce WKO. (2009), 'Groen licht voor bodemenergie.'

[23] Idem.

[24] The requirement to balance has been incorporated into Dutch legislation, and is set out in the permit required for HCS systems.

[25] CE Delft. (2016), 'Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – update 2016, De route naar een klimaatneutraal Nederland.'

DISTRICT HEATING

In a district heating system, heat is produced at one or more central locations, transported to households in the form of hot water, and used via a heat exchanger for domestic hot water consumption and space heating. Figure 5 shows a district heating supply chain, including potential heat sources, and the district heating infrastructure (denoted by the red line) transporting heat to end users. Again, since gas infrastructure is not present, cooking uses electricity.

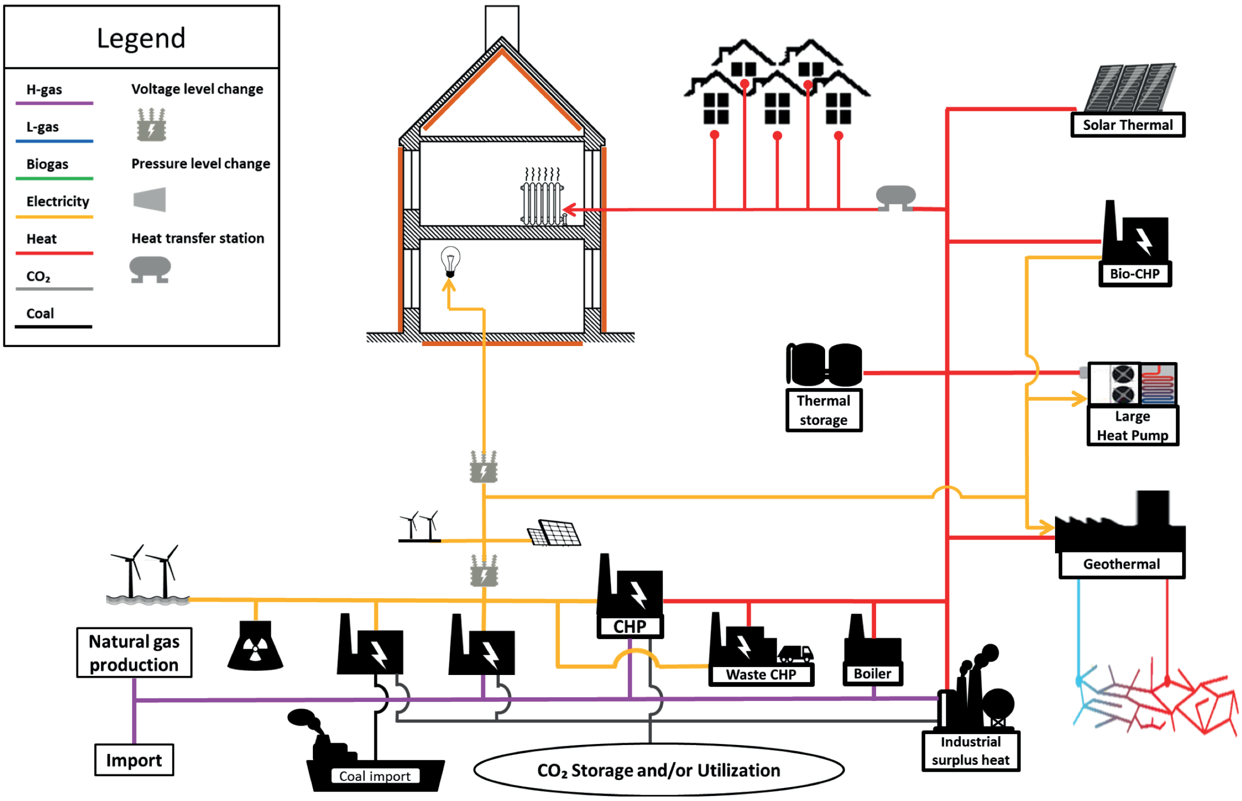

FIGURE 5. SCHEMATIC REPRESENTATION OF THE FUTURE LAYOUT OF THE DISTRICT HEATING SUPPLY CHAIN. SOURCE: CIEP

District heating infrastructure is capital-intensive, and incurs heat losses in the transport phase, making it economical only in densely populated areas with a high density of heat demand.[26] Energy losses in the distribution system are generally between 15% and 25%, depending on the difference between the outside temperature and district heating system temperature. District heating systems are

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[26] Reidhav, C. and Werner, S. (2008), 'Profitability of sparse district heating.' Applied Energy, 85(9), 867–877. http://doi.org/10.1016/j.apenergy.2008.01.006

not strictly confined to large urban centres, however; they can also be relatively small, spanning only a few neighbourhoods.

District heating infrastructure is 'technology neutral,' which has two important implications. First, the production portfolio can consist of multiple heat production technologies, allowing for fuel switching according to the cost of heat and potentially the CO_2 intensity of heat production. Second, the production portfolio of district heating systems can change over time, and the CO_2 intensity can thus vary accordingly. As Figure 5 demonstrates, the district heating system is very much interwoven with the electricity system; while some technologies produce both electricity and heat, others consume electricity to produce heat.

Most district heating is currently supplied by gas-fired and waste incineration combined heat and power (CHP) plants, assisted by gas-fired 'heat-only boilers' to meet peak demand (displayed at the bottom of Figure 5).[27] Electricity and heat production from waste incineration can be deemed partially renewable as a fraction of the waste is biogenic.[28] Often, thermal storage capacity is used to maximise heat production from CHP units, while maximising revenues from electricity sales.

Low-carbon heat sources, such as geothermal, solar thermal and biomass/biogas CHP, have the potential to further reduce and eventually eliminate emissions (displayed on the right side of Figure 5). Large-scale heat pumps could supply relatively low-carbon heat to the system during periods of high intermittent RES-E production, e.g. from wind or solar PV, which are likely to coincide with low electricity market prices. In addition, various ongoing initiatives in the Netherlands aim to utilise industrial residual heat, thereby improving the efficiency of industrial processes, and further contributing to emissions reductions by displacing in-house combustion of gas.

Finally, centralised heat production, as opposed to numerous smaller heat and emission sources, also allows for carbon capture and storage (CCS) and/or carbon capture and utilisation (CCU) to be applied. This might be a way for existing CHP plants and industrial heat sources to continue delivering heat in the long term.

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[27] The share of heat from waste incineration CHP increased from 8% in 2013 to 25% in 2015. See ECN, PBL and CBS. (2016), 'Nationale Energieverkenning 2016.'

[28] The biogenic fraction is determined on an annual basis and stood at 55% in 2013. See RVO and CBS. (2015), 'Protocol Monitoring Hernieuwbare Energie – Herziening 2015.'

HYBRID HEAT PUMPS

Hybrid heat pump systems, consisting of a (small) air source heat pump and a gas-fired boiler, represent an attractive solution for reducing emissions in the short term. There are many variations of these systems, varying in the degree of integration between the two components; the heat pump may only deliver space heating, for example, or may deliver both space heating and domestic hot water.[29]

Figure 6 shows the supply chains for hybrid heat pump systems. Note that this is in effect a combination of the all-electric and gas supply chains. The gas system can be seen as an 'add-on' to the all-electric supply chain, on which the system can fall back in times of scarce electricity production and high electricity prices, or congestion in the electricity (distribution) infrastructure.

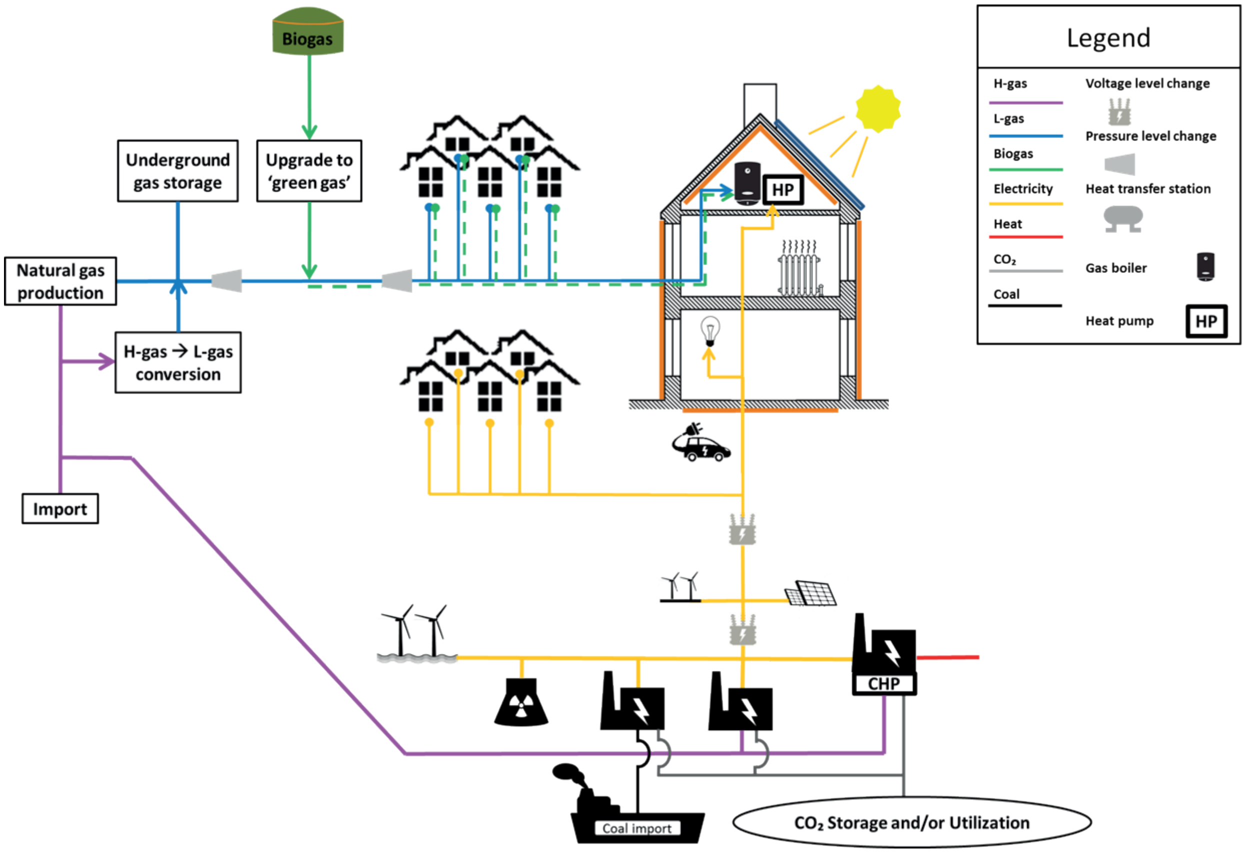

FIGURE 6. SCHEMATIC REPRESENTATION OF THE CURRENT LAYOUT OF THE HYBRID HEAT PUMP SYSTEM SUPPLY CHAIN. SOURCE: CIEP

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[29] Dutch Heat Pump Association. (2016), 'CV-ketel eruit - Warmtepomp erin? Visie Dutch Heat Pump Association, UNETO-VNI regionale bijeenkomsten voorjaar 2016.'

The heat pump is mostly used for supplying the space heating demand, while the boiler supplies the demand for domestic hot water. The latter often requires a rapid response time and high temperatures, making the boiler more convenient. However, during cold spells, the conversion efficiency of the heat pump can decrease substantially, and it may be more economical to rely (partially) on the boiler for space heating needs. Moreover, the ability of the boiler to provide higher temperatures lessens the need for far-reaching energy efficiency measures, by comparison with all-electric heat pump systems. Furthermore, the emission intensity of the gas boiler can be gradually lowered by utilising 'green gas,' i.e. biogas upgraded to natural gas calorific value, using the existing gas distribution infrastructure.

The following chapters provide a qualitative analysis of the supply chains of the alternative heating options, and discuss some important considerations that affect how clean, reliable and affordable they are. Each chapter will end with a discussion on how these three key objectives can be achieved and reconciled for each option.

4 ANALYSIS OF THE ALL-ELECTRIC HEAT PUMP SUPPLY CHAIN

CO_2 EMISSIONS

The emission reduction offered by an all-electric heat pump system compared to a gas boiler depends on its efficiency and the CO_2 intensity of the electricity consumed. The heat pump efficiency is determined by the type of heat pump as well as the temperature difference to be bridged (see Box 2). The CO_2 emission intensity of electricity generation also fluctuates depending on the composition of the generation mix at any point in time (see Box 3).

Ecofys and ECN have performed a scenario study assessing the integral cost and CO_2 emissions of five heating options for the residential sector. Their results, provided in Appendix C, show that when the power generation mix is dominated by coal and gas-fired generation, CO_2 reductions in the all-electric scenarios are negligible compared to the high-efficiency gas boiler scenarios.[30;31;32]

Indeed, to reduce emissions from all-electric heating, the CO_2 intensity of the national electricity generation mix would need to be reduced, by adding more renewable electricity sources, such as wind, solar PV, and biomass fired power plants, or by equipping conventional power plants with CCS and/or CCU systems.

Box 3. The CO_2 intensity of electricity generation

At present, most electricity is produced in thermal power plants, combusting coal or natural gas to run (steam) turbines to produce electricity, with an associated loss of useful energy in the form of heat. To produce 1 GJ of electrical energy, a coal-fired power plant with an electric efficiency of 45% would require 2.2 GJ of primary energy, whereas a gas-fired combined cycle gas turbine (CCGT) with an electric efficiency of 55% would require 1.8 GJ of primary energy.[33] The remaining

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[30] Ecofys and ECN. (2015), 'De systeemkosten van warmte voor woningen.' Commissioned by Alliander, Gasunie and TenneT.

[31] The authors calculated the integral cost of five heating technologies at two energy efficiency levels (medium and high), and the associated CO_2 emissions.

[32] The sensitivity analysis in the study shows that once the CO_2 intensity of the electricity generation mix is substantially reduced, the all-electric option would be able to achieve an 85% reduction in emissions. The main analysis used an emission intensity of 400 kg CO_2/MWh for the Dutch electricity mix, whereas the sensitivity analysis used an emissions intensity of 50 kg CO_2/MWh.

[33] When combusting coal or natural gas, the energy embedded in the chemical bonds of the molecules is converted into heat. The heat is used to produce steam, which is used to drive a steam turbine and thus generate kinetic energy. Subsequently, the turbine shaft spins an electromagnet which converts the kinetic energy into electricity.

energy, which is not converted to electricity, is discharged in the form of heat to the environment.

In addition to the efficiency of power generation, the carbon content of the fuel matters. Coal and gas have a carbon content of 97.8 and 56.1 kg CO_2 per GJ of primary energy respectively.[34] Accounting for the difference in electric efficiency and carbon content of the respective fuels, coal-fired electricity has a carbon intensity of approximately 2.1 times that of gas-fired electricity.

However, even when there is a large amount of RES-E in the generation mix, as is already the case in Germany, there will still be periods of low RES-E production, due to unfavourable wind conditions or low solar irradiation. To illustrate this, Figure 7 shows German power generation by supply source during January 2017 – note the period of very low wind and solar PV production between 15 and 26 January.[35;36] During such periods, conventional coal and gas-fired power plants cover the shortfall.

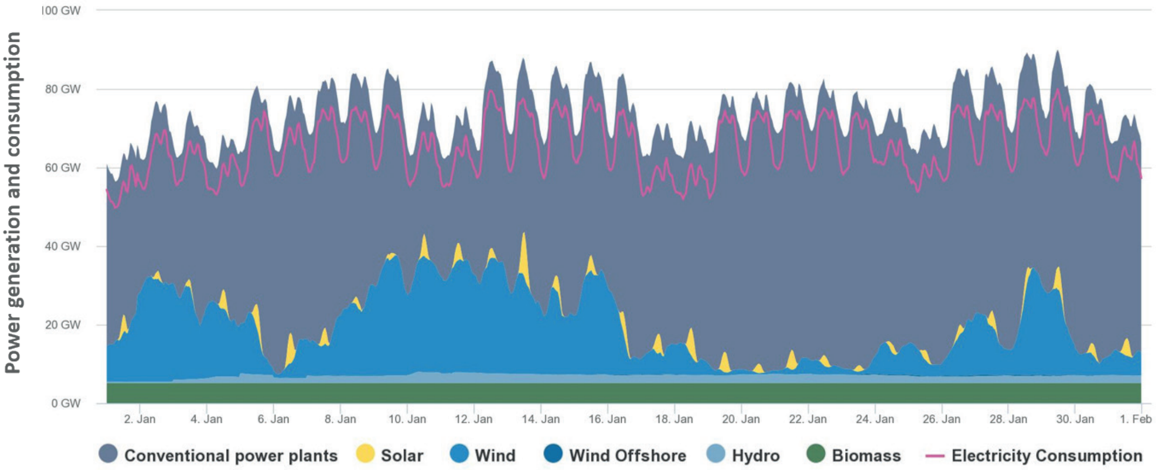

FIGURE 7. OBSERVED POWER PRODUCTION AND CONSUMPTION IN GERMANY IN JANUARY 2017. SOURCE: AGORA ENERGIEWENDE (2017).[37]

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[34] IPCC. (2006), '2006 Guidelines, Volume 2: Energy.'

[35] Note that the surplus electricity produced, shown above the pink line, is exported.

[36] Germany was chosen as its electricity mix already includes a large installed capacity of intermittent RES-E sources. As of January 2017, the installed capacity of solar PV (41 GW), onshore wind (46 GW), offshore wind (4 GW), hydro power (5.6 GW) and biomass (7 GW) together accounts for 103.6 GW. This far exceeds peak electricity production, which does not exceed 90 GW even when exports are included. See https://www.energy-charts.de/power_inst_de.htm. (accessed 04-04-17).

[37] See https://www.agora-energiewende.de/en/topics/-agothem-/Produkt/produkt/76/Agorameter/. (accessed 01-03-17).

If such a period of low RES-E production and thus high emission intensity were to coincide with cold temperatures, and thus relatively low efficiency for air-source heat pumps (see Box 2), this would significantly impair the CO_2 performance of a heat pump system, leaving only minor CO_2 reductions compared to a conventional high-efficiency gas boiler.

To illustrate this, Figure 8 shows the relation between heat pump efficiency and the emission intensity of heating for a range of potential generation mixes.[38] Figure 15 and Figure 16 in Appendix D show the effect of the outside temperature on the efficiency of an air source heat pump supplying space heating at 35°C (to the radiator system)[39] and domestic hot water at 50°C, respectively.

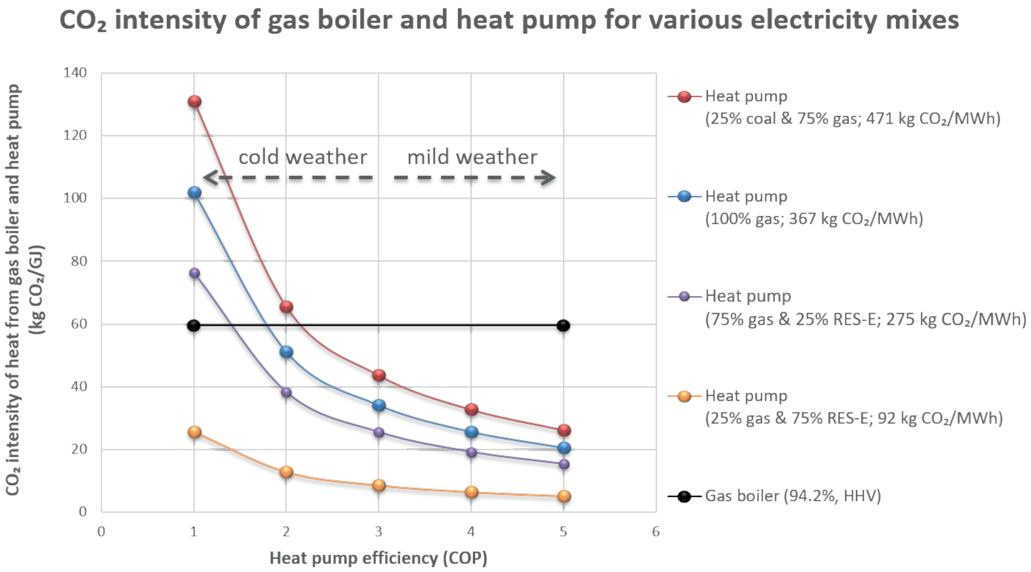

FIGURE 8. THE RELATIONSHIP BETWEEN HEAT PUMP EFFICIENCY, WHICH IS DETERMINED BY THE AMBIENT AIR TEMPERATURE, AND THE ASSOCIATED CO_2 INTENSITY OF AN (ALL-ELECTRIC) HEAT PUMP FOR FOUR DIFFERENT ELECTRICITY GENERATION MIXES, PLOTTED AGAINST THE CO_2 INTENSITY OF A CONVENTIONAL HIGH-EFFICIENCY GAS BOILER (94,2% HIGHER HEATING VALUE). SOURCE: CIEP ANALYSIS, BASED ON EMISSION FACTORS FROM IPCC (2006) AND BOILER EFFICIENCY DERIVED FROM ENERGY MATTERS (2014).

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[38] The generation mixes used for Figure 8 have been estimated while considering the projections for installed capacity and electricity production by source up to 2035 published by ECN, and are by no means unrealistic. In fact, one could argue these generation mixes are quite conservative, as they do not consider potential electricity imports from Germany, which has substantial hard coal and lignite-fired electricity generation capacity. See ECN, PBL and CBS. (2016), 'Nationale Energieverkenning 2016,' pp. 112-115.

[39] Note that accommodating such low temperature levels would require adaptations to the in-house radiator system, such as floor heating, to ensure sufficient heat transfer to heat the building.

From Figure 15, we can see that when outside temperatures are around freezing (between -5°C and 5°C), the air source heat pump delivers space heating with a COP of 3. At a COP of 3, the heat pump only achieves a modest emissions reduction (27%) compared to a gas boiler, if the electricity is generated by a mix of 25% coal-fired and 75% gas-fired power plants.[40] When electricity generation is 100% gas-fired, a CO_2 reduction of 43% is realised. With 25% RES-E, e.g. wind power, and 75% gas-fired generation, the heat pump can attain an even more substantial emission reduction (57%).[41] If the electricity generation mix consisted of only 25% gas-fired power and 75% RES-E, the resulting CO_2 reduction would amount to 86%, though such a generation mix remains a distant prospect in the Netherlands. When weather conditions are milder, with ambient temperatures between 5°C and 15°C, the COP of an air source heat pump is around 4, resulting in emissions reductions of 45%, 57%, 68% and 89% for the four generation mixes. This shows that substantial emissions reductions could be attained when the weather is mild and the emission intensity of power generation is low.

For domestic hot water consumption, the heat pump must bridge a larger temperature difference, resulting in lower efficiency. As Figure 16 shows, when outside temperatures are around 0°C, the air source heat pump delivers domestic hot water, at 50°C, with a COP of approximately 2. When the generation mix consists of coal and gas, the heat pump actually produces 10% higher emissions than a gas boiler. The 100% gas-fired generation mix only leads to a reduction of 14%, while the mix of gas and RES-E attains a reduction of 34%. It should also be acknowledged that the efficiency of a gas boiler is generally lower for domestic hot water consumption, due to heat losses arising from non-continuous operation, which means the exact efficiency varies according to the pattern of usage.[42] Moreover, domestic hot water consumption only represents a minor share of heat demand (approximately 19% in 2010), and is evenly distributed over the course of the year.[43]

These simplified examples illustrate how the CO_2 intensity of air source heat pumps depends on the efficiency of the heat pump *and* the CO_2 intensity of electricity production. This suggests that the pace of all-electric heat pump adoption should be

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[40] These calculations assume electric efficiencies of 45% and 55% for coal and gas-fired power plants respectively.

[41] The calculations underlying these CO_2 reductions are based on a simplified method that skirts over many of the intricacies observed in reality, and merely provide a snapshot of the CO_2 performance of the heat pump at the specified COP. As such, these figures should be viewed as indicative only, and no conclusions can be drawn on the annual average performance or the absolute CO_2 reduction.

[42] Energy Matters. (2014), 'Rendement HR-Ketel – Nader Onderzoek t.b.v. Warmteregeling.' Commissioned by RVO.

[43] Netbeheer Nederland. (2015), 'Energie in cijfers.'

in line with the increase in RES-E sources, in order to guarantee sufficient emissions reductions to justify the potentially high supply chain cost (to be discussed in the remainder of this section). It also underlines the importance of having more flexible renewable electricity sources besides wind and solar PV, capable of delivering continuously and on demand, in the generation mix. Such options could include biomass power plants, or conventional gas and coal power plants equipped with CCS and/or CCU.

Horizontal ground source heat pumps are less susceptible to seasonal fluctuations as the ground temperature is more stable than the ambient air temperature. These systems cool down the ground to approximately 0°C when in operation, usually when reaching the end of the heating season. Nonetheless, they still achieve a minimum COP of 4 for space heating at 35°C, and a COP of 2.5 for domestic hot water at 50°C.[44]

The prospects for HCS systems are particularly promising, as these can attain an even higher efficiency (COP) during winter by consuming electricity in air conditioning mode in summer. Moreover, HCS systems could consume relatively low-carbon electricity during summer, notably from solar PV production as periods of high solar irradiation coincide with cooling demand. Subsequently, during winter the system uses electricity to extract heat from the subsurface, with relatively high efficiency, to service space heating demand. In effect, the system consumes less CO_2-intensive electricity during summer, to save on electricity consumption during winter, when CO_2 intensity is likely to be higher. This can be seen as a form of seasonal storage.

RELIABILITY

During cold periods, building heat losses can be substantial, especially when buildings are only insulated to a low or medium standard.[45;46] In combination with the low COP of air source heat pumps during cold periods (as described in the previous section), this can significantly raise the electricity peak demand for heating. When a large number of heat pumps are installed in a specific area of the distribution grid, i.e. in the same neighbourhood, peak demand for electricity from all-electric heat pumps can even exceed the capacity of the grid. Such a situation, commonly referred to as ‘network congestion’, poses a threat to the stability of the grid. To avoid congestion, the distribution system operator (DSO) will need to invest in

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[44] Ecofys and ECN. (2015), ‘De systeemkosten van warmte voor woningen.’ Commissioned by Alliander, Gasunie and TenneT.

[45] Idem.

[46] In the study, the authors use R values (a measure of the thermal resistance ($m^2 \cdot K/W$)) for roof, façade and floor insulation of 2.5, 1.3 and 2.5 as the ‘medium energy efficiency level’.

increasing the capacity of the grid, or 'smartening' the grid through demand-side management (DSM) techniques. The DSO's ability to accommodate to the growth in electricity peak demand is therefore decisive for the reliability of all-electric heat pumps. The uncoordinated adoption of all-electric heat pumps may thus jeopardize the reliability of the grid.

Energy storage, be it thermal energy or electric energy, offers some possibilities for DSM. Thermal energy storage (TES), in the form of buffer vessels for hot water, can shift electricity consumption over time, avoiding consumption during periods of peak demand while still being able to supply the demand for heat.[47] Similarly, battery electric storage can shift electricity consumption over time, though batteries are considerably more expensive than TES. Nonetheless, the potential for storage technologies to alleviate congestion is contingent on the installation of adequate information and communications technology (ICT) and information sharing by the DSO, which would be able to signal to the heat pump system when there is congestion.

On a national scale, an increase in aggregate peak demand could require investments to increase the capacity of the (high-voltage) electricity transmission infrastructure. The Dutch transmission system operator (TSO) has calculated that an increase in national peak demand of more than 10 GW, which would require substantial but not unthinkable levels of all-electric heat pump adoption, would necessitate investment to increase the capacity of the transmission network. End user costs could potentially reach up to €500 per connection per year in case of a 20 GW peak demand increase.[48]

Not only does the increase in aggregate peak demand affect the electricity infrastructure, but also the production side of the electricity system.[49] To guarantee the stability of the system, sufficient flexible production capacity must be available to

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[47] Arteconi, A., Hewitt, N.J. and Polonara, F. (2013), 'Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems.' Applied Thermal Engineering, 51(1-2): 155-165.

[48] According to calculations from TenneT the Dutch TSO. See Ecofys and ECN. (2015), 'De systeemkosten van warmte voor woningen.' Commissioned by Alliander, Gasunie and TenneT.

[49] Fraunhofer IWES/IBP (2017), 'Heat transition 2030. Key technologies for reaching the intermediate and long-term climate targets in the building sector.' Commissioned by Agora Energiewende.

supply the higher peak demand.[50;51] Failing to do so would jeopardise the stability of the electricity system, potentially leading to blackouts. Market parties will therefore need to invest in sufficient flexible backup capacity, in addition to the required increase in intermittent renewable electricity sources.

A study by McKinsey (2016) explored a possible scenario for the Dutch energy system in 2050, featuring widespread adoption of both electric heat pumps *and* electric mobility. The study found that 28 GW of dispatchable production capacity would be required, of which 15 GW would still be gas-fired backup capacity albeit with relatively few running hours.[52;53] To put this in perspective, current peak demand for electricity is around 18 GW (see Figure 2). Current installed capacity in the Netherlands amounts to roughly 28 GW, but most of this capacity will not be in operation by 2050.[54;55] This suggests that investments in new capacity and retrofitting of existing plants will be required. Given the expected low running hours of these plants, and the seasonal nature of their function, it will be challenging to persuade market parties to make these investments.[56] Electricity storage, meanwhile, is still too expensive and unable to make a significant contribution in case of a prolonged period of peak demand (see Box 1).

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50 France provides a useful example of the relationship between heat demand and peak electricity demand, as the country has a substantial share of (relatively inefficient) direct resistive electric heating appliances. For every 1°C drop in temperature, French electricity demand tends to increase by 2.3 GW. Note that France has a nuclear energy legacy, and that as a consequence the French electricity infrastructure has been dimensioned to cope with high electric demand for heating. See Buchan, D. and Keay, M. (2015), 'Europe's Long Energy Journey: Towards an Energy Union?' pp. 57-58. Oxford Institute for Energy Studies.

51 Direct resistive electric heating has in many countries been the norm for electric heating, but is considerably less efficient, with a COP close to 1, while heat pump systems have a COP of 2 to 6.

52 McKinsey & Company. (2016), 'Accelerating the energy transition: cost or opportunity? A thought starter for the Netherlands.'

53 Although the authors state that their scenario does not concern an optimisation, but rather a credible trajectory towards reaching the desired emission target, their scenario does appear to be a technically optimal configuration. The authors, for example, explicitly incorporate demand-side management (DSM) measures into their analysis. In practice, however, sub-optimal choices are likely to occur, as other variables – such as consumer preferences – play a role in the adoption of technologies. In this regard, sub-optimal outcomes seem inevitable and national peak demand could thus eventually exceed 28 GW in the event of far-going electrification. Especially in the absence or partial application of DSM measures it will rise even higher.

54 TenneT TSO B.V. (2016), 'Rapport Monitoring Leveringszekerheid 2016 (2015-2031).'

55 This is because some of these assets will either reach their economic and technical lifetime, be shut down or mothballed due to unfavourable market circumstances, or have a emission profile which inhibits them from operating in a low-carbon electricity system.

56 This suggest other sources of remuneration for generators could be required, e.g. capacity remuneration mechanisms. See Meulman, L. and Méray, N. (2011), 'Capacity Mechanisms in North Western Europe – Between a rock and a hard place?' Clingendael International Energy Programme.

It is worth pointing out that horizontal GSHPs and HCS systems (see Box 2) are more efficient and have a lower peak demand per household than air source heat pumps. This means that current grid capacity might be sufficient, requiring no additional electricity infrastructure investment. Moreover, the centralisation of the HCS system means that, if grid capacity is insufficient, it may be less costly to increase it. Similarly, this greater efficiency also reduces the need for additional electricity production capacity at the national level.

AFFORDABILITY

While all-electric heat pumps are economically attractive within new build houses, the cost of converting existing buildings and neighbourhoods to all-electric solutions can be substantial. First, heat pumps are simply more expensive than gas-fired boilers; the cost of air source and ground source heat pumps is reported to be €8,000 and €15,000 respectively.[57] Second, in some cases, the far-reaching energy efficiency measures required to ensure comfort can also be costly. At the same time, better insulation also decreases the end user's electricity bill. The costs of HCS depend on the exact configuration of the system, and the required (neighbourhood) heating infrastructure, but the cost to connect individual homes to the heating infrastructure is similar to that of district heating (see next section).[58]

Besides end user costs, there are a number of supply chain costs that add to the total cost of all-electric heat pumps. These include the aforementioned need to increase the capacity of the electricity infrastructure, the cost of ensuring sufficient flexible electricity production capacity, and the cost of additional renewable electricity sources to decrease the CO_2 intensity of the electricity consumed.

The cost of increasing the capacity of the electricity distribution infrastructure varies, depending on local factors, such as population density and distance between homes, and on the presence of other utilities in the subsurface, such as telecoms, water, sewage and gas networks.[59] The cost of 'opening up the street' can represent around 50%-70% of the total cost, which can therefore be substantially reduced by combining these activities with other works, such as sewage maintenance or road construction. This makes timing particularly important, with significant potential value in accelerating or deferring investment in a certain neighbourhood. Note that these considerations are also relevant with respect to district heating infrastructure (see next section).

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[57] CE Delft. (2016), 'Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – update 2016, De route naar een klimaatneutraal Nederland.'

[58] Idem.

[59] MacLean, K., Sansom, R., Watson, T. and Gross, R. (2016). 'Managing Heat System Decarbonisation: Comparing the impacts and costs of heat transitions in heat infrastructure.' Imperial College Centre for Energy Policy and Technology.

Ultimately, electricity grid reliability can be safeguarded. However, it could come at a high cost, especially in the event of an uncoordinated roll-out of all-electric heat pumps. In some areas, an uncoordinated roll-out could incur further costs associated with the premature removal of gas infrastructure or situations of double infrastructure (see Box 4). These costs would gradually become apparent in the form of rising grid tariffs charged by the DSO to end users, reducing disposable incomes.[60]

The uptake of rooftop solar PV and electric vehicles could also necessitate investments in electricity distribution infrastructure, irrespective of the electrification of heat.[61] In effect, this would mean that the infrastructure cost could be 'divided' among multiple energy services, i.e. power production, transport and residential heating, thereby decreasing the cost attributed specifically to the all-electric heat pump supply chain. Nevertheless, the societal cost of expanding the whole grid would still be enormous.[62;63]

Box 4. Costs related to the existing gas distribution infrastructure

Energy network infrastructures are characterised by long economic lifetimes. To ensure low costs for end users, the national regulatory authority has formulated accounting standards to which DSOs must adhere, including a regulatory depreciation period for energy infrastructure. The depreciation period for (low pressure) gas distribution infrastructure is 45 years.[64] When gas infrastructure is removed before the full period has expired, the DSO foregoes the expected grid tariffs for the rest of the period, and must incur the remaining depreciation cost instantly. To cover this cost, it must raise grid tariffs for the remaining connections in its service area, in effect socialising the cost among the remaining gas connections. This phenomenon is known as *premature depreciation*. Costs arising from premature depreciation could, however, be easily minimised if stakeholders coordinate their actions with the DSOs, focusing on areas where the gas infrastructure has fully or almost fully depreciated.

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60 This holds in particular for lower income groups, for whom energy bills make up a larger share of disposable income.

61 The geographically concentrated adoption of rooftop solar PV is already causing local congestion in some parts of the Netherlands. In Groningen, for example, rooftop solar PV production were forced to automatically switch off due to local congestion, requiring the DSO to invest in increasing capacity.
Trommelen, J. (2016), 'Stroomnet kan zonnepanelen-hausse in Groningen niet aan.' de Volkskrant. http://www.volkskrant.nl/binnenland/stroomnet-kan-zonnepanelen-hausse-in-groningen-niet-aan~a4340786/

62 See, for example, Netbeheer Nederland. (2011), 'Net voor de toekomst – een verkenning.'

63 In this respect, one could argue that policy-makers, regulators and DSOs might also need to critically reassess the design of the EV charging infrastructure, and explore concepts such as 'smart charging' more proactively.

64 Within these standards a distinction is made between the various components of the gas distribution and transmission systems, ranging from 30 to 55 years. The depreciation period for the distribution system's main pipelines amounts to 45 years. See Autoriteit Consument and Markt. (2015), 'Regulatorische Accountingregels 2014, Regionale netbeheerders elektriciteit en gas.'

Existing Dutch legislation dictates that end users are entitled to retain their gas connection. If they choose to exercise this right when the neighbourhood is connected to district heating or all-electric, the DSO is obliged to retain (parts of) the gas network. This is referred to as *double infrastructure*, as there are two energy infrastructures capable of servicing the same residential heat demand. This can be costly, as the DSO still bears the cost of operating and maintaining the remaining gas infrastructure, while grid tariff revenues decline as the number of connections decreases. In the recently published 'Energieagenda,' the Dutch Ministry of Economic Affairs has signalled its intention to change the end user's right to retain a connection to the gas infrastructure to a 'technology neutral' right to heating.[65] Following this change, heating could be delivered by multiple energy infrastructures (such as gas, electricity, or district heating), with the government guaranteeing the availability, quality and affordability of the relevant heating infrastructure for the end user.

At present, grid tariffs for gas and electricity infrastructure are determined separately on the basis of their respective costs to the DSOs. Both *premature depreciation* and *double infrastructure* increase the cost of the gas network, resulting in gradual increases in grid tariffs for end users connected to the gas infrastructure. End users who disconnect from the gas infrastructure currently avoid these costs. Given the potentially radical forthcoming shifts in energy distribution infrastructures, in light of the transition in residential heating, regulatory authorities could consider revising the way in which tariffs are set. To ensure a fair distribution of costs among citizens, a 'technology neutral' cost sharing regime for determining grid tariffs, in line with the technology neutral right to energy infrastructure for heating described above, may be an option.

Besides these energy infrastructure costs, further costs result from increasing production of electricity from traditional sources to ensure sufficient supply to meet peak demand, as well as from increasing RES-E to reduce the CO_2 intensity of all-electric heat pumps. The need for sufficient flexible (backup) generation capacity will also be reflected in higher electricity bills for end users. Decarbonising the electricity mix will take time and is also expected to be costly, with these costs likely to be passed on to end users through a gradual increase of the levy added to electricity bills to finance the Dutch support scheme for renewables.

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[65] Ministerie van Economische Zaken. (2016), 'Energieagenda - Naar een CO_2-arme energievoorziening.'

Several studies, although differing in their exact purpose and scope, have shown that all-electric heat pumps are indeed a relatively expensive option when supply chain costs are taken into account. Ecofys and ECN (2015) have calculated the supply chain cost of five residential heating options and different levels of energy efficiency; their results indicate that the all-electric scenarios have the highest costs, while delivering negligible benefit in terms of CO_2 reduction compared to the other scenarios (see Appendix C). The authors attribute the high cost to the requirement for additional electricity distribution and transmission infrastructure. Furthermore, they underline that additional RES-E would be required to reduce the CO_2 intensity of the electricity generation mix, incurring further costs not quantified in the study.

CE Delft (2016) took a different approach in calculating what would be the most cost-efficient distribution of heating options to reach a climate neutral residential heating system by 2050. In this study, calculations were made per neighbourhood, accounting for the cost of heating technologies, the optimal level of energy efficiency and energy infrastructure cost. Their results indicate that the cost of all-electric (air and ground source) heat pumps exceeds those of other options, notably district heating and hybrid heat pumps. In only 2% of dwellings were air or ground source heat pumps the most cost-efficient option. More efficient, collective HCS systems performed substantially better, and were the most economic option for 22% of dwellings. The authors note that the HCS system's cost related to the collective heating infrastructure is offset by cost savings with respect to electricity infrastructure.

HOW TO ACHIEVE THESE OBJECTIVES?

It is important for stakeholders to incorporate the entire supply chain into their economic assessments; only then can the cost-optimal alternative heating option for a given area be accurately identified. This also allows stakeholders to identify possible cost synergies arising from the interplay of different parts of the supply chain. One of the most significant synergies originates from the interplay between energy efficiency and peak demand. Peak demand for electricity can be decreased by installing more efficient types of heat pumps (see Box 2) or investing in energy efficiency measures to reduce building heat losses. Investment in energy efficiency could thus reduce the need for investments in electricity infrastructure and electricity production capacity.

However, some obstacles continue to inhibit stakeholders' ability to consider the entire supply chain and monetise these synergies. One such issue is the distribution of costs and benefits among stakeholders and along the supply chain. For example, while the costs of energy efficiency measures are borne by the end user, the benefits, in the form of avoided infrastructure cost, are reaped by the DSO and thus effectively socialised. This suggest that a redistribution of costs and benefits, e.g. from the DSO to end users, may be required to maximise these synergies and reduce the societal cost.

Another issue concerns the regulatory framework for gas and electricity distribution infrastructure, which still contains elements that discourage stakeholders, such as project developers, housing corporations, homeowners and end users, from considering the cost of electricity infrastructure. Electricity and gas infrastructure in the built environment are within the competence of the regional DSO.[66] The costs incurred by the DSO are socialised through the grid tariffs the DSO charges to the customers in its service area. This means that the investment cost for new infrastructure to accommodate all-electric heating is distributed among all the DSOs end users. Consequently, an end user who installs an all-electric heat pump bears the fruit of the grid investment, but is not (fully) confronted with the cost. In sum, the socialisation of the DSO's costs does not incentivise end users to consider the energy infrastructure cost, or to coordinate their actions with the DSO.

The socialisation of the electricity infrastructure cost also leads end users to make an 'unfair' comparison between the cost of all-electric and district heating. While the energy infrastructure costs of all-electric are socialised, the current regulated pricing regime for district heating explicitly includes the infrastructure cost. Such an uneven comparison can inadvertently lead to a sub-optimal choice for all-electric heat pumps, resulting in unnecessary societal cost.

While socialisation in itself is not undesirable, the distorted incentives which currently arise from it should be corrected. This could be achieved by coordination among stakeholders, and close cooperation with the DSO, to make sure alternative heating options are compared on an equal footing, accounting for the supply chain cost.

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[66] The DSO is responsible for investing in (new) electricity and gas infrastructure, replacing existing assets when appropriate, and operation and maintenance. DSOs are subject to regulation by the national regulatory authority to ensure cost-efficient practices and fair and non-discriminatory access for end users. However, the current regulatory framework stems from an era in which reducing CO_2 emissions, or managing the energy transition in general, was not yet a policy goal.

5 ANALYSIS OF THE DISTRICT HEATING SUPPLY CHAIN

CO_2 EMISSIONS

District heat production by CHP plants results in less CO_2 emissions than the separate production of electricity, by 'electricity only' condensing power plants, and heat, by in-house gas boilers.[67] Utilising industrial residual heat, rather than simply discharging it into the environment, avoids the need for household gas consumption and thus reduces emissions from in-house boilers. There are, however, concerns that the use of fossil fuel-fired CHP plants, and industrial heat sources like refineries and petrochemical plants, can 'lock in' continued reliance on fossil fuels. The application of CCS could be one option to ensure further emission reductions from such heat sources.

To reach a fully carbon neutral district heating production portfolio by 2050, heat production from low-carbon and fully renewable heat sources must increase. These sources include geothermal heat, solar thermal energy, biomass and biogas CHP, and bio-oil combustion in heat-only boilers.[68] Large-scale implementation of such sources is, however, contingent on their spatial availability.

Geothermal energy, which extracts heat by circulating water through water-bearing layers at a depth of 2 to 3 kilometres, is a promising source of low-carbon heat production, but geological conditions are not equally favourable everywhere. Moreover, existing geothermal projects in the Dutch horticulture sector generally yield temperatures in the order of 60°C to 85°C, while the district heating system temperature can be up to 110°C during winter. Higher temperatures can be obtained by drilling deeper, but at increased cost.

Solar thermal energy is already being successfully applied in district heating systems, with over 320 MW of installed capacity in Europe.[69] However, solar thermal, like geothermal, struggles to attain high temperatures, and as such these systems can

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[67] Klaassen, R. E. and Patel, M. K. (2013), 'District heating in the Netherlands today: A techno-economic assessment for NGCC-CHP.' Energy, 54, 63–73. http://doi.org/10.1016/j.energy.2013.02.034

[68] Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F. and Mathiesen, B. V. (2014), '4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems.' Energy, 68, 1–11. http://doi.org/10.1016/j.energy.2014.02.089

[69] RHC-Platform (European Renewable Heating and Cooling Technology Platform). (2013), 'Strategic Research Priorities for Solar Thermal Technology.'

only deliver directly to the district heating system during summer, when there is enough solar irradiation to achieve a sufficiently high temperature. Nonetheless, solar thermal and geothermal temperatures can be upgraded with (green) gas-fired boilers or large-scale heat pumps, and still represent an energy and CO_2 reduction compared to stand-alone natural gas-fired boilers.

Large-scale heat pumps can deliver relatively low-carbon heat to the district heating system when the real-time CO_2 intensity of electricity production is low. Ideally, large-scale heat pumps would utilise (low-grade) waste heat streams, or solar thermal energy, to boost efficiency and thus reduce electricity consumption and the associated CO_2 emissions.

At the moment, peak heat demand is supplied by gas-fired heat-only boilers, as opposed to CHP plants. When accounting for thermal losses in the district heating network, large district heating gas boilers deliver worse energetic performance, and thus higher CO_2 intensity, than in-house gas boilers. However, given their limited operating hours and low capital cost, they are preferred to reduce the overall cost of the district heating profile. In the future, other options such as green gas or bio-oil boilers could be implemented to reduce CO_2 emissions.

In the current electricity market, with increasing shares of near-zero marginal cost intermittent RES-E sources holding down electricity prices, margins from gas-fired CHP plants are being squeezed. In response, some district heating producers reduce the running hours of CHP units, and increase the running hours of gas boilers. At the same time, some coal-fired power plants continue to produce electricity while discharging their residual heat. This outcome is clearly undesirable from a CO_2 perspective.

RELIABILITY

District heating infrastructure is generally dimensioned to meet peak demand for heat. In fact, the capacity of district heating networks is in some cases oversized, in anticipation of new connections being made in future. On the supply side, district heating will, in the short to medium term, shift consumption of gas from in-house boilers to CHP plants. This allows district heating systems to continue relying on the flexibility offered by the Dutch gas system, e.g. from underground storage facilities, to accommodate peak demand. In principle, newly built CHP plants could be connected to the H-gas infrastructure, allowing a gradual shift away from L-gas from the Slochteren field.

Another benefit of district heating is that, unlike some renewable electricity sources such as wind power, a number of renewable heating sources are not intermittent. Geothermal and biomass (CHP) can be operated more flexibly, or at least in baseload mode, and thus do not require flexible backup capacity (which intermittent renewable electricity sources do).[70]

The integration of the district heating and electricity systems can benefit the stability of both systems and provide economic benefits for end users. The combination of CHP plants producing electricity as well as heat, and large-scale heat pumps supplying heat to district heating systems, can alleviate scarcities or surplusses in electricity production.[71] Finally, a balanced heat production portfolio, consisting of CHP and heat pumps, when implemented in smaller-scale district heating networks, can alleviate local congestion in the electricity grid.[72]

Large-scale thermal energy storage provides an important function, matching demand and supply for heat over time, while maximising running hours and revenues from CHP plants. However, in the future, combining large-scale thermal storage with large-scale heat pumps could also store renewable energy from surplus wind and solar PV production, thereby assisting the integration of these intermittent sources.

AFFORDABILITY

In existing neighbourhoods, laying the district heating infrastructure and connecting the individual buildings can be costly. The cost for an individual dwelling varies depending on the exact circumstances, but is reported to be €6,000 per land-based dwelling and €3,000 per stacked dwelling.[73] District heating developers, however, foresee cost reductions from innovations such as pre-fab pipelines and guided drilling, and expect prices to lower gradually with experience.[74]

As with all-electric infrastructure cost, synergies can be attained by waiting for a natural replacement opportunity for the gas infrastructure, or by combining works with other utilities activity in the subsurface, such as sewage or road works. Existing

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[70] Biomass and biogas CHP plants can of course also deliver electricity on demand. Operating these in CHP mode, however, instead of only for electricity, makes optimal use of possibly scarce biogenic resources.

[71] CHP plants can deliver heat and electricity during periods of high heat and electricity demand (resulting from all-electric and hybrid heat pump systems). Similarly, large-scale heat pumps can absorb 'surplus' electricity from renewable electricity sources, by converting this electricity to heat within the district heating system.

[72] International Energy Agency. (2012), 'Energy Technology Perspectives 2012,' ch. 5, p. 192. http://doi.org/10.1787/energy_tech-2012-en

[73] CE Delft. (2015), 'Warmte aan het Stuur.' Commissioned by Alliander DGO, referred to in Alliander DGO. (2016), 'Transitieplan Schaalsprong Warmte Amsterdam - Voorstel aan de gemeente Amsterdam.'

[74] Alliander DGO. (2016), 'Transitieplan Schaalsprong Warmte Amsterdam - Voorstel aan de gemeente Amsterdam.'

gas infrastructure should also be taken into account, as an uncoordinated roll-out of district heating could also lead to the premature removal of gas infrastructure, or a double infrastructure situation, at unnecessary cost (see Box 4).

Despite the considerable infrastructure and connection costs, district heating is still a relatively cost-competitive option in areas of sufficiently high population density, notably urban centres, and new build houses, due to the economic gains from CHP heat production. Moreover, connecting large consumers, such as office buildings or existing neighbourhoods which already have a collective boiler installed (usually governed by housing corporations or 'associations of owners'[75]), is generally economical if there is an existing district heating system in the vicinity.[76]

From an economic perspective, it is sensible to connect existing heat supply sources first, provided these contribute to affordably reducing CO_2 emissions for the energy system as a whole. This improves the economic viability of district heating, and can contribute to the financing of district heating infrastructure to which fully carbon neutral sources can connect at a later point in time. The somewhat controversial extraction of heat from coal-fired power plants could be seen in this light – though policy-makers should be mindful to forestall the possibility of a so-called 'lock-in'.

Ecofys and ECN (2015) have calculated the district heating supply chain cost for both medium and high levels of energy efficiency. In the scenarios, 25% of households is connected to district heating, supplied by a mix of geothermal and gas boilers, while the remaining 75% of households are supplied by (in-house) high-efficiency gas boilers. The cost of the district heating scenarios are the lowest as compared to the other alternative heating scenarios considered in the study, although the authors note that the desired CO_2 emissions reductions are not achieved, largely due to the fact that high-efficiency gas boilers still make up the bulk of heating.

CE Delft (2016) calculated, as mentioned, what would be the cost-efficient heating option per neighbourhood. The study considered a larger range of potential heat sources for district heating than the Ecofys and ECN study. Most notably, the study allows for the use of 'renewable gas' supplies, e.g. obtained from power-to-gas technology, to meet peak heat demand for district heating. The outcome of the study shows that district heating using geothermal heat and renewable gas boilers is

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[75] In Dutch 'Vereniging van Eigenaren' (VvE).

[76] In the Netherlands, having a collective boiler to supply individual dwellings, rather than each building having an individual boiler, is commonly known as 'block heating.'

the most economic option in 44% of residential dwellings. District heating using 'residual heat' (including from CHP plants, sewage treatment plants, waste incineration and the chemical industry) in combination with renewable gas, is the most economic option in 17% of residential dwellings.

HOW TO ACHIEVE THESE OBJECTIVES?

As with all-electric, it is important that stakeholders incorporate the entire supply chain into their economic assessments, to identify cost synergies within the alternative heating supply chains, and to adequately compare the cost of the alternative options. In the context of district heating, this means that production, district heating infrastructure (heat losses) and building energy efficiency have to be considered in tandem.

Energy efficiency measures, in combination with low-temperature radiator systems, can lower the required temperature level within houses and thus the district heating system temperature.[77] This can have a number of beneficial effects on overall system efficiency, and thus reduce the district heating system cost.[78] Unfortunately, in practice, when an existing neighborhood is converted to district heating, stakeholders often do not consider the level of energy efficiency, beyond estimating heat demand to dimension the system. This should not come as a surprise, since the district heating producer does not have any incentive to do so, as lower energy use would undermine its business case.

However, in some cases, the cost of far-reaching energy efficiency measures is prohibitively high, e.g. in monumental buildings in inner cities, and could outweigh the operational cost of heat production. If the heat source is low-carbon, or even carbon neutral, such losses can be tolerated from a CO_2 perspective. Whether far-reaching energy efficiency measures are warranted in the built environment is thus highly case dependent.

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[77] Most district heating systems supply hot water at 90°C to 110°C, depending on the season. The return pipeline transports the water back to the source, at temperatures of 40 to 60°C.

[78] First of all, energy efficiency measures would reduce overall energy consumption and thus CO_2 emissions. Second, lower temperature levels would reduce heat losses within the DH transmission and distribution network. Third, lowering the system temperature would increase the annual utilisation, i.e. load factor, of geothermal and solar thermal sources, reducing the need for gas boilers to increase the temperature. Finally, neighborhoods with far-reaching energy efficiency measures could potentially be connected to the return pipeline of existing DH systems for space heating. Domestic hot water use would need to still be supplied by other means (e.g. an electric boiler). Such a cascading configuration cools down the return stream further, thereby increasing the overall efficiency of the DH system. In Leiden, there is already a pilot project underway using the return stream to supply space heating demand.

It will in some cases be difficult to make a comprehensive assessment of the supply chain cost of alternative heating options. Individual stakeholders will struggle, for example, to assess and compare the cost of reducing CO_2 by means of RES-E to supply (all-electric and hybrid) heat pumps versus using renewable heat sources to supply the district heating system.

As already touched upon, the current regulatory framework for district heating dictates that prices, which include the cost of district heating infrastructure and heat production, may not exceed the cost of gas-based heating. The cost of district heating infrastructure is thereby implicitly taken into account in the business case. However, this is not the case for all-electric heat pumps and electricity infrastructure, leading to an uneven comparison.

Given the expected increase in district heating networks, and specifically smaller networks, new natural monopolies are likely to arise. To forestall regulatory uncertainty that may hinder the uptake of such solutions where these are cost optimal, it is important that policymakers provide clarity on how such natural monopolies will be regulated.

6 ANALYSIS OF THE HYBRID HEAT PUMP SUPPLY CHAIN

CO_2 EMISSIONS

As with all-electric heat pumps, the CO_2 intensity of heat produced by hybrid heat pumps depends on the real-time CO_2 intensity of the electricity generation mix, and the real-time efficiency of the heat pump. Similarly, hybrid heat pumps will require substantial additional investments in RES-E technologies to reduce the CO_2 intensity of the generation mix.

The fact that hybrid heat pumps can switch to the gas boiler means the system effectively caps emissions intensity, which by default will not exceed the emissions intensity of the natural gas boiler. The CO_2 intensity of the boiler can be further reduced when some of the natural gas is substituted with 'green gas,' i.e. biogas upgraded to L-gas calorific value.[79;80]

Figure 9 is an extension of Figure 8 in the all-electric chapter, which also shows the emission intensities of a boiler supplied by two mixtures of green gas and natural gas. Note that increasing the fraction of green gas lowers the 'break-even point' in terms of emission intensity between the gas boiler and the heat pump.

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[79] Biogas has a lower calorific value, approximately 0.63 natural gas equivalent, with a higher concentration of CO_2 and a lower concentration of methane (CH4). Existing natural gas boilers cannot not cope with this low calorific value, so using unprocessed biogas carries a risk of accidents. Regulations therefore dictate that biogas must be 'upgraded' to match the calorific value (i.e. energy content) of natural gas, by separating out the CO_2 content, before it can be injected in the gas grid. In the Netherlands, biogas upgraded to natural gas quality is called 'green gas'. See Groen Gas Forum. (2014), 'Routekaart hernieuwbaar gas.' Composed by De Gemeynt, ECN, Groen Gas Nederland and RVO.

[80] Note that the CO_2 present in biogas is from a biogenic source, such as woody biomass, agricultural residues or manure. Unlike fossil CO_2 emissions, therefore, it does not contribute to climate change. Furthermore, if the source of the biogas, e.g. agricultural waste or manure, were left untreated, it would eventually decay and release its emissions regardless, either in the form of CO_2 or methane. Given that methane (CH_4) has a Global Warming Potential over a period of 100 years (GWP100) of 28 'CO_2 equivalent' (a commonly used measure to express the GWP), reducing methane emissions by capturing biogas and burning it in a controlled manner offers an added benefit in tackling climate change. GWP100 emission factor obtained from: R.K. Pachauri and L.A. Meyer (eds). (2014), 'Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),' p. 151.

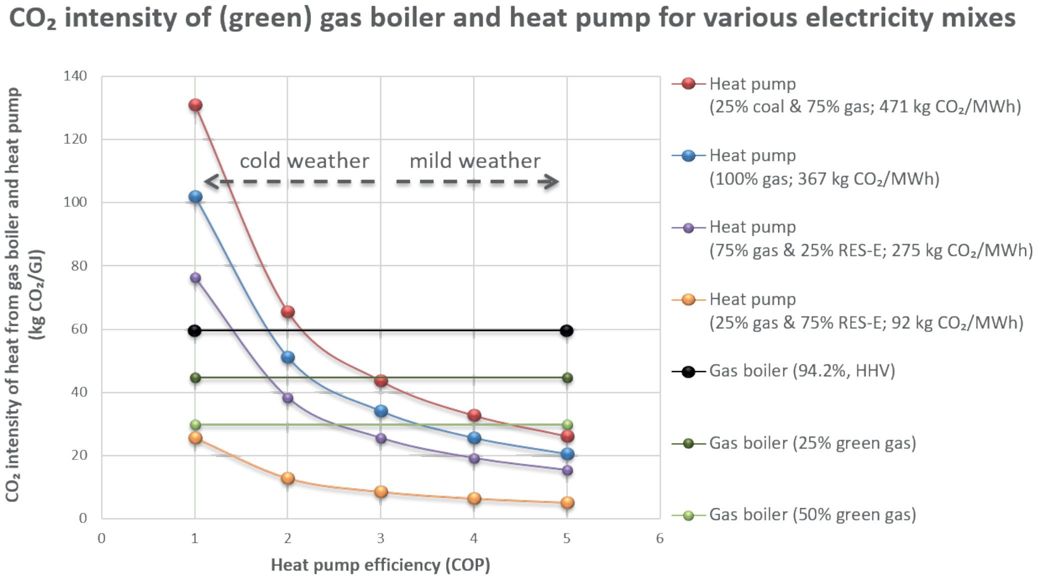

FIGURE 9. THE RELATIONSHIP BETWEEN HEAT PUMP EFFICIENCY, DETERMINED BY THE OUTSIDE TEMPERATURE AS SET OUT IN APPENDIX C, AND THE ASSOCIATED CO_2 REDUCTION FROM AN ALL-ELECTRIC HEAT PUMP COMPARED TO A CONVENTIONAL HIGH-EFFICIENCY GAS BOILER (94,2% HIGHER HEATING VALUE), FOR VARIOUS ELECTRICITY GENERATION MIXES. SOURCE: CIEP ANALYSIS, BASED ON EMISSION FACTORS FROM IPCC (2006) AND BOILER EFFICIENCY DERIVED FROM ENERGY MATTERS (2014).

In the future, hybrid heat pump systems could switch fuels on the basis of the real-time CO_2 intensity of the respective energy inputs.[81] A similar effect could be attained if carbon pricing were applied across the board, i.e. to residential natural gas consumption as well as electricity (to which it already applies on a wholesale level) on a real-time basis.

However, it should be mentioned that the potential for green gas derived from domestic feedstocks is limited. Moreover, it is unclear how much can be produced economically, also compared to other CO_2 reduction options. The potential proportion of green gas to be allocated to the residential heating sector, instead of other energy functions like transport or industrial heating, is also uncertain. Finally, the proportion of green gas, relative to natural gas, consumed by hybrid systems also depends on the number of gas boilers and hybrid systems relative to other alternative heating options, and on the remaining heat demand after the implementation of energy efficiency measures.

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[81] Ideally, this is done on the basis of the CO_2 intensity of the marginal generator of electricity.

RELIABILITY

Hybrid heat pumps would be able to continue to use the gas infrastructure to meet high peak demand, and thus tap into the supply side flexibility of the gas system. Hybrid systems could switch to the gas boiler in case of congestion in the local electricity distribution system, i.e. when aggregate demand exceeds the capacity of the network.[82] Consequently, investments to increase the capacity of the electricity distribution infrastructure could be deferred until a natural replacement moment. However, this would be conditional on a mechanism being in place to share information on local congestion from the DSO´s ICT system to the hybrid system.

In times of tight supply in the electricity system, which would be reflected in high (peak) wholesale electricity prices, households can resort to the gas boiler. The possibility to do so improves the reliability of heat supply for households and reduces the need for reserve electricity production capacity. As with the prevention of local congestion, this is conditional on there being adequate ICT equipment installed, and the implementation of real-time pricing at a household level.

Finally, maintaining a gaseous component in the residential heating system will benefit overall reliability, as the flexibility in the system in terms of production and underground gas storage can be utilised. In fact, in the short to medium term, it seems almost inevitable that this will be necessary in the event of a harsh and lengthy winter, which under current circumstances would raise peak gas demand to 100 GW.[83] Furthermore, in the long term, it could well be envisaged that underground gas storage facilities could be used for seasonal storage of green gas.

AFFORDABILITY

The cost of a hybrid heat pump system amounts to roughly €5,000 for the combined system, i.e. including a small air source heat pump and boiler.[84] This is more expensive than a stand-alone gas boiler, which costs approximately €1,500, but considerably cheaper than an all-electric air source or ground source heat pump system.[85]

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[82] Berenschot, DNV GL and BDH. (2016), 'Flex-potentieel hybride warmtepomp - Haalbaarheidsstudie Systeemintegratie.'

[83] Gasunie Transport Services. (2015), 'Network Development Plan 2015.'

[84] It is also important to recognise that the cost of ancillary parts, i.e. connection pieces, valves, etc., could drive up the total price of installation, especially in the short term as the market for such parts is still relatively immature.

[85] The price of heat pump systems is extremely sensitive to the maximum capacity of the system. Since all-electric air source heat pumps have to cover the entire heat load of a building, these systems require a higher peak capacity, making them considerably more expensive than air source heat pumps within hybrid systems, which are smaller, since these systems can fall back on the boiler and do not need to deliver domestic hot water.

Furthermore, the ability to switch fuels for space heating means hybrid systems can minimise operating costs to end users, by switching according to the price of the respective inputs (i.e. electricity and the mixture of green gas and natural gas). This would require time-of-use pricing of electricity, to save end users from paying the average electricity price for these marginal units of consumption.

In fact, by utilising the existing gas and electricity infrastructures, investments in new infrastructure can be deferred to a natural replacement moment, which in turn would lead to lower societal cost for energy infrastructure. This could also avoid potential costs related to premature depreciation of gas infrastructure (see Box 3).

The adoption of hybrid heat pump systems instead of all-electric would result in a relatively smaller increase in aggregate peak demand for electricity. This would reduce the need for backup electricity production capacity to supply moments of peak demand, resulting in lower electricity prices for end users. Similarly, there would be less need for a costly expansion of transmission system infrastructure by the TSO.

Nonetheless, hybrid heat pump systems would still require substantial investments in RES-E to reduce their CO_2 emission intensity. Moreover, the cost of biogas production and conversion to green gas are substantially higher than equivalent costs for natural gas, and should also be taken into account.[86]

The study from Ecofys and ECN (2015) confirmed the lower supply chain costs associated with hybrid heat pumps than all-electric heat pumps (see Appendix B). Furthermore, the study by CE Delft (2016) shows that hybrid heat pumps, using green gas, are projected to be the cost-optimal option for 10% of residential dwellings in the Netherlands by 2050. By contrast, all-electric (air and ground source) heat pumps were the cost-optimal heating option for only 2% of dwellings.[87] The study also indicates that the potential of hybrid heat pumps is limited primarily by the availability of green gas, and that if an unlimited amount of green gas were available, the share of hybrid heat pumps (and condensing gas boilers) would be considerably larger.

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86 Groen Gas Forum. (2014), 'Routekaart hernieuwbaar gas.' Composed by De Gemeynt, ECN, Groen Gas Nederland and RVO.

87 CE Delft. (2016), 'Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – update 2016, De route naar een klimaatneutraal Nederland.'

Finally, maintaining (parts of) the gas infrastructure provides optionality in the context of uncertain technological developments. Advances in power-to-gas technology to obtain hydrogen, and technologies which increase the economically recoverable amount of biogas, such as supercritical gasification, could render the gas infrastructure useful once more. The possibility of repurposing the existing natural gas distribution infrastructure to transport hydrogen for residential heating has recently gained attention in the United Kingdom (see Box 5).

Box 5. Hydrogen for residential heating – The Leeds City Gate Project

Hydrogen has recently been in the spotlight as a potential alternative residential heating option in the city of Leeds (UK).[88] Hydrogen could be transported to end users using the existing natural gas distribution infrastructure, and combusted in-house using a hydrogen boiler, for both space heating and domestic hot water.

Hydrogen is a flexible, carbon-free energy carrier with potential applications across all end-use sectors. Hydrogen can be used for residential heating, power production and transportation using fuel cell systems, which produce electricity and heat. Hydrogen could also be used as a heating fuel for industrial processes that require high temperatures and would otherwise be hard to decarbonize. Hydrogen could thus potentially fulfil a systemic function in a decarbonised energy system.

In the Leeds project, hydrogen would be obtained from a process called steam methane reforming (SMR), in which methane (CH_4) is split using steam (H_2O) into hydrogen (H_2) and carbon dioxide (CO_2). This is a common process to obtain hydrogen for industrial processes, e.g. in refineries and fertilizer production.[89] Subsequently, the stream of CO_2 is captured and sequestered indefinitely in a geological reservoir such as a depleted gas field.

The feasibility study for the city of Leeds calculated that CO_2 emissions could be reduced by 73% compared to natural gas-based heating, even after accounting for the efficiency penalty of the SMR process, the CO_2 capture efficiency of the

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[88] Northern Gas Networks, Wales and West Utilities, KIWA and Amec Foster Wheeler. (2016), 'H21 Leeds City Gate.'

[89] In fact, SMR is already used in the Netherlands, within the Shell refinery in Rotterdam. Excess CO_2 is captured, transported and sold to the Westland horticulture area to boost the performance of crops. This can be considered carbon capture and utilisation (CCU) rather than CCS. To what extent this form of CCU reduces CO_2 emissions depends on the avoided energy consumption from the horticulturist, which would normally have combusted natural gas to produce heat and CO_2 (and in some cases electricity) to aid the growth process. A residual CO_2 stream allows the horticulturist to use renewable heating sources, such as geothermal, while still having the required CO_2 to boost crop performance.

CCS equipment, and the electrical energy inputs for the SMR and CCS processes.[90] The SMR and CCS processes would, however, add to the cost of hydrogen compared to natural gas.

Alternatively, hydrogen could be obtained from water using electrolysis, with the CO_2 effect dependent on the CO_2 intensity of the electricity used. Electrolysis is considered to be more expensive than SMR, not least because of the cost of electricity and the expected low running hours of the electrolysis installation, due to the fluctuating availability of (zero marginal cost) low-carbon electricity.

HOW TO ACHIEVE THESE OBJECTIVES?

To achieve a cost-optimal alternative heating solution, stakeholders ought to incorporate the entire supply chain into their economic assessments, to identify cost synergies and adequately compare the cost of alternative heating options.

When considering the entire supply chain, and the energy infrastructure in particular, hybrid heat pumps may be a viable solution in areas where strengthening the electricity grid is particularly expensive, and district heating is unattractive due to a low population and heat demand density. This could also apply in areas where it may be economical to defer investment in infrastructure.

As with district heating, the interplay with energy efficiency is two-sided. On the one hand, energy efficiency measures, which allow for low-temperature heating systems, could increase the share of space heating supplied by the heat pump, thereby reducing natural gas and (potentially scarce) green gas consumption. On the other hand, the fact that the boiler is able to deliver higher temperatures allows far-reaching energy efficiency measures to be deferred to a natural replacement moment.

The ability of hybrid heat pump systems to mitigate some of the issues associated with all-electric systems, i.e. the need for backup electricity production capacity and electricity infrastructure investments, hinges on the implementation of 'smart software,' to enable fuel switching in response to local congestion and real-time

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[90] The lifecycle or supply chain emissions of natural gas remain unchanged. If these were taken into account, the overall emissions reduction would be 63%. Note that including the lifecycle emissions does not alter the comparison with natural gas-based heating (as lifecycle emissions occur in both configurations), but does matter when SMR-based hydrogen for residential heating is compared to other alternative heating options, e.g. district heating or all-electric and hybrid heat pumps. In such cases, however, one would also need to incorporate the lifecycle emissions from gas used in power plants for electricity (and heat) production.

electricity prices. Similarly, switching on the basis of the CO_2 intensity of the energy inputs can only be enabled once this information is available.

Hybrid heat pumps have an expected lifetime of 10-15 years, making them a good intermediary solution for reducing emissions in the short run at minimum cost. Since hybrid heat pumps do not need new infrastructure or additional infrastructural capacity, these systems can also be readily adopted by individual end users. This is in stark contrast to district heating, which requires top-down coordination, not least to avoid situations of double infrastructure (as described in Box 4). In short, hybrid heat pump systems could be adopted in a more evolutionary fashion. It seems unlikely, however, that individual end users will adopt hybrid heat pumps on their own initiative, as the costs still surpass those of conventional gas boilers.

7 CONCLUSION

Looking at the current transition efforts being undertaken in the Netherlands, it appears that there are no mechanisms in place to steer stakeholders toward achieving demonstrable CO_2 emission reductions from a supply chain perspective. Further, it seems that the reliability and affordability of alternative heating options are not actively considered in the plans, and that the trade-off in terms of societal cost between these two aspects is, as yet, insufficiently recognised.

At the heart of these issues lies the fact that some stakeholders do not take account of the whole supply chain of alternative heating options. Stakeholders generally only consider the costs with which they are directly confronted, such as for heating equipment or building energy efficiency, limiting their ‘system boundary’ to a small part of the supply chain. Not surprising, this leads to a number of issues, which must be addressed in order to ensure a successful transition of the residential heating system.

First, the shift of CO_2 emissions from the residential sector to electricity and district heating systems is not sufficiently recognised. As a result, the costs associated with decarbonising the respective alternative heating supply chains are opaque, which prevents these costs from being adequately compared. In addition, the fact that the emission intensity of the electricity generation mix fluctuates continuously, is not considered in the context of all-electric heat pumps. This also means that the potential merits of fuel switching, within the district heating production portfolio or by hybrid heat pump systems, cannot be properly valued.

Second, energy infrastructure costs are not consistently incorporated into the alternative heating options. For all-electric heat pump systems, for instance end users, project developers and housing corporations do not and cannot consider the cost of increasing the capacity of the electricity distribution (and potentially transmission) infrastructure. They have no incentive to do so, since these costs are borne, and subsequently socialised, by the DSO (and TSO). The uncoordinated adoption of all-electric heat pumps may, at some point, jeopardise the reliability of the electricity infrastructure, and could increase the cost of strengthening the capacity of distribution and transmission infrastructure, not least because these investments have a considerable lead time. This is in stark contrast to district heating, where the current regulated pricing regime ensures that infrastructure costs are incorporated, and thus implicitly taken into account. Conversely, the potential avoided or at least deferred infrastructure costs associated with hybrid heat pump systems are not adequately valued. Finally, stakeholders disregard the potential cost associated with (partially) removing the existing gas infrastructure, which may lead to premature depreciation cost or double infrastructure.

Third, stakeholders do not seem to recognise the immense flexibility of supply that the current gas system provides, and the challenges that will arise if alternative heating options must provide similar levels of flexibility. This is particularly relevant in the context of all-electric heating, as the resulting increase in electricity peak demand requires sufficient dispatchable generation capacity to guarantee a reliable supply of electricity at all times. In the context of the current over-capacity in the Dutch electricity market, this may not seem relevant, but in the event of an unbridled expansion of all-electric solutions this will most certainly become an issue. Likewise, enormous investments will be required to shift towards more district heating production, though the need for additional district heating capacity in the form of CHP plants could potentially provide synergies for the electricity system. Finally, the fact that the security of supply of hybrid heat pumps is underpinned by the flexibility of the gas system is not sufficiently recognised.

The consequences of the lack of a supply chain perspective are twofold. First, it inhibits stakeholders from identifying and exploiting synergies arising from the interplay of the supply chain components. Some examples include the potential of far-reaching energy efficiency measures to reduce peak demand for electricity, and thus the required (national) backup capacity, or the potential of energy efficiency measures to reduce the system temperature of district heating systems, thereby reducing cost, improving overall system efficiency, and assisting the integration of renewable energy sources. Second, the lack of a supply chain perspective means that stakeholders are not able to make an adequate assessment of *which* alternative heating options are to be implemented *where* and *when*. This can result in the adoption of sub-optimal solutions and lead to higher societal costs.

At present, additional supply chain costs are not visible to end users. Ultimately, however, end users are exposed to these costs, be it in the form of higher grid tariffs (for energy distribution infrastructure), higher electricity prices (due to tighter electricity market conditions in terms of production capacity), or higher increments on electricity bills (to finance the cost of renewable energy technologies). Excessive costs to end users could eventually erode public support for the transition, and jeopardise its effectiveness in reducing CO_2 emissions.

One way of incorporating the supply chain costs into the economic assessment of stakeholders is to make these costs transparent to all stakeholders, which can be achieved by stakeholder coordination at a local level in a framework set by the government to ensure equal access and reliability for all citizens. To eventually determine what is the most cost optimal heating option for reducing CO_2, while maintaining an acceptable level of reliability, a uniform 'technology neutral' assessment framework might prove useful. Such an assessment framework would also allow for 'upstream' supply chain costs to be incorporated that do not directly accrue to a specific party.

The Dutch Ministry of Economic Affairs recently published the 'Energieagenda,' giving an indication of the approach the government intends to take with regard to the transition of the residential heating system. One important element is the coordinating role delegated to local governments, i.e. the municipalities and provinces. Municipalities are already in contact with important stakeholders, such as housing corporations, and are responsible for permitting procedures for construction works and other activities. This makes them aware of the timing of large-scale renovations, spatial reconfigurations and sewage works. Municipalities are also positioned close to the end user, and enjoy a certain degree of democratic legitimacy, and as such they are well-placed to coordinate the relevant actors, as well as inform citizens and act on their concerns. DSOs are expected to cooperate closely with these local governments and provide their expertise. Other stakeholders, such as market parties, utilities, installation firms and energy service companies also play an important role, as they directly offer their heating solutions to end users and are closely involved in the execution phase.

The development of the residential heating system up to 2050 is inherently uncertain, as technological progress will continue to change the relative costs of alternative heating options. Adaptive policy will be crucial to manage this uncertainty. Ultimately, the challenge is to institutionalise a 'technology neutral' approach, enabling affordable CO_2 reductions while maintaining an acceptable level of reliability, and ensuring sufficient flexibility to react to changing relative costs over time. Here the central government plays an important role in the governance of the new systems.

APPENDIX A

Figure 10 shows the distribution of residential final energy consumption by fuel for the EU-28, Belgium, Denmark, France, Germany, Luxembourg, the Netherlands and the United Kingdom in 2014. Compared with other European countries, the Netherlands consumes almost no heating oil. Another remarkable feature is the large share of heat in the Danish residential energy mix, which is due to the widespread adoption of district heating in large urban centres, and of smaller collective heating networks in rural areas where local population density is high enough to justify the heat losses in the transport phase.

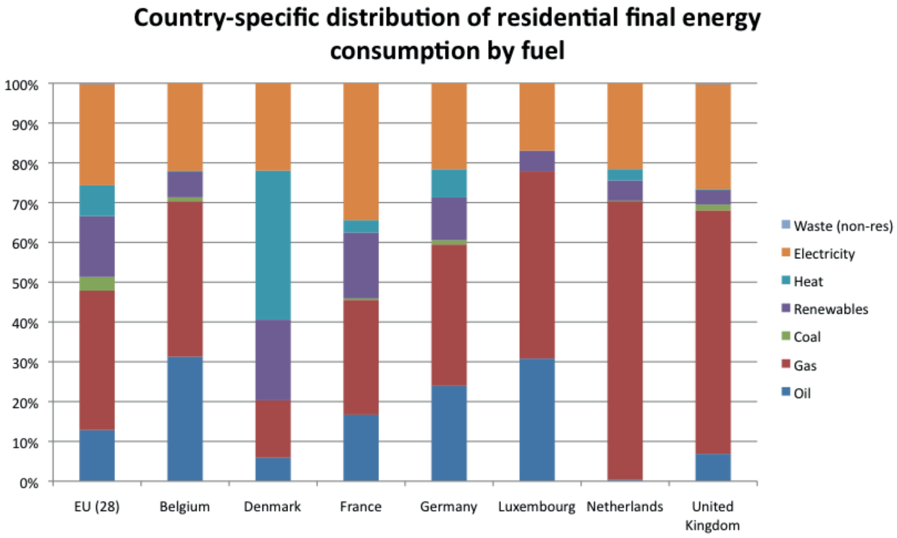


FIGURE 10. COUNTRY-SPECIFIC DISTRIBUTION OF RESIDENTIAL FINAL ENERGY CONSUMPTION BY FUEL IN THE EU-28 AND SELECTED EU COUNTRIES IN 2014. SOURCE: CIEP ANALYSIS BASED ON EUROSTAT DATA (2014).

APPENDIX B

Figure 11 shows the patterns of industrial gas demand (red) and national electricity demand (green) in the Netherlands in 2015. Figure 12 shows the aggregated (industrial and LDC level) gas demand pattern (brown) and the national electricity demand pattern (green) in the same year.

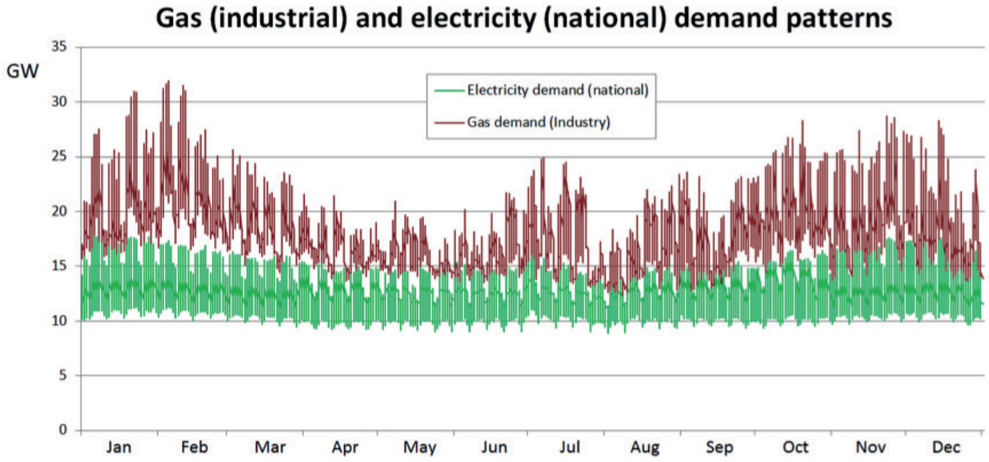


FIGURE 11. NATIONAL HOURLY ELECTRICITY LOAD VALUES FOR THE NETHERLANDS IN GW AND INDUSTRIAL GAS CONSUMPTION (H-GAS) FOR 2015. SOURCE: CIEP ANALYSIS, DATA OBTAINED FROM ENTSO-E AND GASUNIE DATAPORT.

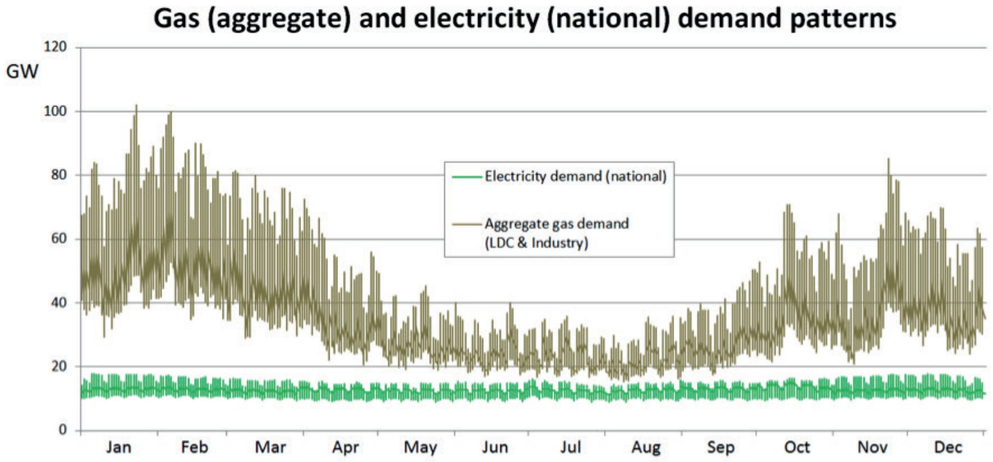


FIGURE 12. NATIONAL HOURLY ELECTRICITY LOAD VALUES FOR THE NETHERLANDS IN GW AND AGGREGATE NATIONAL GAS CONSUMPTION (INCLUDING LARGE AND INDUSTRIAL USERS). SOURCE: CIEP ANALYSIS, DATA OBTAINED FROM ENTSO-E AND GASUNIE DATAPORT.

APPENDIX C

Figure 13 and Figure 14 show the outcomes of the study by Ecofys and ECN (2015). It is worth pointing out that, in contrast to the study by CE Delft (2016), the scenarios are considered separate from each other and none of them achieve the targeted CO_2 reductions. Figure 13 depicts relative supply chain costs for the high-efficiency gas boiler scenario, the electric heat pump scenario, the district heating scenario, the hybrid heat pump scenario and the decentralised (40% micro CHP and 60% all-electric heat pumps to balance peak demand at a distribution infrastructure level) scenario. Note the trade-off between the cost of energy efficiency measures (categorised as building cost) and the cost for energy infrastructure in the electric heat pump scenario. This clearly underlines the issue of the distribution of costs and benefits between end users and the DSO.

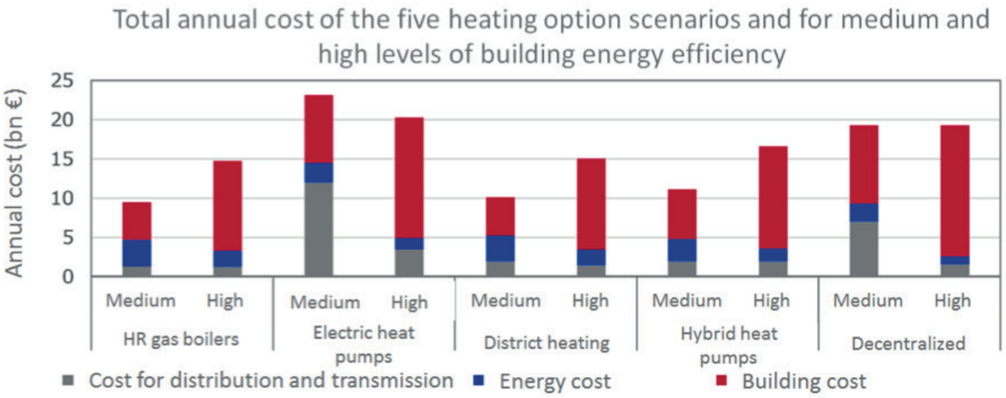


FIGURE 13. TOTAL ANNUAL COST PER HEATING OPTION FOR THE MEDIUM AND HIGH ENERGY EFFICIENCY SCENARIOS. SOURCE: ECOFYS AND ECN. (2015), 'DE SYSTEEMKOSTEN VAN WARMTE VOOR WONINGEN.' COMMISSIONED BY ALLIANDER, GASUNIE AND TENNET.

Figure 14 shows the results with respect to the CO_2 reductions of these heating technology scenarios at different energy efficiency levels. It is worth mentioning that the authors do assume a certain proportion of 'green gas,' i.e. upgraded biogas, to be available for the condensing boiler option and hybrid heat pump system.

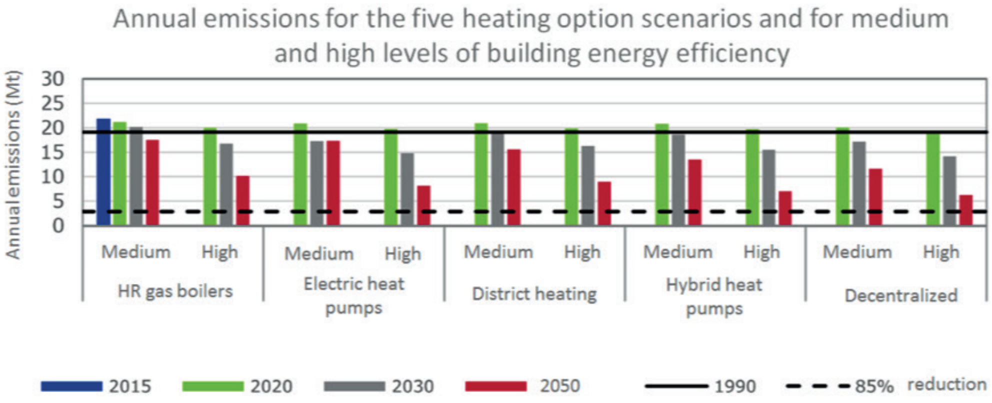
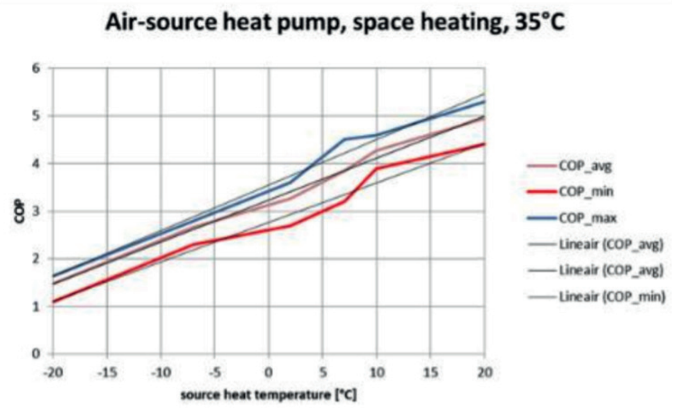


FIGURE 14. TOTAL ANNUAL CO_2 EMISSIONS PER HEATING OPTION FOR THE MEDIUM AND HIGH ENERGY EFFICIENCY SCENARIOS. SOURCE: ECOFYS AND ECN. (2015), 'DE SYSTEEMKOSTEN VAN WARMTE VOOR WONINGEN.' COMMISSIONED BY ALLIANDER, GASUNIE AND TENNET.

APPENDIX D

The figures below have been derived from the study by Ecofys and ECN (2015). Figure 15 plots the relationship between source temperature (the temperature of the outside air) and the efficiency of an air source heat pump delivering space heating at 35°C. Note that at this temperature the in-house radiator system will need to be adapted, e.g. by installing floor heating, to guarantee sufficient heat transfer and ensure comfort. Sufficient insulation measures would also be needed to reduce heat losses and thus the energy required. Likewise, Figure 16 shows the relationship between source temperature and heat pump efficiency for an air source heat pump delivering domestic hot water (DHW) at 50°C.



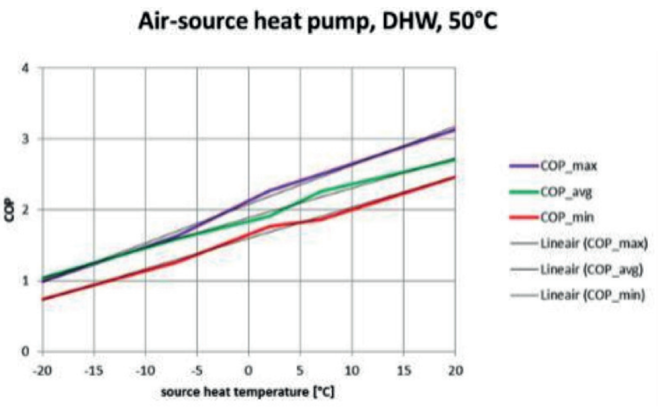


FIGURE 15. EFFICIENCY CURVE FOR AN AIR SOURCE HEAT PUMP, DEPENDENT ON THE TEMPERATURE BRIDGE BETWEEN THE OUTSIDE TEMPERATURE AND SPACE HEATING NEEDS OF THE IN-HOUSE RADIATOR SYSTEM AT A TEMPERATURE OF 35°C. SOURCE: ECOFYS AND ECN. (2015), 'DE SYSTEEMKOSTEN VAN WARMTE VOOR WONINGEN.' COMMISSIONED BY ALLIANDER, GASUNIE AND TENNET.

FIGURE 16. EFFICIENCY CURVE FOR AN AIR SOURCE HEAT PUMP, DEPENDENT ON THE TEMPERATURE BRIDGE BETWEEN THE OUTSIDE TEMPERATURE AND IN-HOUSE DOMESTIC HOT WATER CONSUMPTION AT A TEMPERATURE OF 50°C. SOURCE: ECOFYS AND ECN. (2015), 'DE SYSTEEMKOSTEN VAN WARMTE VOOR WONINGEN.' COMMISSIONED BY ALLIANDER, GASUNIE AND TENNET.

CLINGENDAEL INTERNATIONAL ENERGY PROGRAMME | CIEP

VISITING ADDRESS
Clingendael 12
2597 VH The Hague
The Netherlands

POSTAL ADDRESS
P.O. Box 93080
2509 AB The Hague
The Netherlands

TEL +31 (0)70-374 67 00
www.clingendaelenergy.com
ciep@clingendaelenergy.com