The energy and material related impacts of the transition towards low-carbon heating: a case study of the Netherlands

Verhagen, T.J.

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THE ENERGY AND MATERIAL RELATED IMPACTS OF THE TRANSITION TOWARDS LOW-CARBON HEATING:

A CASE STUDY OF THE NETHERLANDS

Teun Johannes Verhagen

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Promotores: Prof. dr. E. van der Voet
Prof. dr. A. Tukker

Co-promotor: Dr. B. Sprecher

Promotiecommissie: Prof. dr. P.M. van Bodegom
Prof. dr. D.P. van Vuuren (Universiteit Utrecht)
Dr. M. Hu
Prof. dr. J.W. Erisman
Prof. dr. G. Liu (University of Southern Denmark)
Dr. R. Kleijn

"Ut est rerum omnium magister usus"
"Experience is the teacher of all things"

- Gaius Julius Caesar

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Chapter 1

Introduction

1.1 Environmental impact of global energy production

The discovery of fire was a landmark in the development of human civilization. Fire provided foremost a source of heat, protection from predators, and over time allowed humans to create more advanced tools. The use of fire in slash-and-burn fields allowed hunters-gatherers to settle down and practice agriculture and herd domesticated animals. The rise of agriculture was crucial for the development of the earliest civilizations, known as complex societies, and allowed people to specialize in non-agricultural work and flourish within a relatively confined area.

Fire was the earliest form of energy available to mankind and fuelled the ability of a society to become increasing complex. Since then, we as a species have exponentially increased society's complexity and its demand for energy. The industrial revolution was fuelled by the access and efforts to mine coal on a large-scale. This has led to an unprecedent rise in population growth and allowed for a consistent increase for the standard of living for the general population in the western world. Over time, the use of coal was largely replaced with more efficient and widely available sources of energy such as oil and gas. The almost unsatiable demand for energy has created a strong reliance on fossil fuels of our modern society.

It is already well known that the globally large-scale use of fossil fuels also has downsides. Since the industrial revolution, the amount of CO_2 in the atmosphere has increased by more than 50% (US EPA, 2021). This increased accumulation of greenhouse gasses in earth's atmosphere has triggered a long-term change in the average weather patterns, known as climate change or global warming. Climate change negatively influences our health, environment and even the economy (IPCC, 2021).

Of all the greenhouse gases produced in the world, energy production is responsible for 72% (IEA, 2020). To reduce emissions and adapt to the impacts of climate change, 196 countries signed the Paris agreement in 2015. In this agreement, countries aim to achieve a climate neutral world by 2050, and therefore completely abolish the use of fossil fuels. For the energy sector, this has resulted in the energy transition, the shift from fossil-based systems of energy production and consumption to renewable energy sources.

Energy transition research has mainly focussed on the electricity sector and transport fuels (Liang et al., 2022; Tang et al., 2021). Up to now, very little attention has been paid to the heating sector. This thesis fills that gap by exploring a critical piece of the energy transition: the transition towards fossil-free urban heating. Buildings are responsible for 40% of the global energy demand, of which most is used for space heating. Three-quarters of this energy demand is met by using fossil fuels (IEA, 2021).

We use the Netherlands as a contemporary case study as its heating system is heavily reliant on the use of natural gas. Its country-wide natural gas grid is one of the largest in Europe and also acts as a major gas hub for neighbouring countries (Harris et al., 2020). The Netherlands also has one of the most ambitious policy goals to transition towards fossil-free urban heating: before 2030, all heating related greenhouse gas emissions have to be reduced by 50% while in 2050 the use of fossil fuels such as natural gas for space heating have to be completely abolished (Rijksoverheid, 2017). This is referred to as the heating transition.

1.2 Transitioning towards a low-carbon heating system

The current Dutch heating system uses natural gas as its main source of energy. Between 90-95% of all Dutch residential buildings are connected to the country-wide natural gas grid and use gas boilers for space heating (Rijksoverheid, 2017). Also, Dutch residential buildings are relatively poorly insulated (Verhagen et al., 2020; Yang et al., 2020). Operational heating-related GHG-emissions can be considerably reduced by the use of low-carbon heating technologies, such as heat pumps and heating networks (Francisco Pinto & Carrilho da Graça, 2018; Verhagen et al., 2020).

The existing heating system, including in-house heating, infrastructure, and energy production, will have to be adapted to accommodate low-carbon heating technologies that operate on different sources of heat. Low-temperature (LT) and high-temperature (HT) heating networks utilize a network of underground pipes for heat transmission, while heat pump technologies are dependent on the electricity grid and will require additional grid capacity (Love et al., 2017). Furthermore, low-carbon heating technologies require additional insulation in most buildings to operate efficiently.

To realize the transition towards a low-carbon heating system, many changes will have to be made to buildings. Designing new buildings without natural gas boilers is one thing, but in the short term it is just as important to provide the existing building stock with low-carbon heating technologies. This requires information on the material composition of existing buildings, and the materials required to realize this transition (Verhagen et al., 2021).

All the changes required for the transition towards low-carbon heating to buildings, infrastructure and energy production will over time lead to: 1) the obsolescence of the current natural-gas-based heating system and; 2) the build-up of a separate low-carbon heating system. Furthermore, besides the reduction in operational GHG-emissions, the implementation of these low-carbon heating technologies requires additional - and different - materials compared to the current heating system (Deetman et al., 2018; Elshkaki, 2019; Elshkaki & Graedel, 2013; Seck et al., 2020)

Part of the operational GHG emission reductions achieved by low-carbon heating technologies could be undone by the increased emissions related to the production of the materials required for these technologies (Greening & Azapagic, 2012; Heeren et al., 2013; Koezjakov et al., 2018; Oliver-Solà et al., 2009b). For example, the material stock of the electricity system will increase significantly with the development towards a renewable energy system (Deetman et al., 2021; van Oorschot et al., 2022). The implementation of low-carbon electricity technologies also increases the demand for metals, which have a considerable environmental impact (Kleijn et al., 2011).

1.3 The role of the circular economy in the heating transition

The heating transition will influence the operational emissions and the material intensity of the Dutch heating system. As stated above, part of the operational emission reduction could be undone by the increased material intensity of the new heating system. To achieve the climate goals of the Paris agreement, a balance between climate targes (operational emission reduction) and material use (embodied emissions) should be pursued.

The concept of the circular economy could reduce the increased material use of the transition towards low-carbon heating and its associated environmental impact. A circular economy is designed for the optimal use and reuse of raw materials, retaining the highest value for the economy and the least damage to the environment (PBL, 2021). For the transition towards low-carbon heating, this means that the new low-carbon heating system has to be designed with circularity, or reusing, refurbishing, remanufacturing and recycling in mind. At the same time, the soon-to-be obsolete natural-gas-based heating system can serve as an urban mine, a source of secondary materials. These secondary materials can be used as a partial replacement of primary material demand in a circular economy.

To promote the recovery and recycling of materials in a circular economy in the Netherlands, it is essential to explore the stock and flows of the urban mine of the current natural-gas-based heating system. Additionally, it is also important to quantify the material stocks and flows and associated environmental impacts of the transition towards low-carbon heating in 2050.

1.4 The Netherlands as a contemporary case study

The Netherlands is a relatively small but densely populated country in western Europe with 17.6 million inhabitants. In the 1950's huge natural gas resources were discovered in the Groningen gas field. The natural gas reserve within the Netherlands is currently estimated at 25% of the natural gas reserves within the EU. The country acts as a natural gas hub for its neighbouring countries and has one of the most developed natural gas grids in the world (Harris et al., 2020). Due to this ample supply, the Dutch built environment has been mainly using natural gas for its space heating, which is responsible for 36% of overall Dutch CO_2 emissions (ECN & CBS, 2017).

There are multiple challenges that the Netherlands is currently facing that influence its energy policies. Almost a third of its landmass is situated below sea level, and the country is one that may suffer the most from climate change due to rising sea levels and overflowing rivers. The Netherlands is also concerned with intensifying earthquake activity related to the extraction of natural gas. In 2018, over 90 earthquakes have been recorded in the Groningen region, which is responsible for the bulk of the Dutch domestic natural gas production (KNMI, 2020). Furthermore, the absence of substantial new discoveries has resulted in a relatively fast decrease of the existing natural gas reserves in recent years.

In 2017, the political decision was taken to transition towards fossil-free urban heating, on a very ambitious time-schedule: heating-related CO_2 emissions should be reduced by 50% before 2030, and 90% before 2050 (Rijksoverheid, 2017). For the existing Dutch building stock, this means that more than 80% are to be renovated. Besides the transition towards low-carbon heating, the Dutch government also formulated circular economy policy to reduce the country-wide use of primary materials (minerals, metals, and fossil fuels) by 50% before 2030, and become fully circular by 2050.

1.5 Methods – Modelling the energy and material related impacts of the transition towards low-carbon heating in the Netherlands

To determine the influence of the transition towards a low-carbon heating system on the Dutch built environment and its heating system, it is first necessary to explore the size of the existing material stock, and how it changes over time. It is also essential to explore the development of operational GHG-emissions produced by space heating from 2020-2050 during this transition. To do this, we use development scenarios on the composition of the Dutch heating system, and the following methods widely used in the field of Industrial Ecology: material flow analysis (MFA), Geographic Information System (GIS) and life cycle assessment (LCA).

For the development scenarios of the composition of the Dutch heating system, we mainly use the heating scenarios report by Berenschot (Berenschot, 2020a). This report explores multiple heating system pathways for the Netherlands from 2020-2050. In their analysis, the local availability and capacity for sources of low-carbon heat were considered. These scenarios are used to determine the market share of low-carbon heating technologies, and the corresponding material demand and development of the operational emissions of the Dutch heating system from 2020-2050.

MFA is a analytical methodology used to quantify stocks and bulk flows of materials within a system (Ayres & Ayres, 2002). This method is suitable to quantify for example: the flow of concrete and cement through China's industry in 2010 (Wang et al., 2016), and the global material cycles for more than 60 metals (Chen & Graedel, 2012). With a dynamic MFA, the element of time is added to assess past, present and future stocks and flows of materials (Graedel, 2019; Müller, 2006).

A more recent development is the combination of MFA with GIS data, which is very suitable for the estimation of material stocks. In the past decade, a wide range of studies used this methodological combination to estimate building material stocks on a country-wide level. Examples of this are, amongst others: for China (Hu, et al., 2010a; Hu, et al., 2010b), Switzerland (Heeren & Hellweg, 2018a; Ostermeyer et al., 2018), Luxembourg, (Mastrucci, 2017), Japan, (Tanikawa et al., 2015; Tanikawa & Hashimoto, 2009), Padua, Italy, (Miatto et al., 2019), US, (Reyna & Chester, 2015). With knowledge on the size of the stocks and flows of the Dutch heating system, the next step is to determine the impact of the materials.

LCA is a method to compile the inputs and outputs, and evaluate the potential environmental impact of a product system throughout its life cycle (Guinée et al., 2011). The aim of this method is to document the overall environmental profile of a product system and identify possible improvements. It has been applied to determine for example, the difference in environmental impacts between conventional and wooden construction materials (Heeren et al., 2015). LCA is generally known for the micro-level analysis of one functional unit, while we apply it on a larger scale to assess the impact of a system change. In this thesis, we use elements from the LCA method to determine the material-related impacts from different subcomponents of the Dutch heating system.

Throughout this thesis, a combination of the above-mentioned methods is used. The exploration of stock sizes for different parts of the Dutch heating system is based on combining MFA with GIS-data. For the calculation of the development of material stocks and flows over time, a stock-driven dynamic MFA is applied. The associated environmental impacts of the material demand are calculated with a cradle-to-gate LCA for the materials of each subcomponent of the Dutch future heating system.

1.6 Research questions and thesis outline

In the previous sections, we have established that the transition towards low-carbon heating will significantly alter the composition of Dutch buildings and the heating system, and over time causes the obsolescence of the existing natural-gas based heating system. At the same time, it is unknown how much material the build-up of this low-carbon heating system will require, and if this transition towards low-carbon heating will make the 2050 climate goal of reducing heating-related GHG emission by 90% attainable.

The aim of this thesis is to investigate the transition towards low-carbon heating in the Netherlands, in the context of the Dutch climate and circular policy goals. This results in the following **main research question**: *How is the Dutch heating system expected to change towards 2050, and how does this affect the Dutch policy goals related to climate change and the circular economy?*

As a starting point of our analysis, we explore the material stock of the current Dutch natural-gas-based heating system using mainly GIS-data, and the potential application of this material stock in a circular economy in chapter 2. After this, we look at the possible development pathways of the Dutch heating system over time and the corresponding operational GHG-emissions reduction in chapter 3. This resulted in the following sub-question:

1. What is the size of the material stock of the current Dutch natural-gas based heating system, and can this material be used in a circular economy?
2. What are the possible development pathways and operational GHG-emissions of the Dutch heating system towards 2050?

We explore the materials flows resulting from demolition and construction in the built environment, and how much of the primary material demand could be replaced with secondary materials in a circular economy in an MFA study in chapter 4. Based on the development pathways, we quantify the material demand of the transition towards low-carbon heating with a dynamic MFA study in chapter 5. In chapter 5, we also compare the operational GHG emission reduction with the cradle-to-gate GHG-emissions of the corresponding material demand of transition towards the low-carbon heating system These topics are covered in the following sub-question:

3. What are the consequences of the heating transition for the use of materials and how can this transition contribute to the circular economy transition?
4. What is the impact on GHG-emissions of the transition towards a low-carbon heating system from 2021-2050?

Finally, in chapter 6 we discuss the results for each sub-question, and the implications for the main research question in a broader context. In that chapter we also discuss the limitations of our research, and potential future research. This dissertation contains chapters (2 to 5) that are based on research articles (published or under review).

Chapter 2

Exploring Legacy Residential Natural-Gas Infrastructure: Urban Mine or Hydrogen Infrastructure?

Teun Johannes Verhagen
Sander van Nielen
Ester van der Voet
Benjamin Sprecher

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Abstract

The consumption of natural gas for space heating in buildings is expected to decrease considerably as a result of the energy transition. A new heating system will be built up, and at the same time, the natural-gas based heating systems will become obsolete. We explore the consequences of the heating transition for the material stocks and flows in the heating system in the Netherlands. One the one hand, we develop scenarios for the fate of the obsolete gas-based system. On the other hand, we compare the material stocks and flows of the gas-based heating system with those of the to-be-built-up renewables-based system as reported in previous research (Verhagen et al., 2022). In general, the renewable heating system is expected to be much more material intensive than the gas-based system. Nevertheless, a considerable stock of materials will become available. The expectation is that these materials will become a hibernating stock. Alternatives are proposed, either to reuse part of the system (gas pipes), or to recycle the materials and thus use the opportunity for the urban mining of valuable materials.

2.1 Introduction

Currently natural gas is supplying 20% of the total energy demand of space heating worldwide (IEA, 2020). For Western Europe this number is twice as high, as 38% of all buildings in this region use natural gas as their source of energy for space heating (Ürge-Vorsatz et al., 2015). If Europe is to achieve its climate neutrality goals, this will significantly decrease its consumption of natural gas (EU, 2016).

Of all the European countries, the Netherlands has the highest reliance on the use of natural gas for space heating, with 95% of all Dutch buildings connected to the natural gas grid (Rijksoverheid, 2017). Its country-wide natural gas grid is one of the largest in Europe and also acts as a major gas hub for neighbouring countries (Harris et al., 2020). Furthermore, the Netherlands has one of the most ambitious policy goals to transition towards fossil-free urban heating: before 2030, all heating related greenhouse gas emissions have to be reduced by 49% while in 2050 the use of fossil fuels such as natural gas for space heating have to be completely phased out (Rijksoverheid, 2017).

To achieve these policy goals, the Dutch government decided in 2017 to abolish the use of natural gas-based heating technologies in the construction of new buildings, and to replace the natural gas boilers in existing buildings in favour of low-carbon alternatives. In a previous article, we have explored the material requirements of this new, renewables-based heating system (Verhagen et al., 2022). Here, we compare both systems on their material intensity, and add a focus on the fate of the soon-to-be-obsolete gas-based system.

When the transition is complete, not just boilers and heating systems in buildings will be affected, but large parts of the gas production and distribution network will not be needed anymore. This raises the question of what will happen with the soon-to-be-obsolete Dutch natural-gas-based heating system, and in particular the natural gas grid. Without active policy measures, the materials in the Dutch gas grid will likely remain underground and become a hibernating stock. Instead of leaving the materials in hibernation, these could be extracted from the urban mine as they present a potentially valuable source of secondary materials for use in the circular economy. Not just recycling, but also re-use could be an option, such as using the existing natural gas pipelines for the distribution of renewable gasses, for example green gas or hydrogen. This adds to the research on urban mining, i.e. the recovery of materials from anthropogenic stocks, which so far has focussed largely on buildings (Deetman et al., 2020; Heeren & Hellweg, 2018; Marinova et al., 2020; Tanikawa et al., 2015), while the electricity (Deetman et al., 2018, 2021; Kleijn et al., 2011; van Oorschot et al., 2022; Yanan et al., 2022) and heating system (Xining & Steubing, 2021) are slowly gaining attention. The future development of a renewables based heating system has been explored (Verhagen, Cetinay, Voet, et al., 2022), but little is known about the materials in the current heating system. These materials, and their fate under various assumptions of a progression of the transition towards a renewable heating system, are investigated in this paper.

The purpose of this article is therefore twofold: (1) to compare the material intensities of the old gas-based heating system and the new, renewables based system that we expect to emerge, and (2) to explore end-of-life (EOL) options of the soon-to-be-obsolete Dutch natural-gas-based heating system on their consequences for material flows and stocks, and compare these options across multiple development pathways from 2020 to 2050. (Verhagen, Cetinay, van der Voet, et al., 2022).

2.2 Materials and Methods

In our assessment we take the following steps:

1. Calculation of the materials embedded in the Dutch natural-gas-based heating system in 2020, including the natural gas infrastructure, heating boilers in dwellings and the domestic natural gas production installations.
2. Calculation of the in-use stocks development of the Dutch natural-gas-based heating system from 2021-2050, based on the 2020 stocks and assumptions on the market penetration of hybrid heat pumps
3. Calculation of the material inflows and outflows for the in-use material stock from 2021-2050.
4. Exploration of possibilities for repurposing of the no-longer-used stocks in terms of reuse, recycling and hibernation. As an additional input for this, we determine what part of the Dutch gas infrastructure is suitable for the distribution of hydrogen based on literature.

These steps are discussed below in more detail.

2.2.1 Calculating the materials of the Dutch natural-gas-based heating system

The following components of the Dutch natural-gas-based heating system were included in the material inventory: natural gas pipeline infrastructure, heating boilers, and domestic onshore natural gas productions installations. In the results section we show the material stock of this heating system in the Netherlands in 2021, and its material intensity per dwelling. We show the material intensity per dwelling because in literature and Dutch policy documents on building space heating this is often used as the unit of reference (Bergsdal et al., 2016; PBL, 2014).

GIS-datasets of the natural gas infrastructure were collected from the Dutch network operators. Using the GIS-data, material densities and pipeline diameters, the material stock of the natural gas pipeline infrastructure was calculated with a Python script. In the Netherlands, around 6 million gas-boilers are in use in residential buildings, and the annual domestic gas production in 2020 was 7.77E+09 Nm3. Scientific literature and the EcoInvent database were used to obtain information about material contents in heating boilers and natural gas production installations.

2.2.1.1 Natural gas infrastructure

Spatially explicit GIS-datasets from 7 network operators were used to determine the materials in the Dutch natural gas pipeline infrastructure in 2020. This GIS-data were obtained through the websites of the network operators or through a data request by e-mail and contain the location and length of pipelines in the natural gas network. In addition to this, the data set from grid operator Enexis also contains further information about the pipe diameter and the material composition of the pipes. Through the use of a Python script using the GeoPandas module, the average material densities per meter of pipe length from the Enexis GIS-dataset were extrapolated and applied to the GIS-datasets of the other network operators. Official figures for the length of the gas infrastructure have been used to verify the data received from the network operators.

The Enexis dataset contains the material information and the diameter and geometry (location and shape) of the natural gas pipelines. The wall thickness has been added based on documentation from gas pipeline manufacturer Walraven (Walraven, 2020). The cross-section of the pipe is then calculated with the following formula:

$$Pipe\ cross\text{-}sectional\ area\ (m^2) = (\pi \times r^2) - (\pi \times (r - thickness)^2) \tag{1}$$

To calculate the mass of the materials in the network we included the specific weight for all the mentioned materials in the dataset, and used the following formula:

$$Pipe\ mass\ (kg) = pipe\ cross\text{-}sectional\ area\ (m^2) \times length(m) \times specific\ weight\ (\frac{kg}{m^3}) \tag{2}$$

The pipeline cross-section and material information from the Enexis dataset have been applied to the other datasets by extrapolating the material density and composition per meter of pipeline. In the results, the average values of the material density and the percentage of material that make up the pipeline are shown separately per unit length of the Enexis dataset.

2.2.1.2 Heating boilers

It has been assumed that 90% of all households in the Netherlands use a heating boiler in 2020 (CBS, 2021). For the application of the material stock in the Netherlands in 2020, the number of households in the Netherlands using a heating boiler has been multiplied by the required materials. The research of Oliver-Sola et al,.(2009) was used to calculate the materials present in heating boilers in Dutch homes (Oliver-Solà et al., 2009a). In this study, the materials in a heating boiler are described, and consists of brass, bronze, copper, cast iron, PVC and steel.

2.2.1.3 Natural gas production installations

The materials used in Dutch gas production have been estimated based on production volume, and the cradle-to-gate material intensity of gas production from the EcoInvent 3.8 database (EcoInvent, 2010). This EcoInvent data includes the materials used in natural gas extraction, the pipeline infrastructure surrounding the gas field, and the natural gas processing plant. The materials included in this documentation are steel, cement and concrete. The materials are reported in the EcoInvent database in kg of material required per production unit of natural gas in Nm^3. To obtain the material stock in this section, we have multiplied these values by the natural gas production of the Netherlands on land in 2020 (Rijksoverheid, 2021). An overview of the calculation of this material stock has been added in Table AI.2 in Appendix I.

The Dutch natural gas consumption for the heating of buildings is currently partially dependent on foreign imports (Rijksoverheid, 2021). For the stock inventory, we only look at natural gas production within the borders of the country, and not at the production installations required to meet the domestic demand for natural gas (Rijksoverheid, 2021).

2.2.2 Dutch heating system outlook to 2050

In this research, we explore three EOL-options of the Dutch natural-gas-based heating system in combination with three development pathways on the extent that this heating system will remain in use.

In addition to the material stock that we calculated as described above, we use the development of the in-use stock from 2021-2050, and the associated material in-and outflows. The in-use stock development is based on the heating scenarios developed by Berenschot, outlining the composition of the Dutch heating system in 2050 (Berenschot, 2020b). For the associated flows, we look at the phase-out of stocks, as well as the maintenance flows for the remaining in-use stock of the natural gas-based heating system. We use this information to determine the possible amount of materials that could be recovered from the stock over time. We also explore what part of the natural gas infrastructure is suitable for the distribution of renewable based gas, especially hydrogen. Taken together, we use this information to calculate three EOL-options for the materials in the Dutch natural-gas-based heating system:

1. Leave in the ground (hibernation)
2. Reuse as infrastructure for hydrogen or green gas (reuse)
3. Recovery and recycling of out of use materials (recovery)

In the next sections, we describe the modelling assumptions in more detail.

For all development pathways, we assume that part of the gas pipelines will continue to be used for the distribution of hydrogen, replacing the consumption of natural gas before 2050. Scientific and grey literature were used to determine whether the Dutch natural gas pipelines are suitable for the transport of pure hydrogen (Cerniauskas et al., 2020; Ma & Spataru, 2015; Moreno-Benito & Agnolucci, 2016; Ogden et al., 2018; Pellegrino et al., 2017). In our assessment, we use the materials deemed suitable by the Dutch national natural gas network operator to determine the potential of hydrogen in the existing Dutch natural gas infrastructure (Netbeheer Nederland, 2018). The materials are steel, (S)PVC and PE.

The in-use stock in 2050 of the Dutch gas infrastructure is based on the market share of alternative heating technologies, such as hybrid heat pumps and heating boilers, based on the scenarios by Berenschot (Berenschot, 2020a). This translates to the following development pathways for Dutch dwellings still using the gas infrastructure in 2050:

- No repurposing, total abolition of the natural gas infrastructure.
- 20% repurposing: 20% of all dwellings (mostly buildings built before 1949) will still use the gas grid, but for hydrogen instead of natural gas
- 45% repurposing: 45% of all dwellings (mostly buildings built before 1965) will still use the gas grid, but for hydrogen instead of natural gas

We have not investigated the EOL of the natural gas production installations in the Netherlands for 2050. Therefore, we assume that the natural gas production installations will be taken out of use from 2021 to 2050 and are available for recovery. The heating boilers currently used in Dutch buildings are not suitable for the use of green gas or hydrogen (Netbeheer Nederland, 2018) and are therefore also assumed to be completely phased out and available for recovery from 2021 to 2050. The EOL-options together with the development pathways result in the following (Table 1):

To determine if the future Dutch low-carbon heating system is more material-intensive that the current natural gas-based heating system, we compare the development of in-use stocks of both systems. The materials in the future Dutch low-carbon heating system are based on Verhagen et al., (2022), and both heating systems are reported in kilotons of material stock for 2020, 2030 and 2050 (Verhagen, Cetinay, van der Voet, et al., 2022). We show the stock development of a selection of materials which are present in both heating systems. These materials are: steel, copper, cast iron, brass, PE and (S)PVC.

2.2.3 Modelling the in-use stock and material flows of the natural-gas-based heating system from 2021-2050

With the availability of GIS-data on the location of pipelines in the Netherlands, we calculated the relative size and material composition of the remaining Dutch natural gas infrastructure in 2050 for each pathway. To achieve this, we selected the residential buildings and surrounding gas pipelines that are most likely to continue to use the gas network for hydrogen, depending on the remaining market share of hybrid heat pumps. The oldest residential buildings were chosen as these will be the least suitable for other low-carbon heating technologies, which translates to buildings built before 1949 for the 20% repurposing pathway, and buildings built before 1965 for the 45% repurposing pathway. This approach enables us to more realistically determine which natural gas pipelines will most likely be phased out over time, and which will remain in use. The uncertainty found in literature about the suitability of certain materials for the distribution of hydrogen is further discussed in the discussion section.

Table 1, overview of the EOL-options and development pathways:

		Re-use: development pathways (Berenschot)		
		No repurposing	**20% repurposing**	**45% repurposing**
EOL-options	**Leave in the ground (hibernation)**	100% of the gas pipelines go into hibernation	Gas pipelines will remain in use to supply 20% of residential buildings with hydrogen, 80% of the materials go into hibernation	Gas pipelines will remain in use to supply 45% of residential buildings with hydrogen, 55% of the materials go into hibernation
	Recycle materials	100% of gas pipelines will be recovered	Gas pipelines will remain in use to supply 20% of residential buildings with hydrogen, 80% of the gas pipelines will be recovered	Gas pipelines will remain in use to supply 45% of residential buildings with hydrogen, 55% of the gas pipelines will be recovered

The municipality of Eindhoven was used for this analysis because it is a good example of a large Dutch city and because we have detailed information on its local natural gas infrastructure. By using ArcGis Pro and the BAG3D (Kadaster, 2018), the dataset of the Dutch built environment of the Dutch government, we examined which residential buildings are most likely to continue to use the gas network for hydrogen, depending on the development pathways on the remaining market share of hybrid heat pumps.

With the buffer tool in ArcGis pro, the corresponding natural gas distribution network within 15 m around the residential buildings that are most likely to utilize hybrid heat pumps in 2050 were selected from all the currently existing natural gas pipelines. This was performed for all development pathways. We visually validated the phased-out pipelines for each neighbourhood and included segments of the pipeline manually if these were not included in the first selection. Repeating the analysis without the visual validation on a larger scale would make the outcome therefore less reliable.

The remaining materials in the selection for each development pathway were compared with the original number of materials in the case study and based on the calculated percentages extrapolated to the country-wide natural gas grid for each material. See Appendix AI.4 for the resulting outflow of materials per year of the local case study and the country.

With a dynamic material flow analysis (dMFA), lifetime distributions for the infrastructure, heating boilers, and natural gas production installations, and the in-use stock predictions of the Dutch heating system, the in-and outflow of materials from 2021 up to 2050 were calculated. Since Weibull distribution parameters were not available for the pipelines and natural gas production installations, we used standard Weibull distribution values based on the average lifetime distributions. Stock accumulation models are mainly sensitive to the average lifespan, and almost insensitive to the choice of lifespan distribution function (Miatto et al., 2017).

To calculate the development of the material flows over time of the Dutch natural-gas-based heating system, we used the *Open software framework for DYnamic Material systems* (ODYM) module (Pauliuk & Heeren, 2020). ODYM is an open-source framework for dynamic material systems modelling in Python. In our analysis we used a stock driven model (Müller, 2006) together with lifetime distributions for each subsection of the Dutch natural-gas-based heating system.

We determined the in-and outflow per year with a distributed life span (L) using a Weibull function. For the calculation of a stock (S), in and outflow at certain years (t) the following functions were used in the model:

$$Inflow\ (t) = S(t) - S(t-1) + Outflow\ (t) \tag{3}$$

$$Outflow(t) = Inflow(t-L) \tag{4}$$

We included the outflow of the obsolete natural-gas-based heating system, and the in-and outflow for the maintenance of the remaining stock. The lifetime distributions for each subcomponent of the natural-gas-based heating system can be found in Table A1.5 in Appendix AI.IV.

The phasing out of the materials of the natural-gas-based heating system is modelled in line with the build-up of the new low-carbon heating system from 2021-2050 as described in the Berenschot report (Berenschot, 2020a). Also, for all the development pathways, we have presumed that improved insulation will reduce the total heat demand from dwellings over time (PBL, 2014), and that newly constructed buildings will use heat pumps of heating networks for the space heating. As a result, we have assumed that the current capacity of the Dutch gas grid will not grow and would be sufficient for meeting the space heating demand, even with the construction of new houses and the population growth of 2021-2050 (Ogden et al., 2018). An overview of the stocks and flows for all development pathways can be found in Appendix AI.IV.

2.3 Results

2.3.1 Material stock of the Dutch natural-gas-based heating system in 2020

Based on the GIS-data provided by the Dutch grid operations, we find a total length of the Dutch natural gas grid of 148,000 kilometres, which is in line with the official numbers from the Dutch government (Netbeheer Nederland, 2020). Table 2 provides an overview of the stock, pipelines length and material density for each material present in the natural gas pipelines.

Table 2, stock, pipeline length and material density of the Dutch natural gas pipelines for each material:

Material	(S)PVC	Steel	PE	Cast iron	Asbestos Cement	Total
Stock (ton)	277,055	376,557	23,707	73,800	1,428	752,546
Length of pipelines (km)	103,188	22,449	18,732	3,462	345	148,172
Material intensity (ton/km)	2.7	17.7	1.3	21.3	4.4	5.1

Table 3 shows that the Dutch natural-gas-based heating system contains 1,080 kilotons of materials in 2020. Most of this stock consists of steel (582 kilotons), and (S)PVC (320 kilotons). Smaller material groups are cast iron (75 kilotons) and copper (55 kilotons), while even smaller material groups consist of PE, bronze, cement, concrete and brass (>25 kilotons).

Table 3, materials in the Dutch natural-gas-based heating system in 2020 (kilotons):

	Brass	Bronze	Cement	Concrete	Copper	Cast iron	PE	(S)PVC	Steel	Asbestos cement	Total
Infrastructure	0	0	0	0	0	73.8	23.7	277	376.5	1.4	752.4
Heating boilers	12.6	1.6	0	0	54.8	1.2	0.0	42.8	178.1	0	291.3
Natural gas production installations	0.0	0.0	3.1	7.2	0.0	0.0	0.0	0.0	26.6	0	36.9
Total	12.6	1.6	3.1	7.2	54.8	75.0	23.7	319.8	582.3	0	1080.6

The largest part of this stock, 750 kilotons, is present in the natural gas pipeline infrastructure. The natural gas pipelines consist mainly of steel (50%) and PVC and (S)PVC (37%). The smaller material groups are cast iron (10%) and PE (3%). In addition, there is still a small fraction of asbestos cement in the current gas infrastructure (>1%), which the Dutch grid operators will completely replace with PVC or steel within the next few years due to safety concerns (Netbeheer Nederland, 2021). As seen in Figure 1, the density of materials in the Dutch natural gas infrastructure varies from 2.6 tons per square kilometre to 220 tons per square kilometre. The material density is highest in the urban environment, after which the density drops sharply again in the outlying areas.

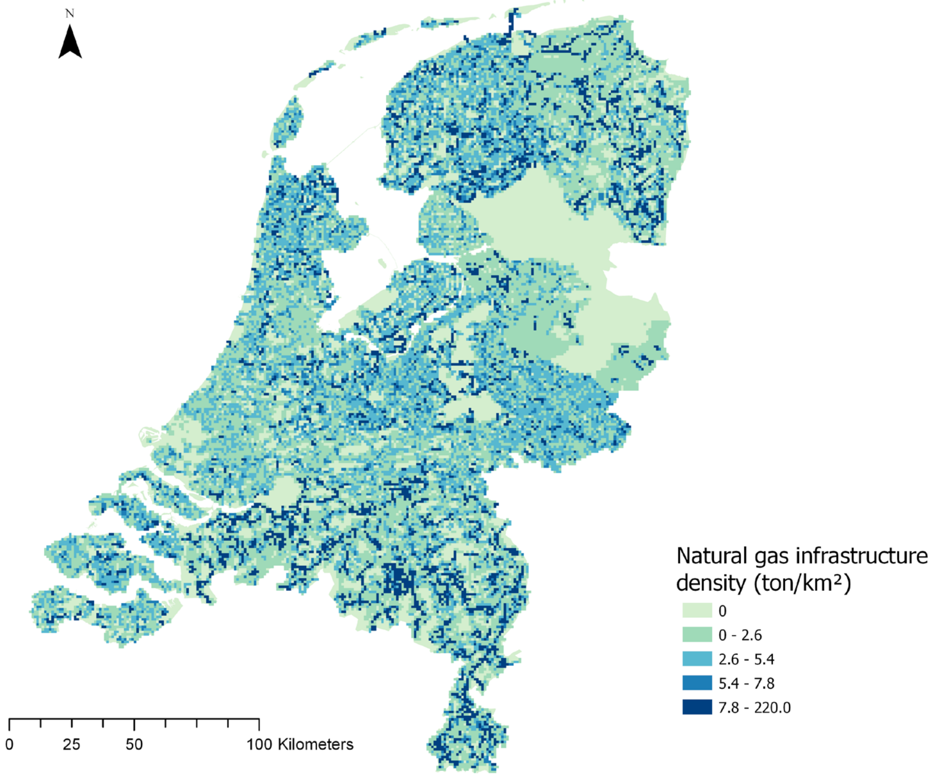

Figure 1, the material density of the Dutch natural gas pipeline infrastructure in 2020 in ton/km2:

The second largest stock (290 kilotons) is found in the heating boilers in homes and consists mainly of copper, bronze, (S)PVC, and steel. The natural gas extraction installations consist of steel, cement and concrete and are a relatively small stock (37 kilotons) compared to the rest of the natural-gas-based heating system.

The material intensity of the natural-gas-based heating system in 2020 is 160 kg per dwelling. As shown in Figure 2, the largest amount of materials, 115 kg per dwelling, is present in the pipelines required for the natural gas infrastructure, while the heating boiler has the second-highest material intensity of 45 kg per dwelling. These are on average the materials required for when a Dutch dwelling will be connected to the natural gas grid. We excluded the natural gas production installations in this overview as most of the natural gas consumed by Dutch buildings is imported. Therefore, adding more dwellings to the Dutch gas grid does not influence the amount of materials in domestic natural gas production installations.

Steel is the largest material category across all the subsections of the natural-gas-based heating system (89 kg per dwelling), with (S)PVC as the second largest (49 kg per dwelling). Copper is only present in the heating boilers (8.4 kg per dwelling), while cast iron is mostly used in the natural gas infrastructure (11.3 kg per dwelling) and with a small fraction present in boilers (0.2 kg per dwelling). Cast iron, brass, bronze and PE are the smaller material groups with less than 4 kg per dwelling. For an overview of all the material intensities per dwelling see Table A1.6 in Appendix I.IV.

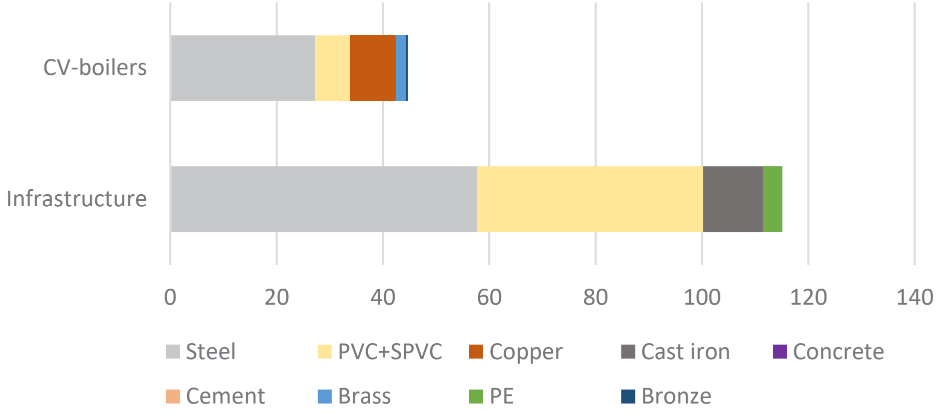

Figure 2, the material intensity in the natural-gas-based heating system in 2020 in kg per dwelling:

2.3.2 Development pathways of the Dutch natural-gas-based heating system from 2021 to 2050

Based on the development pathways, the in-use material stock of the natural gas-based heating system will be reduced by between 64% and 100% from now until 2050 (Figure 5). In the no repurposing pathway, the total in-stock of the Dutch natural gas-based heating system of 1,080 tons will flow out and could become available as a potential source of secondary materials. In the 20% repurposing pathway, 857 kilotons flow from the in-use stock and 223 kilotons of the materials remain in use, while in the 45% repurposing pathway, 687 kilotons flow out from the in-use stock while 393 kilotons of the materials remain in use. In all three of the development pathways, the gas boilers and natural gas production installations will completely go out of use.

In the no repurposing development pathway, the stock of the natural gas heating system will be completely decommissioned. In the two other pathways, part of the stock will remain in use in the form of the natural gas pipeline infrastructure. For this part, the "normal" stock dynamics are applied: to maintain that stock, the outflow of EOL materials needs to be replaced by an inflow of new materials. Obviously, these inflows and outflows are smaller than in the present situation. A detailed overview of all material flows per development pathway can be found in Appendix AI.V.

The cumulative outflow from the Dutch heating system from 2021-2050 is 2,078 kilotons for the no repurposing pathway, 1,914 kilotons for the 20% repurposing pathway and 1,782 kilotons for the 45% repurposing pathway. These materials could potentially be used again in a circular economy.

2.3.3 Comparing the in-use material stock of the Dutch natural-gas-based heating system with the future low-carbon heating system over time

The total in-use material stock of the low-carbon heating system consists largely of steel and copper, just like the natural-gas-based heating system. For metals, the transition to a low-carbon heating system in 2050 will mainly see an increase in steel (5x) and copper (5x) compared to the current gas-based heat system in 2020 (Figure 4a). For cast iron, the stock remains about the same, while for bronze the stock even decreases over time. In 2050, the stock of copper and brass in the natural-gas-based heating system will be zero as these materials are found in the gas boilers that will be completely taken out of use. In total, the amount of metals in the heating system will increase significantly due to the increased stock of steel. The situation is slightly different for plastics, where the stock of PE in the transition to a low-carbon heating system increases by a factor 10-15x, while for (S)PVC the stock decreases by about 20x (Figure 4b). Both plastic stocks are comparable in size to the copper stock, but are significantly smaller than the steel stock in 2050.

Based on the selection of materials shown here, the low-carbon heating system will likely be more material-intensive. Especially the metal stocks in the Dutch heating system will increase over time.

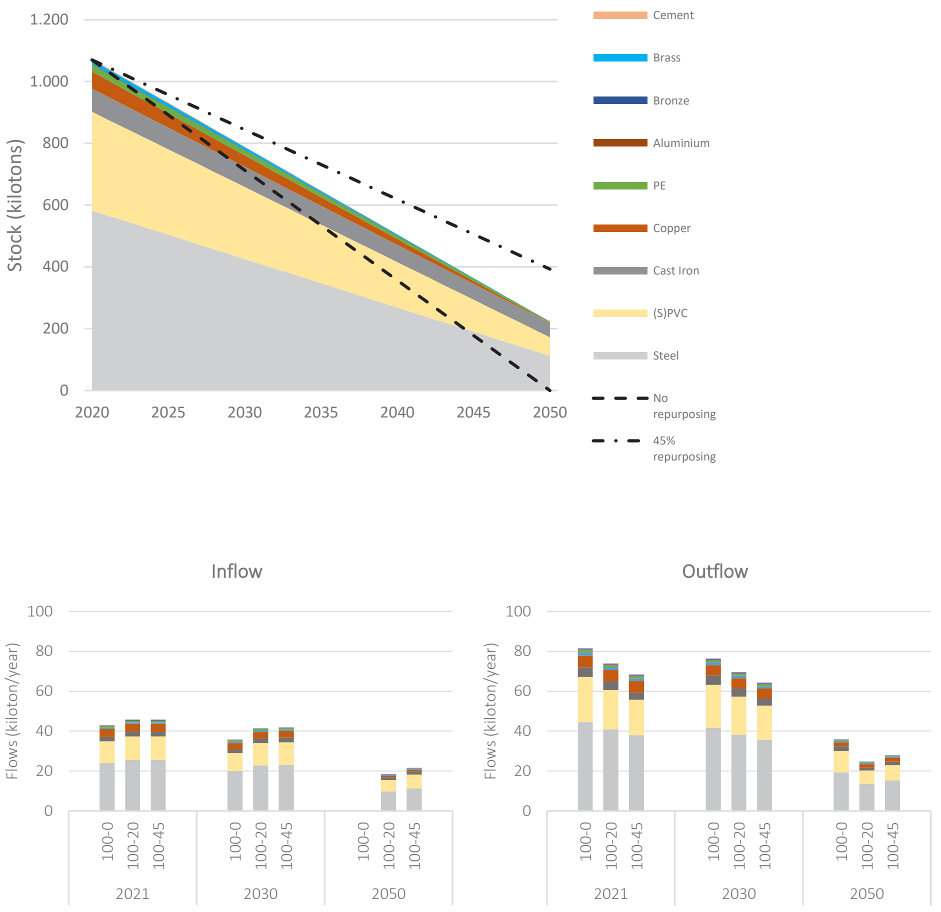

Figure 3, in-use material stock (top) and flows (bottom) of the natural-gas-based heating system for 2021, 2030 and 2050 for the development pathways. The top figure shows the material stock of the 20% repurposing development pathway (100-20), with the no repurposing (100-0) pathway as the lower limit and the 45% repurposing (100-45) development pathway as the upper limit.

2.3.4 End-of-life options of the Dutch natural-gas-based heating system

In this section we discuss the three EOL-options for the Dutch natural-gas-based heating system, that will be obsolete by 2050. These obsolete stocks contain, besides the outflow resulting from stock maintenance, the outflow of all cv-boilers in residential buildings and the natural gas production installations.

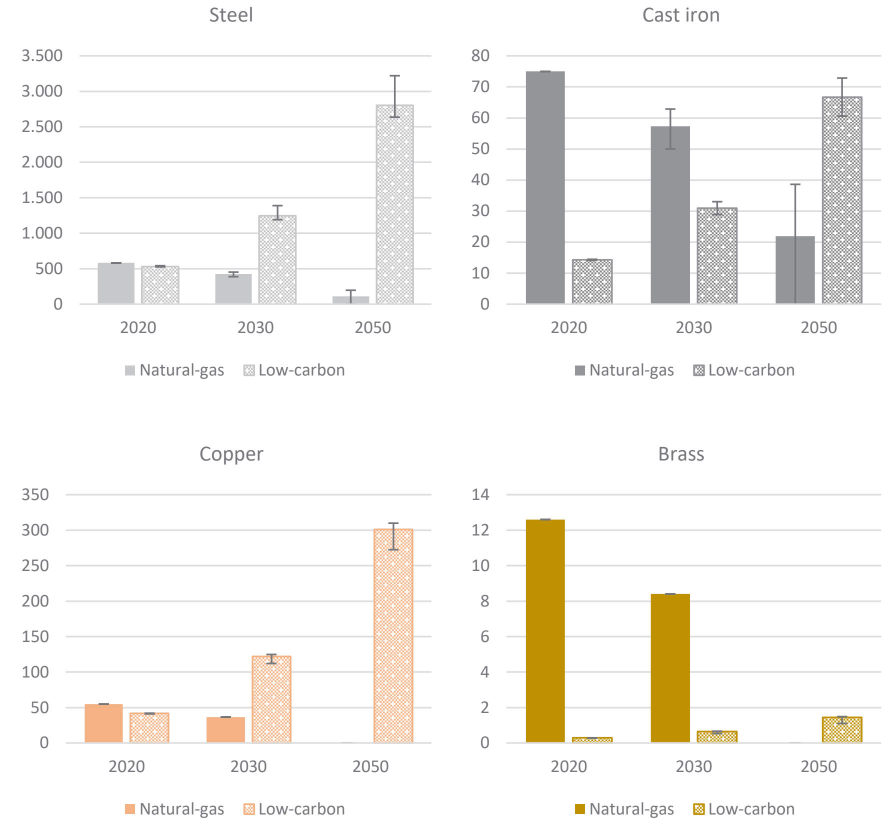

Figure 4a, in-use material stock of metals in the natural-gas-based heating system and the low-carbon heating system in 2020, 2030 and 2050 (kilotons). The different development pathways for both systems are shown with the error bars.

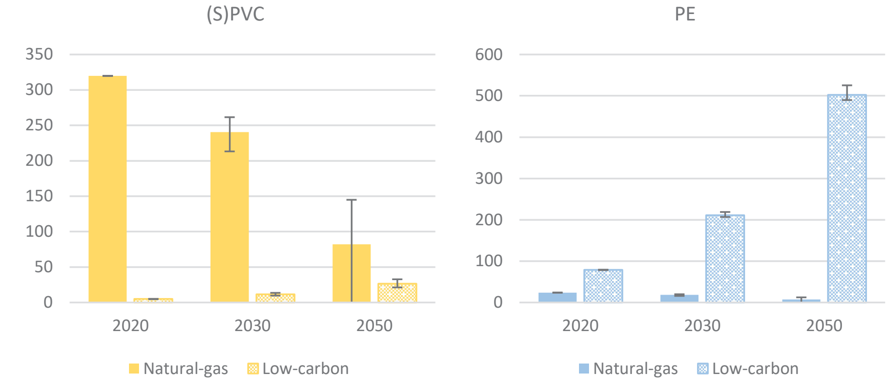

Figure 4b, in-use material stock of plastics in the natural-gas-based heating system and the low-carbon heating system in 2020, 2030 and 2050 (kilotons). The different development pathways for both systems are shown with the error bars.

The EOL-options refer especially to the pipeline grid. In the Berenschot scenarios, a varying part of the grid is repurposed and therefore will be re-used. The remainder of the grid will either remain in the ground and go into hibernation, or it will be extracted from the ground and is then assumed to be recycled.

Of the total material stock, between 358 and 751 kilotons potentially goes into hibernation, depending on the development pathway (Table 4). In the 45% repurposing pathway, where 45% of the residential buildings keep utilizing the gas grid for their heating demand in 2050, the obsolete stock going into hibernation is 358 kilotons. In the no repurposing pathway, the whole natural-gas pipeline infrastructure of 751 kilotons potentially goes into hibernation and will remain underground.

Looking at the cumulative material outflow from 2021-2050, between 1,327 and 1,424 kilotons of materials can be recovered to be recycled as an EOL option. When including the recovery of the pipeline materials, the cumulative material outflow increases to 1,782 – 2,078 kilotons. These materials could be used as secondary material input in the circular economy, and reduce primary material use.

For the reuse of existing pipelines, we find that 90% is suitable for the distribution of hydrogen because they are made of appropriate materials. Providing 45% of residential buildings with hydrogen through the existing grid will therefore not be a matter of suitability of the gas grid, but more based the availability of hydrogen and the adaptation of dwellings. Between the different development pathways, a stock of 0 up to 393 kilotons will then remain in use. The remaining part of the material stock will then become a hibernating one, or can be recovered. In Table A1.6 in the Appendix AI.V, we show an overview of the natural gas pipelines and their suitability for hydrogen distribution.

The EOL options and the development pathways of the in-use material stock cover the potential variety in the development of the Dutch natural gas pipelines (Overview in Table 4). Taking into account the increased material-intensity of the low-carbon heating system, the recovery and recycling of as much materials of the natural-gas-based heating system as possible has to be considered. The use of these materials in a circular economy could alleviate some of the material-related impacts of the build-up of the low-carbon heating system. In reality, a combination of all the different EOL options will most probably take place. Part of the material stock will go into hibernation; a part will remain in use for the distribution of hydrogen or another renewable gas.

Table 4, EOL-options for each of the development pathways of the Dutch natural-gas-based heating system in 2050 (kilotons). The cumulative outflows contain stock maintenance, the outflow of cv-boilers and the natural gas production installations, and when applicable the outflow from the gas pipelines from 2021-2050.

		Re-use: development pathways (Berenschot)		
		No repurposing	**20% repurposing**	**45% repurposing**
EOL-options	**Leave in the ground (hibernation)**	0 kt pipes reused, 751 kt pipes in hibernation, 1,327 cumulative outflows to recycling	223 kt pipes reused, 528 kt pipes in hibernation, 1,386 cumulative outflows to recycling	393 kt pipes reused, 358 kt pipes in hibernation, 1,424 cumulative outflows to recycling
	Recycle materials	0 pipes reused 2,078 kt cumulative outflows to recycling	223 kt reused, 1,914 kt cumulative outflows to recycling	393 kt reused, 1,782 kt cumulative outflows to recycling

2.4 Discussion

In this study, we analysed the EOL options of the soon-to-be obsolete Dutch natural-gas pipelines from 2021 to 2050 across multiple development pathways. We quantified the size of the potential hibernating stock, materials available for recovery over time, and the reuse potential for the distribution of hydrogen of the Dutch natural-gas pipelines.

The total urban mine of the Dutch natural gas-based heating system in 2021 is estimated in this study at 1,080 kilotons, and consist mostly of steel, (S)PCV, cast iron and copper. To put the size of this material stock in perspective, a comparison with the Dutch electricity grid is made. The total amount of steel and iron in the Dutch electricity grid is estimated at 707 kilotons in 2018 (van Oorschot et al., 2022), while our estimate of the material stocks for steel and iron in the Dutch natural-gas-based heating system is 657 kilotons. This implies that the Dutch natural-gas-based heating system is comparable in size to the Dutch electricity grid.

In contrast, the emerging renewables-based heating system expected to be in place is much more material intensive, although there is a shift in the materials used. For steel, copper and PE the in-use stocks of the renewable system are an order of magnitude higher.

Between 358 and 751 kilotons of materials of the Dutch natural gas infrastructure will most likely go into hibernation after the use phase, as the recovery of underground obsolete material stocks is often considered unprofitable (Krook et al., 2011). To further promote the transition towards a circular economy, collection of these considerable stocks of steel, PVC, and cast iron would need to be incentivized by the Dutch government with active policy measures for the network operators. An example of this would be combining the collection of unused pipes with maintenance operations for which the excavation work in a certain area was already required. Gas boilers in residential buildings (291 kilotons) are more accessible than the underground pipelines, making collection and recycling more likely for these products. Furthermore, the natural gas production installations (37 kilotons) are assumed to go out of use and available for recovery in our analysis, while in reality both their obsolescence and their EOL fate is unknown. In total, recycling and reuse of materials of the existing natural-gas-based heating system could alleviate at least some of the material demand of the build-up of the more material intensive low-carbon heating system (Verhagen, Cetinay, van der Voet, et al., 2022).

Another consideration for the gas infrastructure network is that it could also be left underground in hibernation for potential future reuse if even more dwellings have to switch to hydrogen than anticipated. This is a weigh up between urban mining of this material stock, or potentially preventing a new material demand in the future for additional hydrogen infrastructure.

A limitation of this research is that only one dataset of the Dutch network operators contains information about the pipeline diameter and the material of which the pipelines are made. The average values of weight and material per pipeline length have been extrapolated to the rest of the dataset for stock analysis throughout the Netherlands. The rest of the natural gas infrastructure could have a slightly different material composition than this dataset contains. A smaller limitation of this research is that the GIS-datasets of smaller 2 network operators are missing from our analysis. This is compensated by extrapolating the material inventory over the network length of the missing part of the natural gas infrastructure. Furthermore, it is also unknown what the size of the current hibernating stock is of the Dutch natural-gas based heating system. In our current assessment we assumed that all the modelled stocks are in use. Further research is required to explore how much hydrogen can be produced in, or imported to the Netherlands, and how much of this will be available for the heating of residential buildings.

Although we have assumed that the almost all of the current Dutch natural gas pipelines are suitable for hydrogen distribution, monitoring of the long-term effects of hydrogen on the pipelines materials is required. In several countries, studies have shown that the materials steel, PE, cast iron and PVC are suitable for the distribution of pure hydrogen (Hermkens et al., 2018) (Adam & Heunemann, 2020). In addition, the Dutch governmental natural gas network organization, Netbeheer Nederland, has conducted tests and also found that natural gas pipelines made from steel PE, cast iron and PVC have no noticeable degradation due to the use of pure hydrogen (Netbeheer Nederland, 2018). However, the tests conducted in these studies lasted from 4 up to 10 years, while the lifetime of natural gas pipelines is at least 30 years. In addition, research has also shown that using hydrogen in steel natural-gas pipelines can lead to a reduced lifetime (An et al., 2017). The long-term effects of the use of hydrogen in natural gas pipelines are therefore not clear. Pipelines suitable for the distribution of hydrogen are ideally made of different alloys, have a different shape and a different operating pressure than existing natural-gas pipelines (European Industrial Gases Association, 2004). This could influence our results on the amount of pipelines that could be reused for the distribution of hydrogen, making recovery and recycling a more suitable option for the pipeline materials.

Uncertainty exists over to what extent hydrogen will be used in the future for the space heating of residential buildings. Hydrogen scenarios were explored in the analysis, but green gas is also a possibility in a renewables-based heating system. Another important aspect of the use of hydrogen in existing natural gas infrastructure is safety. Several studies have stated that hydrogen leakage in infrastructure and buildings is well within the safety margins stated by the network operators to prevent fires and explosions (Hormaza Mejia et al., 2020; Netbeheer Nederland, 2018). Still, the transition from natural gas towards hydrogen for use in residential space heating will require new safety protocols for installation and operation to be developed that focus on the characteristics of hydrogen (Netbeheer Nederland, 2018).

2.5 Conclusion

The Dutch natural-gas-based heating system is a valuable urban mine that is comparable in size to the Dutch electricity system. In total, we find a stock of 1,080 kilotons of materials in the heating boilers, natural gas production installations and gas pipeline infrastructure for 2020. We also found that the future Dutch low-carbon heating system will be more material, and especially more metal intensive than the current natural-gas-based heating system. The amount of material potentially available for recovery from the outflows of the natural gas-based heating system from 2021 to 2050 varies from 1,327 and 2,078 kilotons, depending on the extent to which the existing natural gas pipelines will go into hibernation, or be recovered and recycled. Of the currently existing natural-gas pipelines, more than 90% is made of materials appropriate for the distribution of hydrogen, showing a lot of potential for reuse.

Chapter 3

Alternatives for Natural Gas-Based Heating Systems, a Quantitative GIS Based Analysis of Climate Impacts and Financial Feasibility

Teun Johannes Verhagen
Ester van der Voet
Benjamin Sprecher

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Abstract

The heating of buildings currently produces six percent of global greenhouse gas emissions. Sustainable heating technologies can reduce heating-related CO_2 emissions by up to 90%. We present a Python-based GIS-model to analyse the environmental and financial impact of strategies to reduce heating-related CO_2 emissions of residential buildings. The city-wide implementation of three alternatives to natural gas are evaluated: high temperature heating networks, low temperature heating networks, and heat pumps. We find that both lowering the demand for heat and providing more sustainable sources of heat will be necessary to achieve significant CO_2 emission reductions. Of the studied alternatives, only low temperature heating networks and heat pumps have the potential to reduce CO_2 emissions by 90%. A CO_2 tax and an increase in tax on the use of natural gas are potent policy tools to accelerate the adoption of low-carbon heating technologies.

3.1 Introduction

Urban heating is responsible for six percent of global GHG emissions (Intergovernmental Panel on Climate Change & Edenhofer, 2014). In Europe, the use of natural gas for urban heating has been steadily increasing in the last decades, currently providing 68% of urban heat. Of the European countries, Germany and the Netherlands are amongst those most reliant on fossil fuels, with more than 90% of their heat supplied by natural gas (Persson & Werner, 2015). Reducing CO_2 emissions from urban heating will therefore involve transitioning away from fossil fuel-based urban heating technologies.

The Netherlands is an interesting contemporary case study. Its urban heating sector is responsible for 36% of overall Dutch CO_2 emissions (ECN & CBS, 2017). In 2017, the political decision was taken to transition towards fossil-free urban heating, on a very ambitious time-schedule: heating-related CO_2 emissions should be reduced by 49% before 2030, and 90% before 2050 (Rijksoverheid, 2017). This is referred to as the '*warmtetransitie*', or heating transition. Besides reducing GHG emissions, the Netherlands is concerned with intensifying earthquake activity related to the extraction of natural gas. In 2018, over 90 earthquakes have been recorded in the Groningen region, which is responsible for the bulk of the Dutch domestic natural gas production (KNMI, 2020).

There are three often discussed alternatives to fossil-fuel based heating systems: high-temperature heating networks (HT, supply temperature of around 85 °C), low-temperature heating networks (LT, supply temperature of around 55 °C), and heat pumps (Petrović & Karlsson, 2016; Werner, 2018). Heating networks (also known as district heating) are based on a central heat source and a network of underground water pipes to distribute the heat. Sources of heat include combined heat and power plants (gas, coal, biomass), industrial waste heat and geothermal heat (Lund et al., 2014). Heat pumps use electricity to transfer heat from an outside source, such as the air or water (either stored for this particular purpose or surface water), to a building. There is a wide variety of heat pump technologies available, ranging from small air-to-air heat pumps to large water-to-water heat pumps capable of delivering heat to multiple homes. The Dutch government is considering these three often discussed technologies as viable replacements for the current gas-based heating system (Rijksoverheid, 2017). In this work, we explore their environmental and financial consequences in the context of the Dutch heating transition.

One of the first steps in achieving a reduction in urban heat consumption is improving the insulation of the building stock. Although this will provide a significant reduction of emissions (38-59%), it is not enough to reach the climate goals determined by policy (Buffat et al., 2017; Francisco Pinto & Carrilho da Graça, 2018; Werner, 2018).

In literature, we find considerable CO_2 emission reductions (20-70%) across different alternative heating technologies (Bianco et al., 2017; Delmastro et al., 2016; Lund et al., 2014; Persson & Werner, 2015; Sayegh et al., 2018). However, comparing technologies across different countries is difficult. Their performance is dependent on the climate of the country and the available sources of heat. Furthermore, these comparisons often exclude the effects of increased insulation and the required additional infrastructure. Conclusions about the overall CO_2 reduction potential of alternative heating technologies can only be drawn after a consistent system analysis.

As alternative heating technologies do not operate on natural gas, they require different supporting infrastructures. Heat pumps use the electricity grid, while HT and LT heating networks utilize specific heating networks. This change in infrastructure is generally not taken into account in the assessment of the impact of these technologies. We are aware of only one paper: Love et al. (2017) that established the possible impact of heat pumps on the electricity grid. They found that the peak grid demand could increase substantially as a result of implementing heat pumps.

A large-scale change of the heating system is costly and will require investments over a long period of time. It is therefore critical to assess both the technical and financial feasibility of this transition before making irreversible policy choices. The main factor in establishing the price of heat delivered by heating networks is the cost of infrastructure. Further factors influencing the total cost of a system-wide heating technology replacement are determined by retrofitting buildings and the replacement of the heating technology. Even though financial insight in this transition is crucial for its implementation, system-wide costs including infrastructure are seldom mentioned in the literature (Buffat et al., 2017; Francisco Pinto & Carrilho da Graça, 2018; Serrano-Jimenez et al., 2017; Werner, 2018).

Research related to alternative heating technologies has focused on individual technological implementations across different countries, making it difficult to compare their CO_2-emission reduction potentials. This body of literature contributes significantly to the understanding and solving of the multifaceted challenge of the heating transition. However, these models only discuss building refurbishment options and/or a single alternative heating technologies, while the desired situation of the overall heating system could be a combination of these (Bokhoven & D, 2018).

In addition, the literature has not addressed the system-wide reduction of heating-related CO_2 emissions. The financial implications of sustainable heating technologies are similarly not included in a system-wide analysis. It is therefore unclear how much the emissions related to urban heating can be reduced and what the financial impact of different technologies would be. Especially for home-owners, the heating transition could prove to be an unexpected financial burden (Rijksoverheid, 2017).

We use a bottom-up model based on GIS data to examine the environmental and financial aspects of sustainable heating technologies on a city-wide scale. We evaluate HT and LT heating networks with heat pumps as an alternative to natural gas for the heating of residential buildings. Building retrofitting and the different infrastructures required are also included in our analysis. The climate goals set by the Dutch government will be used as a basis for comparison

3.2 Method

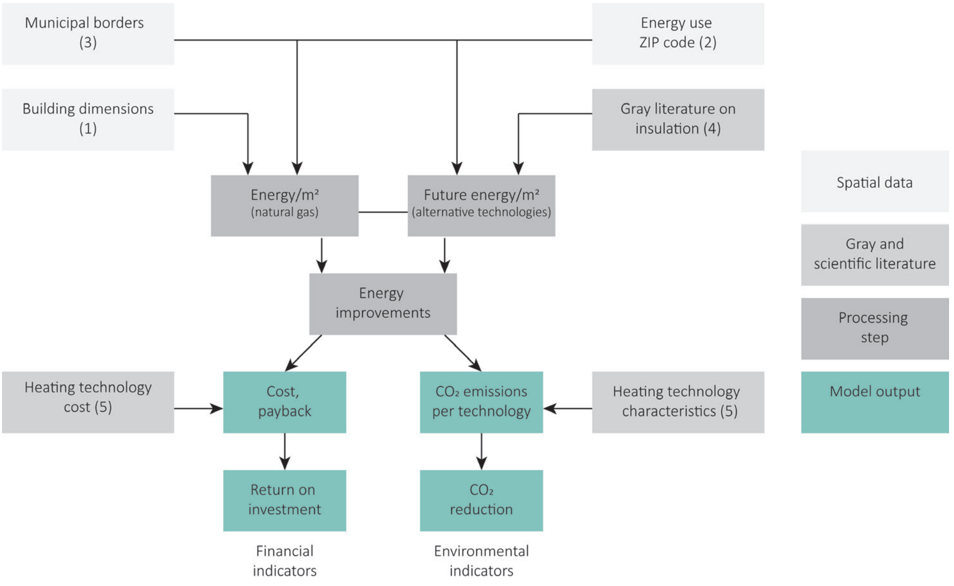
Through literature research we identified a selection of heating technologies that can act as a more sustainable replacement to the existing fossil-fuel based heating systems. Through the use of public GIS-data, we were able to analyse the impact of each technology on the Dutch built environment on a city-wide scale. In order to compare the impact each technology, we developed a Python-based model. We used GeoPandas, an open-source GIS Python package, to analyse multiple GIS-datasets. First, two spatial datasets were merged to create one coherent dataset containing building information. Second, the current and future energy consumption of buildings was calculated. Third, this information was used to determine the CO_2 emissions, operating costs and total investment cost. Finally, the return on investment and CO_2 reduction potential in comparison with the existing natural gas network was calculated. An overview of our model is shown in Figure 5, visualizing data flows and sources.

The Dutch government has placed the responsibility for the implementation of this heating transition on its local governments. Current policy plans focus on the replacement of heating technologies on a city-district scale. For the case study of our research, the city of The Hague is used because it represents a typical Dutch city with an old historical centre and a variety of building types in its outskirts.

3.2.1 Technologies

The current plan to replace natural gas for the most densely urbanised areas of the Netherlands is mostly based on using large scale HT heating networks. This network is envisioned to use waste heat from industrial areas to supply heat to multiple cities (known as the *warmterotonde*, or 'heating-roundabout' in the Netherlands). The use of these thermal sources is controversial, as this heat will mostly be sourced from refineries and other fossil-fuel related industries, potentially creating a technological lock-in with fossil energy sources (Ensoc & RVO, 2018).

The use of water-to-water heat pumps with a 12-kW heating capacity (around 200 m^2 of functional floor area) was assumed. Other heat pump technologies are available with different price ranges. However, these alternatives are more susceptible to extreme cold weather due to their dependency on the outside temperature (Petrović & Karlsson, 2016). Other heating technologies such as pebble heaters, electric resistance heaters, solar boilers, and infrared panels are considered as supporting technology and not capable of fully replacing natural gas as the main heating technology for a building (RvO, 2018).



Number	Data used	Processing steps	Source
1. Building dimensions	BAG3D GIS-dataset	Clipping to municipal border and spatial join with the energy use per ZIP code	(Kadaster, 2018)
2. Energy use per ZIP code	Gas & Elektra GIS-dataset	Clipping to municipal border and spatial join with the BAG3D dataset	(CBS, 2019b)
3. Municipal borders	CBS Wijk en buurtkaart 2017 GIS-dataset	Outline for the clipping of the datasets	(CBS, 2019a)
4. Grey literature on insulation	Building renovation steps & cost	Technological parameters used in the model	Appendix AII.V
5. Heating technologies characteristics	Multiple sources	Technological parameters used in the model	Table 1 & 2

Figure 5, overview of the information flows in the model:

Our analysis includes the infrastructure transporting the energy from the source to the residential buildings. Infrastructure investment in the electricity grid together with the digging of a well for heat pumps were taken into account. For the heating networks, the implementation of a city-wide heating network was assumed. Replacement of the in-house heating system (existing radiators) with an LT heating system was included in the calculation for the LT heating networks and heat pumps. For the HT heating network, we assumed that the old HT heating system remained sufficient as these are often oversized for reliability (Nord, 2016). All assumptions regarding the alternative heating technologies are available in Appendix AII.II.

3.2.1.1 Calculation of current and future heat demand

Building gas consumption (m^3/year) was compared with the potential future reduction in this heat demand. Natural gas consumption was converted from m^3 gas to kWh/m^2 on an annual basis. This calculation of the urban energy consumption was based on the paper by Nouvel et al., (2015). Different technologies and their energy sources are simpler to compare using kWh/m^2. The future heat demand was calculated and based on retrofitted buildings: including an increase in insulation, replacement of the heating technology and heating system.

The future heat consumption of the residential buildings was assumed to be around 70 kWh/m^2 per year after improving the insulation. This is roughly comparable to the average thermal performance the Dutch government aims to achieve for their future built environment (Rijksoverheid, 2017). This improvement in the thermal performance of a building also reduces the impact of a very harsh winter, which some alternative heating technologies are vulnerable to (Werner, 2018). Building heat demand improvements due to insulation were calculated as follows:

$$\textit{Future heat demand } (70)\left(\frac{\frac{kWh}{m^2}}{year}\right) = \textit{Current heat demand }\left(\frac{\frac{kWh}{m^2}}{year}\right) - \textit{insulation improvements }\left(\frac{\frac{kWh}{m^2}}{year}\right) \tag{1}$$

This difference in heat demand was used to determine the investment cost of insulation. Buildings were not given an increased amount of insulation in the model when consuming less than 70 kWh/m^2 per year.

3.2.1.2 Calculation of CO_2 reduction potential

In order to determine the CO_2 reduction potential of each alternative heating technology, the change in heating demand through insulation, the replacement of the heating technology and the efficiency of the corresponding infrastructure was evaluated. Each alternative heating technology was compared to the CO_2 intensity (g CO_2/kWh) of the existing natural gas system. Based on the reduction potential of each technology, we identified city districts most suitable for a certain alternative heating technology.

A coefficient of performance (COP) was used to describe the energy efficiency of the technology and infrastructure. Heating network transportation losses were assumed to be between 12 and 24%, depending on the technology (Lund et al., 2014). The lower value of 12% was used as the network losses for the LT networks, while the higher value of 24% was used for the HT networks. The heat pumps also have transportation losses from the electricity network, although these will be more marginal (Love et al., 2017). As a result, in the model, the CO_2 reduction is calculated as follows

$$CO_2 \textit{ reduction } \left(\frac{kg}{year}\right) = \frac{\textit{Heat demand } (kWh/year)}{COP} * CO_2 \textit{ intensity } \left(\frac{kg}{kWh}\right) \tag{2}$$

where the future heat demand of a building is used in kWh/m^2/year, COP as the efficiency of the technology and infrastructure, and the CO_2 intensity the CO_2-emissions of the used energy source in comparison with natural gas. The calculation of these CO_2 intensity values is shown in section 3.2.2, scenarios.

3.2.1.3 Calculation of investment cost and return on investment

For the return on investment, the total operating costs of running a natural gas-powered heating system was compared with the required investment and operating cost of the alternative technologies. The total investment cost in € per technology is defined as

$$\textit{Investment } (€) = C_{retrofit} + C_{heatsys} + C_{technology} + C_{\text{infra}} \tag{3}$$

The investment cost was calculated per building by taking the building retrofitting cost, replacement of in-house heating systems and the addition of a heat pump and/or heating network infrastructure. An overview of these costs is shown in Appendix AII.I.

Alternative technologies operating costs were based upon replacement costs, consumption of electricity or network heat with the improved insulation and standing charges. The replacement cost of the boiler, the consumption of natural gas and the standing charges were included. Current and potential future prices of heat, gas, and electricity were included to predict the influence of changing prices of energy on the overall system. A return on investment (ROI) per technology was calculated from the payback over 30 years (2020-2050) and the total investment costs.

For the replacement cost, a 15-year lifetime was assumed for both appliances, while for the heating networks a 50-year lifetime was used. For LT and HT heating networks the infrastructure investments were based on a large scale heating network project in the Netherlands (CE Delft, 2016). There is however a lack of sources to compare this number with. To illustrate which stakeholder (home-owners and heating network companies/government) will most likely pay for the technology, a breakdown of this investment cost per building was used. In Appendix AII.II, an overview is given of the cost per technology and sources.

3.2.2 Scenarios

Reduction in emissions and the pricing of alternative heating technologies determine their viability as an alternative to natural gas. Development of energy prices and possible governmental interventions influence the affordability and ROI of technologies. Furthermore, the source of heat for each chosen technology influences its CO_2 emission reduction potential. Its viability as an alternative to natural gas can be explored by looking into potential future developments. For all the technologies, we assume a city-wide implementation.

3.2.2.1 Available sources of heat

The three mentioned alternative heating technologies operate with different sources of heat. For this analysis, the most widely available sources and potentially sustainable sources of heat available in the Netherlands were evaluated (TNO, 2017). These sources of heat range from grey electricity to the use of PV panels for the heat pumps, geothermal and sustainable heat sources for the LT heating networks, and CC power generation and HT waste heat for the HT heating networks. An overview of these sources of heat and their CO_2 emissions per kWh of urban heat for heating networks are given in table 5. These sources of heat were compared based on a direct implementation of the technology and its source of heat.

In the first section of the results these sources of heat are compared in a city-wide implementation for each heating technology based on their current and potential CO_2 reductions. A steady-state implementation from 2020-2050 was assumed. The average CO_2 production per building in the case study is shown for each technology and source of heat. Additionally, these results are compared with the climate goals for 2030 and 2050 of the Dutch government.

Table 5a, CO_2 intensity per kWh of supplied heat for heating networks and heat pumps sources (MRA & TNO, 2017) (Stimular, 2016):

Energy source	Gram CO_2/GJ	gram CO_2/ kWh heat	CO_2 intensity (natural gas = 1)	Temperature
Natural gas		192.8	1	N/A
Biomass	13000	46.8	0.24	LT
Waste heat without additional burning	8800	31.7	0.16	LT
Geothermal	25050	90.1	0.47	LT
Heat from burning waste	26000	93.6	0.49	HT
Waste heat Tata Steel	26000	93.6	0.49	HT
Waste heat from gas fired power plant	32000	115.2	0.60	HT
Waste heat from coal fired power plant	45000	162.0	0.84	HT

Table 5b, CO_2 intensity per kWh of supplied heat for heat pumps (COP = 3.5):

Energy source	Gram CO_2/kWh electricity	gram CO_2/kWh heat	CO_2 intensity (natural gas = 1)
PV	50	14.3	0.07
'Grey' electricity	365.83	104.5	0.54

3.2.2.2 Cost effectiveness scenarios

Pricing is often used by governments as a method to regulate policy. The alternative heating technologies and possible future interventions of the government should also be included in the analysis to assess their cost-effectiveness. Examples of these pricing methods are: (a) the increase of the price of natural gas to promote the transition to alternative energy technologies, (b) increasing the tax on heat to stimulate the installation of insulation and more energy-efficient heating technologies, and (c) a CO_2 tax to make the reduction of CO_2 emissions more financially attractive. To implement these possible developments in the model, the following scenarios were used:

- An increased price of natural gas, 20% and 50% on average until 2050.
- A CO_2 tax of 50 euro per metric ton CO_2, and 80 euro per metric ton CO_2 (EU, 2016).
- Increased tax on heat with an average increase of 20% and 50% until 2050.

An overview of the impact of these scenarios on the input parameters is given in Table 6.

Another aspect of an alternative heating technology is its total investment cost. The build-up of the pricing of each technology is described in section 3.2.2.3. It is also possible that the overall cost is higher or lower than we anticipated in this research. To address this uncertainty, we included three investment cost ranges: the standard, low and high cost. For these low and high ranges, the total alternative heating technologies investment cost is varied with -5000 and +5000 euro to account for the uncertainty in technology and infrastructure pricing.

In the second section of the results, we compare the return on investment (ROI) across the cost effectiveness scenarios and the total cost ranges of the alternative heating technologies.

3.2.3 Data selection

The spatial datasets were supplied to us on a ZIP-code 6 level due to privacy concerns. On this spatial resolution, it was not possible to identify the different types of buildings and their age. As a result, the calculation of the future energy demand and potential reduction of CO_2 emissions was aggregated and less accurate for a building-level analysis. Buildings in the dataset with a residential occupancy and existing connection to the gas network were selected. The number of households per zip code is derived from the number of existing connections to the gas network.

Table 6, input parameters for each scenario:

	Cost effectiveness scenarios						
	Baseline	CO_2 tax low	CO_2 tax high	Price of natural gas +20%	Price of natural gas +50%	Increased heat tax +20%	Increased heat tax +50%
Price of natural gas (€/m3)	0.67	0.67	0.67	0.80	1.01	0.73	0.83
Price of electricity (€/kWh)	0.21	0.21	0.21	0.21	0.21	0.22	0.23
Price heating network heat (€/kWh)	0.067	0.067	0.067	0.067	0.067	0.067	0.067
CO_2 tax (€/ metric ton CO_2)	0	40	80	0	0	0	0

The datasets used in this model have their limitations. Occasionally the data was incomplete or inaccurate, skewing the results of our model. To extract these outliers, a filter on buildings with less than 200 m^3 of gas consumption per year or >400 kWh/m^2 per year was used. From the original 83.343 residential buildings in the dataset 66.598 were included in the model after removing incomplete or faulty datapoints. The original datasets were clipped to the boundaries of the case study to accommodate for more effective file size and processing time. Additionally, to determine the most influential input parameters a localized sensitivity analysis was used. The input values of the model were used for the baseline scenario, while these were adjusted with -10% and +10% to determine their impact on the output. The python code (named Python_code_appendix) and the output of the GIS model (named JIE_GIS_data) are included in Appendix II.

3.3 Results

3.3.1 The CO_2 emission reduction potential

Across all alternative heating technologies, we find that the CO_2 reduction potentials range from 41% to 95% (Figure 6). For HT heating networks, the CO_2 reduction potential ranges from 41% with heat from CC power generation (coal) to 65% with heat coming from waste incineration. For LT heating networks, the residential CO_2 production is reduced by 65% with a geothermal source and 90% when utilizing sustainable waste heat. Heat pumps with 'grey' electricity decreases the CO_2 emissions with 60%, which further decreases to 95% when electricity from PV panels is used.

Another important aspect is the CO_2 reduction from the improved insulation of a building. In Figure 2 we show that 33% of the reduction of annual CO_2 is achieved by the improved insulation. This reduction is identical for each technology as they use the same assumptions for the insulation and has nothing to do with the chosen technology.

With the more sustainable sources of heat (lower CO_2 emissions per kWh of supplied heat), LT heating networks and heat pumps are capable of reaching the required 90% reduction in CO_2 emissions. It is also worth mentioning that without the increased insulation, none of the heating technologies and sources will be sufficient for the 2050 climate goal. Besides replacement of the heating technology and source of heat, a reduction in the overall heating demand is required.

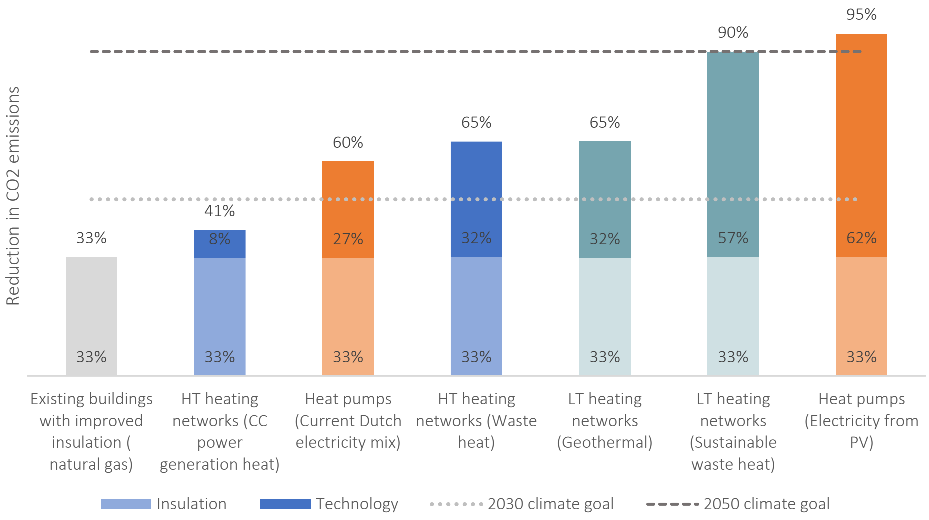


Figure 6, the impact of different sources of heat per technology on the CO_2 reduction:

Based on the spatial results shown in Figure 7, we identify several city districts particularly suitable for a particular sustainable heating technology. Some districts will still have a relatively high heat demand (mostly older buildings), even after refurbishment, and will therefore be more suited for a HT heating network. The distribution of the CO_2 emission reduction potential of the LT heating networks and the heat pumps are more evenly matched. The choice for these technologies will have to be based on the availability of local sources of heat. It is most likely that a combination of the technologies will eventually replace the current city-wide natural gas-based system.

3.3.2 ROI and investment cost

3.3.2.1 Return on investment

The ROI varies from -86% up to 28% across all technologies and scenarios. The ROI, calculated in the model for 3 different investment ranges and 7 future scenarios are shown in Figure 8. We find that in all scenarios the heat pumps have the highest ROI, ranging from -64% in the 'high-cost' baseline scenario, up to 28% in the most optimistic 'low-cost +50% price increase for the natural gas' scenario. Also, in this technology, the highest disparity between the different results is found. The LT heating networks ROI ranges from -74% for the high-cost baseline scenario and up to -1% in the low-cost scenario with a 50% price increase for natural gas. The variation of the ROI in the HT heating networks ranges from -86% in the high-cost baseline scenario up to -7% in the low-cost +50% price of natural gas scenario.

Even with economic incentives, none of the alternative heating technologies has a positive ROI. Only in a low-cost investment range and with a significant increase in the price of natural gas do the heat pumps have the potential to break even or generate a small profit.

3.3.2.2 Investment costs

Investment costs range from €37,000 to €44,000 between the technologies. Figure 8 provides a comparison of the investment per building for each technology in the standard cost baseline scenario. The investment per building for the heat pumps is the highest with €44,000, but still comparable with the HT-heating networks €40,000. LT-heating networks require €37,000 per building. From this result and figure 9 it becomes apparent that although heat pumps have the highest relative payback, only in very specific set of circumstances will this technology have a positive return on investment. Implementation across an entire city will require significant investment. In our case study, The Hague, investment costs range from 1.73 billion to 2.91 billion euros.

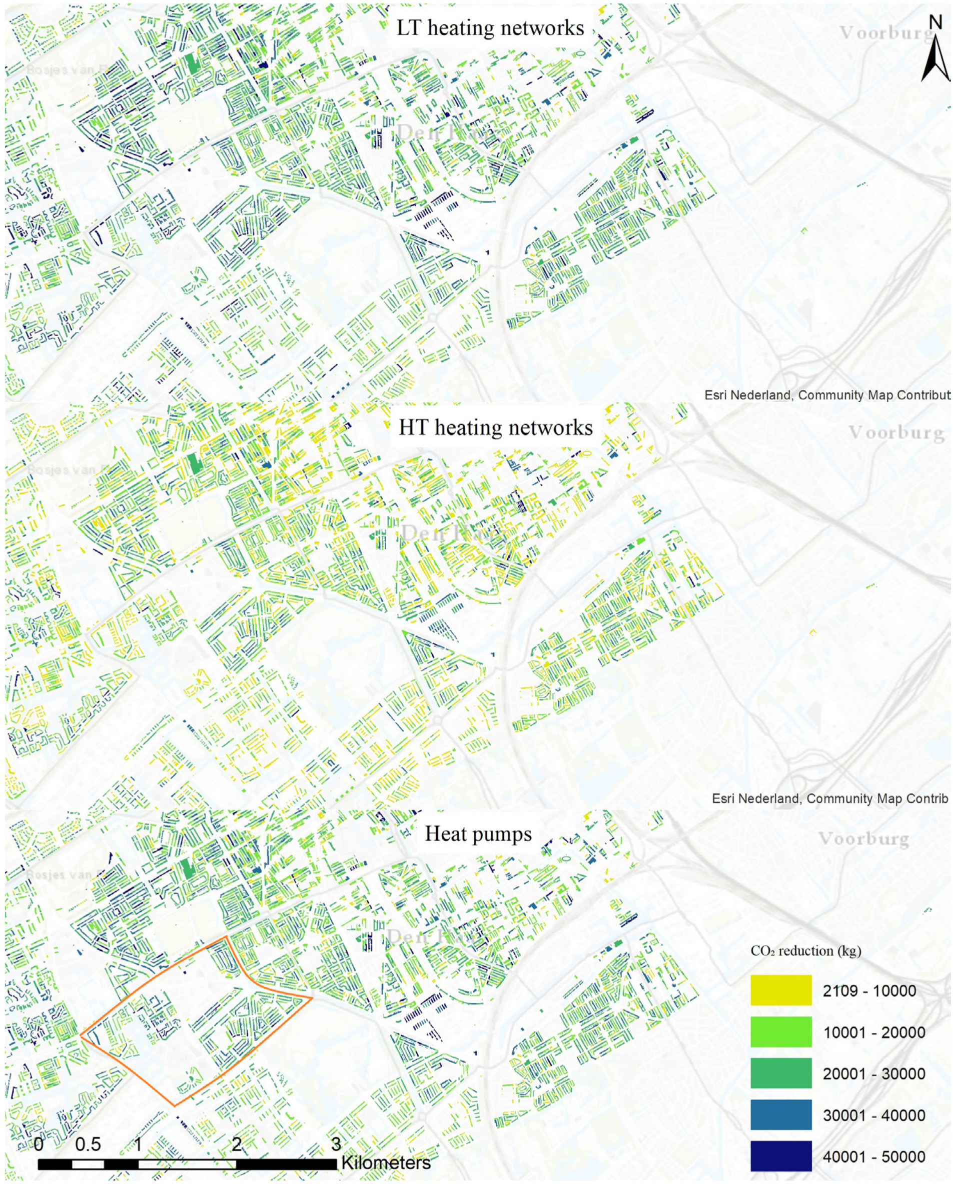


Figure 7, Annual CO_2 reduction potential for the alternative heating technologies per ZIP code in the city of The Hague (city districts best suited for a certain technology highlighted in orange): (a) LT heating networks; (b) HT heating networks; (c) Heat pumps.

The cost attributed to infrastructure improvements differs strongly per technology. For the heat pumps, €10,000 per building is required to improve the electricity network and dig a well. The cost of the heat pumps is the biggest factor in this technology as €23,000 per building is required. Both the heating network technologies require

€26,000 per building to construct the infrastructure. For the heating networks, this is the biggest expense. For each alternative heating technology, the investment in insulation for the case study is €10,700 per building. The technological investment for the LT and HT heating network technologies is between €175 and €4,000 per building. An overview of the investment per technology and subsections can be found in Appendix AII.II.

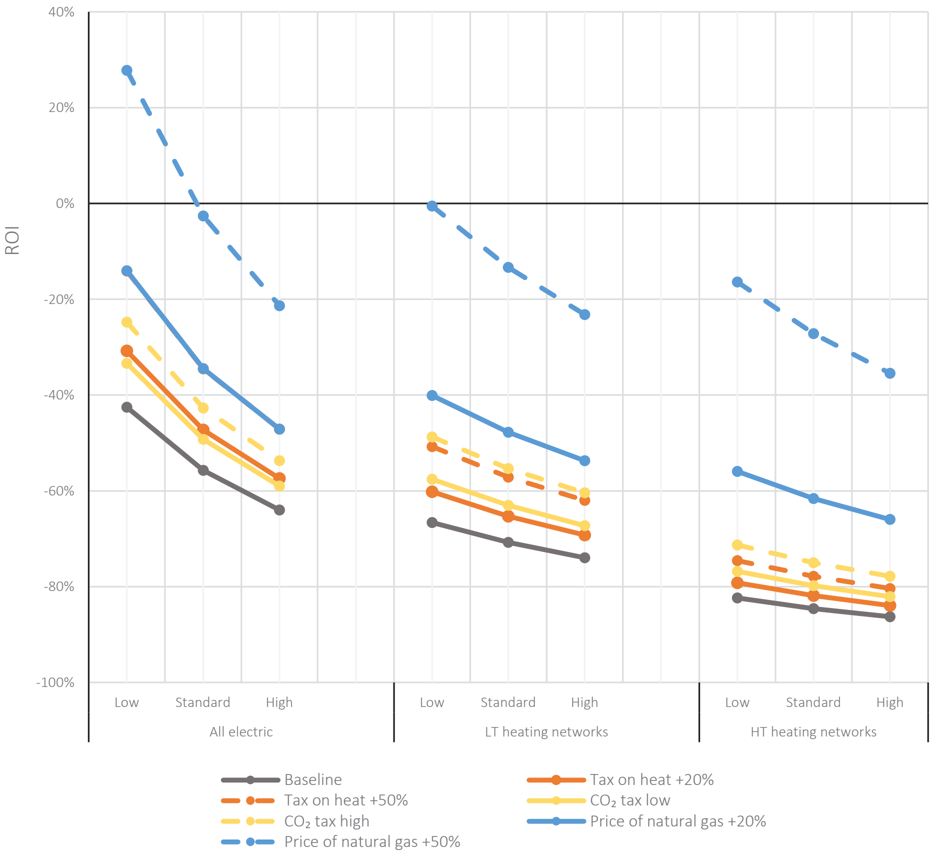


Figure 8, return on investment over 30 years for each investment range and cost effectiveness scenario in % (higher is better, tabular form provided in supporting information 6):

In the Dutch context, home-owners will pay for insulation and replacement of the heating technology, while the government and energy companies are responsible for infrastructure investments. Therefore, home-owners will be investing €15,000 for the heating network technologies and €34,000 for the heat pump technology. The government and/or energy companies will be investing €26,000 per building for the heating networks scenario and €10,000 for the heat pump scenario. Infrastructure investment has the most influence on the cost of the heating networks, considerably increasing their overall cost.

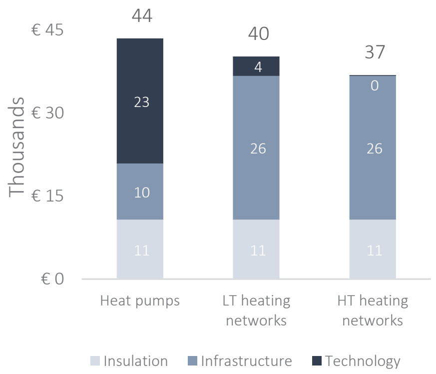


Figure 9, average investment cost in the standard cost scenario per building:

The results show that even with economic incentives the alternative heating technologies have a difficult business case. Only in the best-case scenario when the heat pumps are cheaper than expected, and with a significant increase in the price of gas will the technology investment generate a small return on investment. This means that, in contrast to insulation, the incentive to utilize alternative heating technologies will have to be different for home-owners. For example, making these technologies mandatory for newly constructed buildings and implementing subsidies from the government for the current building stock.

3.3.3 Sensitivity of the input parameters

Adjusting the input parameters with +-10%, the output of the model varied from +27% and -27%. The price of natural gas is the most influential input parameter with +-27%, while the COP varies the output with +-14% for the ROI. We show that the price per m^3 of natural gas is the most influential input parameter for this model on the ROI. This corresponds to the results in section 3.3.2, where increasing the price of natural gas with +50% leads to the highest ROI. It can also be observed that the COP has a positive influence on the CO_2 reduction. Heat pumps have a high COP in comparison with the other technologies, and consequently the highest CO_2 reduction potential. Additionally, the investment cost of the model is affected by the technology cost (infrastructure, insulations, etc), and its lifetime.

The results of the sensitivity analysis are in line with the high impact of the price of natural gas on the ROI in figure 10. The relatively high impact of the COP on the ROI also explains why the heat pumps generate the most ROI of all the alternative heating technologies.

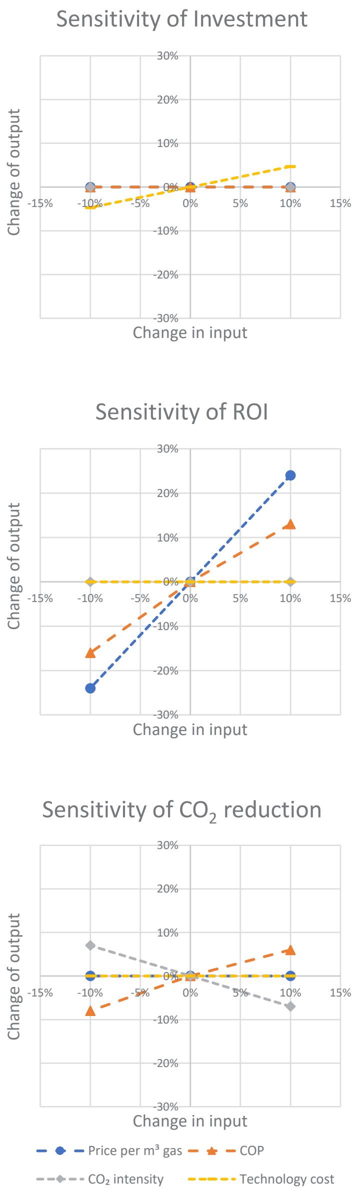


Figure 10, Sensitivity of the input parameters on the output of the model, (tabular form provided in Appendix AII.VI): (a) sensitivity of investment; (b) sensitivity of ROI; (c) sensitivity of CO_2 reduction

3.4 Discussion

Achieving a 90% reduction of CO_2 emissions requires a drastic change in the current Dutch heating infrastructure. This study provides a GIS-based model that clarifies the environmental and financial implications of the Dutch heating transition. We compared the implementation of HT heating networks with LT heating networks and water-to-water heat pumps on a city-wide scale. Besides contributing to the understanding of the 2030 and 2050 climate goals, the financial impact is shown to be of importance for multiple stakeholders in this research.

Through the modelling of the three selected technologies and the evaluation of multiple scenarios, we show that LT heating networks and heat pumps both have the potential to reach the Paris agreement goal (90% reduction of CO_2 emissions before 2050). HT heating networks could reach the 2030 climate goal (49% reduction of CO_2 emissions), but would significantly limit further reductions. Our findings underline the importance of the sources of heat in reducing the CO_2 impact of residential heating.

We show that the return on investment is generally negative for all technologies over 30 years if no changes are made to energy prices and taxes. Government intervention is required to improve the business case for alternative heating technologies and accelerate the heating transition. The total investment of around €40,000 per building is quite similar for each technology. The heat pump and digging of a well largely determine the investment cost for the heat pump technology. Most of the heat pump investments required for a building are likely going to be paid for by the home-owners, making it difficult to implement on a centralized large-scale. For the heating networks, the infrastructure investment dictates most of the costs. Also, the heating network infrastructure will be government-funded or laid down by the heating network companies, lowering the investment for the home-owner significant. Nonetheless, it is doubtful that every Dutch home-owner is able and/or willing to invest €15,000-€34,000 in the next 30 years with current energy prices and taxes.

The adjustment of energy prices or a CO_2 tax has the highest impact on the ROI of the heat pumps and the LT heating networks. With the right policies and tax instruments, they could surpass the break-even point. The results further limit the affordability of the HT heating networks considering they currently even lack taxation. In our model, we also show that the price of natural gas has the highest impact on the ROI of alternative heating technologies. Currently, the energy bill of a Dutch household is largely determined by the consumption of natural gas instead of fixed tariffs. Increasing the price of natural gas improves the business case for alternative heating technologies significantly, but also makes the cost of urban heating more expensive.

We believe that this research gives some insight into the CO_2 reduction potentials for the Dutch residential building stock. Replacing heating technologies is not sufficient on its own. Acquiring more sustainable sources of urban heat is also required to achieve significant CO_2 reductions before 2050. The development of long-term spatial planning and financial incentives, in cooperation with home-owners, is essential to accelerate this heating transition. Usage of HT industrial waste heat for the 2030 climate goal could limit further reductions in CO_2 emissions and obviate the 2050 climate goal.

In comparison with previous literature, we compared the environmental and financial impact of multiple heating technologies within the same case study. This alleviates the problem of comparing heating technologies across different climates and building types. Also, the inclusion of infrastructure and multiple sources of heat in our analysis gives a broader perspective on the consequences of this adjustment to a heating system.

Although we use GIS data, our results are currently not spatially explicit, beyond visually identifying spatial patterns on a district scale. Further research could identify the buildings most suitable for adjustment to a specific alternative heating technology. For example, a spatially explicit analysis could identify buildings which would be most suitable for HT heating networks. Also, comparing these heating options with further spatial characteristics such as available sources of heat and socio-demographic characteristics would provide a more in-depth spatial analysis. A further development of indicators, and the inclusion of more alternative heating technologies would also improve the outcomes of our model.

A limitation of this study is that we relied on implied data due to a lack of information on heating networks. Especially the infrastructure prices of the heating networks are generally unspecified. The price ranges of the heat pump technology and the chosen technology could also be debated. We were also unable to include inflation in the model. Lastly, the embodied energy of alternative heating technologies and their material impact is not included. With more fitting data this methodology can be easily updated and applied to other future scenarios.

3.5 Conclusion

This study highlights the differences between three main natural gas-free heating technologies, on their environmental, technical and financial aspects. Our main results show that the business cases for the alternative heating technologies is only profitable with the right combination of economic incentives. Without significant subsidies for existing buildings and home-owners, the financial implications could prove fatal for the heating transition.

We show that low temperature (LT) heating networks and heat pumps both have the potential to reduce the Dutch urban heat-related CO_2 output by 90%. A combination of these technologies could be used as an environmental and financial alternative to natural gas. However, these replacement technologies will require a considerable capacity of sustainable sources of heat to reduce CO_2 emissions by 90%.

A combination of policies together with subsidies will give home-owners a strong incentive to refurbish their buildings and lower the residential consumption of heat. In the larger context, our study shows that using industrial HT waste heat for residential urban heating in the *warmterotonde* will not be sufficient to achieve the 2050 climate goal.

Further research in this direction is encouraged to provide multiple energy evaluation tools for the heating transition. The development of this heating transition could also be influenced by energy storage solutions. At present, the use of energy storage is limited, but in the future, this could have a strong influence on the system (Petrović & Karlsson, 2016). Phase change materials (PCM's), improvements in battery technology and localized hydrogen storage present a potentially disruptive development for the overall energy grid (heat and electricity). The material demand for such a large-scale transition of an energy system could also influence, or even disrupt critical material supply chains (Sprecher et al., 2017). These developments should be considered in future research on this topic.

Acknowledgements
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Chapter 4

Matching Demolition and Construction Material Flows, an Urban Mining Case Study

Teun Johannes Verhagen
Marijn Louise Sauer
Ester van der Voet
Benjamin Sprecher

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Abstract

The recycling of demolition waste is essential to lower the construction sectors primary material demand, responsible for 50% of the global primary material consumption. Almost all demolition waste is used as filler material for the construction of roads, preventing further reuse or recycling after this application. The built environment generates considerable annual material in-and outflows. However, there has been little discussion on the availability and further application of this potential supply of secondary materials as a replacement for primary materials. In this study, we quantify the percentage of demolition waste that can be repurposed as secondary materials in the Dutch construction sector. We analyzed the yearly building material flows for the municipality of Leiden using municipal data on demolition and construction to explore the viability of the Dutch government's policy goal to reduce primary materials consumption by 50% before 2030. From this analysis, we find that the recycling of demolition waste has a sizable potential but just falls short of the stated policy goal. Even in a situation with more construction than demolition, there will remain a considerable mismatch in the yearly construction material demand and available supply of demolition waste for our municipal-wide case study. More importantly, the current processing of demolition waste in the Netherlands will require significant improvements to achieve this goal. New governmental policies are required to focus on maintaining material quality and allowing further use of recycled materials as buildings materials.

4.1 Introduction

The worldwide extraction of materials has tripled over the past 40 years. Driven by the urbanization of the developing world and an ever-growing population, the global demand for materials is expected to triple again before 2050 (IRP, 2016). The construction sector is currently responsible for a significant share (50%) of this material demand (UN Environment, 2017). In Western Europe, the construction sector accounts for 40% of primary material use (CRI, 2014). At the same time a substantial percentage of the built environment is demolished each year, especially in already developed urban regions, which generates large volumes of waste that could be reused as secondary construction material.

Currently, construction and demolition waste (C&DW) is most commonly reused as aggregates as road foundation (Di Maria et al., 2018). The materials are downcycled, and further reuse is not possible. To prevent this wasteful form of reuse, one can look at urban mining as a concept for reclaiming and high-level recycling materials from the built environment (Cossu and Williams 2015; Schiller, et al 2017).

Based on the European Commission's Circular Economy Action Plan, the Dutch government formulated its circular economy policy to reduce the country-wide use of primary materials (minerals metals and fossil fuels) by 50% before 2030, including the construction sector. (European commission, 2017)(Rijksoverheid, 2018b).

In this paper, we quantify to what extent secondary materials generated through urban mining could replace the primary material demand in the Dutch construction sector. We also explore the potential yearly mismatch between the building material supply and demand and its influence on the recycling of demolition waste. We use the municipality of Leiden as a representative case study for three reasons. First, it is a typical medium-sized Dutch municipality (around 125,000 inhabitants) with a lot of old historical buildings in the city centre and more modern surrounding areas. Second, based on the Dutch policy goals (Rijksoverheid, 2018b), the municipality of Leiden developed their building material policies (Municipality of Leiden, 2019). Finally, the municipality of Leiden has been registering data on demolition and construction work, which enables us to quantify the construction material demand and supply in this municipality over time. Our municipal-wide analysis provides implications for building material recycling for the Netherlands as a country. Furthermore, we analyse the yearly building material flows and explore the Dutch construction sector's goal to reduce primary material consumption by 50% before 2030 (Rijksoverheid, 2018b).

4.1.1. Building material stock dynamics and reuse potential

Recently, multiple building material databases have been published to harmonize the available data on building materials, enabling the comparison of studies and their data between multiple countries. Continuing on the earlier work by Kleemann et al. (2017) and Ortlepp et al. (2018), Heeren & Fishman summarized 301 building material data points across 21 countries (Heeren & Fishman, 2019). Using the currently available building data, Marinova et al. (2020) and Deetman et al. (2020) were able to estimate global building material stocks and flows for residential and service sector buildings.

Müller, (2006), established the cyclical behaviour of demolition and construction materials flows, with the availability of demolition waste lagging behind the construction material demand in size and time. Until a building stock is saturated, logically, a mismatch in the availability of demolition waste and the demand for construction materials will occur (Heeren & Hellweg, 2018a; Schiller et al., 2017). Numerous studies further developed the modelling of stock dynamics for a wider variety of construction materials and case studies, amongst others, for China (Hu, et al., 2010a; Hu, et al., 2010b), Switzerland (Heeren & Hellweg, 2018a; Ostermeyer et al., 2018), Luxembourg, (Mastrucci, 2017), Japan, (Tanikawa et al., 2015; Tanikawa & Hashimoto, 2009), Padua, Italy, (Miatto et al., 2019), US, (Reyna & Chester, 2015). Hypothetically, evenly matched quantities of demolition and construction material flows can lead to a closed construction material cycle. However, as noted by Heeren & Hellweg, (2018) it is important to further explore the recycling potential of demolition waste as secondary materials to achieve this.

Besides the studies that explored the dynamics of the building material stocks for a wide range of building materials, a few studies have been able to quantify the recycling potential of these building materials. Most of these studies focused on the recycling of a single material or material type, ranging from glass (Mohajerani, 2017), gypsum (Vrancken & Laethem, 2000) and concrete (Zhang et al., 2019) to metals (Graedel et al., 2011).

In the present study, we explore the topic of urban mining and C&DW, by quantitatively assessing the potential supply of secondary materials as a replacement for primary materials. By using real-world data sourced from a medium-sized Dutch city, we can quantify potential yearly (mis)match between the demand for construction material on the one hand, and the supply of demolition waste that realistically be reused as a construction material on the other hand.

4.2 Materials and Methods

We quantified the building material stocks and flows for 12 materials in the municipality of Leiden for the period 2019-2030. First, we calculated the municipal-wide material stocks and the material flows for this period using the information provided by the municipality on the demolition and construction projects planned between 2019 and 2030. The BAG3D, a dataset of the Dutch government containing GIS data on the Dutch building stock was used for the building properties (Kadaster, 2018). We used an end-of-life (EOL) collection rate to determine the demolition waste available for recycling. Based on scientific and grey literature, a recycled content potential in the production of new material was used to determine the maximum amount of demolition waste that can be used as a secondary construction material. Furthermore, to determine the reduction in primary material demand, the future demand for construction materials was compared to the potential yearly available supply of secondary materials.

When available, the yearly surplus of secondary materials was used to determine the overall material mismatch. In this research, we use our case study, the municipality of Leiden, and their available data on demolition and construction to explore the country-wide implications for the Dutch construction sector. The recycling of demolition waste within a municipal-wide boundary is a theoretical assumption and not necessarily the preferred option in a real-life situation. We will debate more on this topic in the discussion section.

4.2.1. Building typology and material intensities

Volumes of building materials were calculated using material intensity (MI) data derived from Sprecher et al. (2021), which compiled a MI database for the Netherlands. The average MIs in Sprecher et al., (2021) range from 604 kg/m2 for row houses to 2216 kg/m2 for apartments. Detached houses are among the most material-intensive building categories because foundations have a standardized minimal size and are over-dimensioned for this type of building. Apartments have the highest average MI as Dutch apartment buildings often include a parking garage. The other included building categories are more comparable, with an average MI of 604 to 1148 kg/m2. The MIs found for the Dutch built environment are in line with the findings of other studies (Sprecher et al, (2022).

In our analysis, the following building types are used for residential buildings: [a] detached houses, [b] row houses, [c] apartments, [d] high rise; for utility buildings: [e offices, [f] commercial buildings, and [g] other. Most of these building types were already included in the BAG3D dataset and could easily be identified. Only the high-rise buildings were identified separately as residential buildings with more than 5 floors (approximately 20 metres in height).

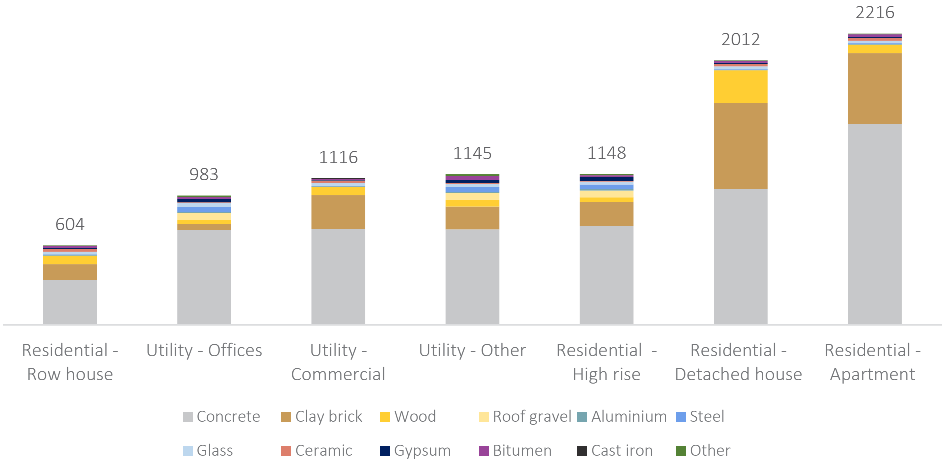

Figure 11. average MI in kg/m2 per building type (Sprecher et al, 2020):

The analysis includes structural materials and also materials extracted from window frames, ceilings, doorframes, etc. For the building materials, the following materials were included: concrete, brick, wood, roof gravel, glass, ceramic, gypsum, bitumen, steel, cast iron, aluminium, and other. The category 'other' contains a multitude of materials resulting from the demolition process which are difficult to identify and quantify. This category includes all the materials present in buildings that were not mentioned earlier in this paragraph. Figure 11 shows an overview of the average MIs per building type.

4.2.2. Modelling of the municipal-wide material stocks

To model the building stock, we combined the MIs with the BAG3D GIS database for the municipality of Leiden using a Python script and the GeoPandas Python package. For the Python script, see Appendix D. The BAG3D database contains the dimensions, location, year of construction and building type of each building in the Dutch built environment (Kadaster, 2018). Of the 38,990 buildings in the case study, 29,013 are residential and 9,997 utility. Buildings with less than 15 m^2 of functional floor area, representing sheds and small garage boxes, were filtered out of the dataset.

The MI per building type was projected on the GIS file of buildings planned for demolition. For each building, the material stocks were calculated, based on the building type, functional floor area and year of construction. As a result, the material stocks per building were calculated as follows

$$Materials_{j,k,l}\,(tonnes) = MI_{j,k,l}\left(\frac{tonnes}{m^2}\right) * Floor\ area\ (m^2) \qquad (1)$$

Where the MI for each material (j) is dependent on the building type (k) and the year of construction (l). For roof gravel and bitumen, the roof area was multiplied with the MI. To identify the density of material stocks in the municipality, the total amount of material per building was converted to tonnes per land-related area. In the first part of the results, the material stocks per material category and the total building weight are shown.

4.2.3. Modelling of the material flows and stocks for the period 2019-2030

The material supply and demand used in our analysis was based on present knowledge of the planned demolition and construction projects for the case study. Between 2019 and 2030, 585,483 m^2 of building floor area is planned to be demolished, while 995,480 m^2 floor area is scheduled for construction. The predictability of new materials flows as a result of the planned demolition and construction projects (the opening of new urban mines) allows a short-term forecast of supply and demand. The long-term development of this material supply and demand is more challenging because building material composition is influenced by more factors, such as the energy transition, increasing residential floor area per capita, and different buildings techniques. The overview of the annual planned demolition and construction per building type can be found in table A3.1 & A3.2 Appendix AIII.I.

The information provided by the municipality included the number of planned buildings to be demolished and constructed, m^2 of floor area, building types and construction timeframe. Material flows are also generated by refurbishment and repurposing of buildings, but these were not described in the construction and demolition dataset.

Materials involved in the demolition and construction projects were calculated based on the information of the building types and m^2 of floor area. With this method, we quantify the potentially available material for reuse in a circular economy and the possible mismatch of material demand and supply. The material flows resulting from demolition projects per building type for the period 2019-2030 are visualized and quantified in a Sankey diagram. For the years 2026-2028, there was no data available on the predicted construction and demolition of buildings. To fill this gap, we extrapolated the average demolition- and construction rate of the years 2019-2025, assuming a short-term continuity in the demolition and construction projects.

The demolition- and construction rate, or the yearly demolition/construction in tonnes divided over the total building stock in tonnes, was also included to explain the size of demolition and construction in comparison to the total building stock. This rate was calculated as follows

$$\textit{Demolition or construction rate}\ (\%) = \frac{\textit{Annual demolition or construction (tonnes)}}{\textit{Existing building stock (tonnes)}} \qquad (2)$$

The total material balance resulting from demolition and construction is calculated and visualized for each year in the period 2019-2030. To improve readability, only the two materials with the biggest mass are shown. This overview shows the yearly available materials for reuse and illustrates the difference in the available quantities from demolition and the construction demand over time. The extrapolated data for 2026-2028, no data was available for those years, is shown in the corresponding figure with a dotted pattern fill gradient. In Appendix B, the material balance per year is given for each material.

4.2.4. Available supply of secondary materials

To determine the viability of the stated policy goal to reduce primary material consumption in the construction sector by 50% before 2030, we calculated the share of primary material demand that can be potentially replaced with demolition waste. First, we determined the available supply of materials resulting from demolition within the case study and the given timeframe. Second, to determine the percentage of demolition waste that could potentially replace primary materials, we used an EOL collection rate and potential recycled content (IRP, 2011). The yearly surplus in secondary materials was defined as the mismatch in material supply and demand. Lastly, we quantified how much of these materials could potentially be recycled and utilized as secondary materials by using an End of Life recycling rate (EOL recycling rate) (IRP, 2011). The total available supply of demolition waste was determined with the calculation presented in section 4.2.3. The EOL recycling rate was calculated as follows

$$\textit{EOL recycling rate}\ (\%) = \frac{\textit{Recycled demolition waste (tonnes)}}{\textit{Available supply of demolition waste (tonnes)}} \qquad (3)$$

4.2.4.1. End-of-life collection of demolition waste

The recyclability of a material is not only determined by its intrinsic properties, but also by the quality of the recycling streams (IRP, 2011). For the demolition of existing buildings, we assumed the use of a circular demolition process. In this process, all the materials are individually harvested from a building to prevent contamination and mixing of material streams. For example, concrete is separately collected instead of mixed in the waste container with the other demolition waste. Smaller objects, such as doors and toilets, are separately collected and kept in good condition. This process is more time-consuming and more labour-intensive than conventional demolition, but it increases the EOL collection rate and the purity of the demolition waste (M. Baars, personal communication, March 2, 2020). The EOL collection rate was calculated as follows

$$\textit{EOL collection rate}\ (\%) = \frac{\textit{Demolition waste suitable for recycling (tonnes)}}{\textit{Available supply of demolition waste (tonnes)}} \qquad (4)$$

We determined the EOL collection rate for each material by conducting interviews with a Dutch demolition company. An overview of the EOL collection rate for each material is given in Table 7.

4.2.4.2. Recycling of demolition waste

Recycling is currently the most widely applied solution for the recovery of demolition waste as construction materials, while the reuse of building components is far less common (Di Maria et al., 2018). For our analysis, we assume the use of recycling for the processing of the demolition waste. To determine the potential maximum amount of primary materials that can be replaced with demolition waste, we used the recycled content potential (%). We defined this as the potential maximum fraction of secondary materials in the total input of material production (IRP, 2011).

Table 7. EOL collection rate and recycled content potential for demolition waste:

Material	EOL collection rate (%)	Recycled content potential
Concrete	85% (M. Baars, personal communication, March 2, 2020)	50% (Zhang et al., 2020)
Clay brick	95% (M. Baars, personal communication, March 2, 2020)	50% (Tam & Tam, 2006)
Wood	95% (M. Baars, personal communication, March 2, 2020)	90% (Hendriks & Pietersen, 2000)
Glass	95% (M. Baars, personal communication, March 2, 2020)	91% (Mohajerani, 2017)
Ceramic	95% (M. Baars, personal communication, March 2, 2020)	80% (M. Baars, personal communication, March 2, 2020)
Gypsum	95% (M. Baars, personal communication, March 2, 2020)	40% (Jiménez Rivero et al., 2016) (Vrancken & Laethem, 2000)
Bitumen	50% (M. Baars, personal communication, March 2, 2020)	50% (Tam & Tam, 2006)
Steel	95% (M. Baars, personal communication, March 2, 2020)	85% (Broadbent, 2016)
Cast iron	95% (M. Baars, personal communication, March 2, 2020)	96% (Broadbent, 2016)
Aluminium	95% (M. Baars, personal communication, March 2, 2020)	50% (Shamsudin et al., 2016)

For most of the mentioned materials, the main limiting factor of their recycling potential after ensuring the material quality and mechanical properties is the legislation regarding construction materials. While useful to standardize material characteristics, the current legislation limits the addition or recycling of secondary materials in the production process (M. Baars, personal communication, March 2, 2020). New legislation is required to achieve the mentioned recycled content potentials without adversely affecting the material properties whilst maintaining the structural integrity of newly constructed buildings.

Whereas policy on the recycling of demolition waste is designed and implemented by the Dutch national government, municipalities have a strong influence on a large number of tender contracts. Through requirements in tender contracts to at least use recycled materials, or the proper processing of demolition waste in a demolition project, the municipalities have a method to align the interests of the commercial construction and demolition companies with those of the local and national government.

The recycled content potentials of the different types of demolition waste were derived from multiple scientific sources (see Table 11 for the overview). By taking the recycled content potential per material from Table 7 and multiplying these with the material demand, we calculated the recycled content limits for each material. These limits were used to calculate the amount of primary material demand that can be replaced with demolition waste in our case study. In reality, the recycling of demolition waste will not be limited to the case study boundaries. During disposal, roof gravel is treated as dangerous waste as it contains multiple harmful chemical compounds (Hendriks & Pietersen, 2000), and therefore we excluded the material from the collection and recycling process in the analysis. Our calculations for the recycling of demolition waste can be found in Appendix AIII.III.

Though some materials theoretically have a recycled content potential of 96%, it is impossible to completely avoid the extraction of primary materials by recycling old materials. For example, in metals impurities and different alloy combinations makes it more difficult to recycle them and keep their desired material properties (Reck & Graedel, 2012) (Ellen McArthur Foundation, 2016). Primary material input will remain necessary to retain desired material properties, and this input is influenced by the quality of the recycled material (Reck & Graedel, 2012). The secondary materials available for use in the construction of new buildings were calculated by multiplying the EOL collection rate and the recycled content potential with the demolition waste. Based on the following, the availability of the secondary materials was calculated as follows

$$\begin{aligned}&Secondary\ materials_j\ (tonnes) = \\ &\quad demolition\ waste_j(tonnes) * EOL\ collection\ rate_j(\%) * Recycled\ content\ potential_j\ (\%)\end{aligned} \tag{5}$$

With the secondary material availability calculated for each material (j). This calculation is applied to the results in sections 4.3.2.1. and 4.3.2.2.

4.3 Results

4.3.1. Municipal-wide material stocks

The built environment of Leiden 2018 contains 18 x 10^3 kilotons of materials. The two largest material stocks are concrete (11 x 10^3 kilotons) and clay brick (4.0 x 10^3 kilotons). Wood, glass, steel and Gypsum stocks comprise between 0.64 x 10^3 and 0.18 x 10^3 kilotons. The smallest material stocks are ceramic, roof gravel, aluminium, cast iron and bitumen, ranging from 110 to 42 kilotons. Furthermore, in the total material stock, we found 930 kilotons of other materials. The material density of most buildings was measured at around 1 - 4 tonnes per m^2. For taller buildings in Leiden, material density varies between 5 and 30 tonnes per m^2 of ground space.

Figure 12. the material density of building material stocks in the municipality of Leiden:

Table 8a. building materials in Leiden (kilotons):.

Concrete	Clay brick	Wood	Roof gravel	Glass	Ceramic	Gypsum	Bitumen	Other
11,036	4,022	642	85	365	110	180	42	928

Table 8b. metals in buildings in Leiden (kilotons):.

Steel	**Cast iron**	**Aluminium**
197	53	63

The results presented in Figure 12 show that the material stocks largely consist of concrete and clay brick, followed by wood, glass, steel, and gypsum. Metals constitute relatively small stocks in the overall material composition.

4.3.2. Material flows resulting from construction and demolition for 2019-2030

4.3.2.1. Material flows resulting from demolition, aggregate 2019-2030

The demolition of buildings in Leiden for the period 2019-2030 will result in a total of 94 x 10^3 tons of material flows. As shown in Figure 13, concrete (63 x 10^3 tons) and brick (18 x 10^3 tons) account for the largest materials streams. The greatest share of the materials results from the demolition of apartment buildings, offices, high-rise and other types of buildings. Their material impact is explained by the fact the municipality plans to demolish a larger share of these building types. The other material outflows are ranging from 36 x 10^3 tons for wood to 5.2 x 10^3 tons for the other materials category. In Appendix AII.II, table A3.3 & A3.4 give this information the material flows for each year and building type in tabular format.

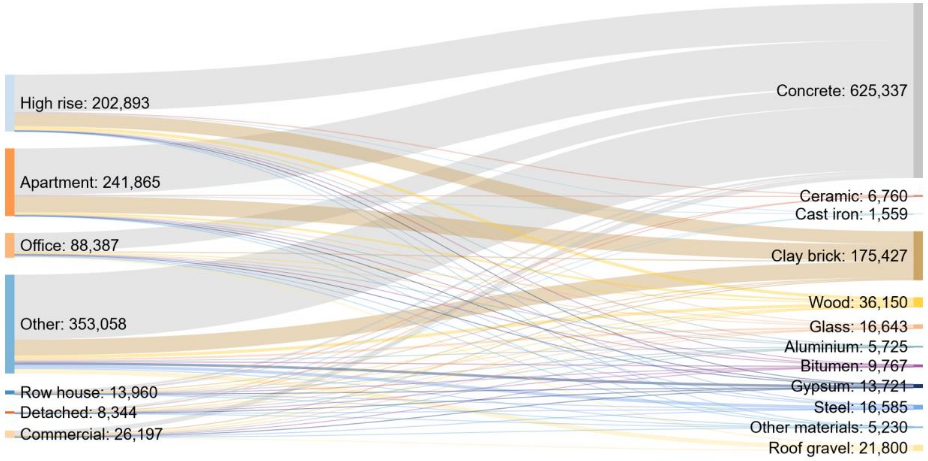

Figure 13. the aggregate material outflow per building type in Leiden based on the demolition plans over the period 2019-2030 (tonnes):

On average, we found an annual demolition rate of 0.7% and a construction rate of 0.8%. This means that each year the total mass of the building stock in our case study increases with 0.1%.

4.3.2.2. Secondary materials availability from demolition, compared to construction material demand on a timeline from 2019 to 2030

By matching of materials flow on an annual basis, we found that there is a greater demand for construction material than the volume of secondary materials that could be supplied locally from demolition projects. This deficit means that even with a full implementation of circular economy policies, there will be a primary material demand of 41 (2019) up to 170 (2025) kilotons per year within the case study.

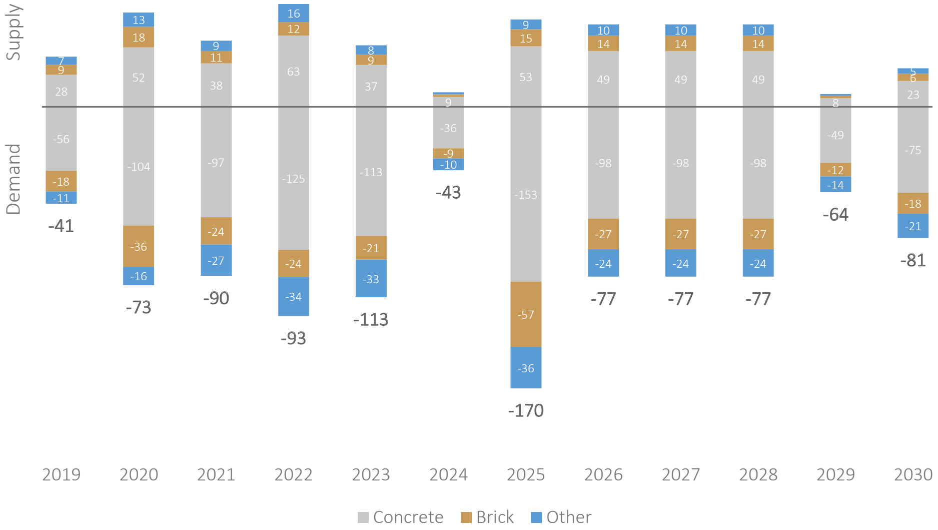

Figure 14. annual secondary material availability resulting from demolition (positive) and material demand from construction (negative) for the municipality of Leiden from 2019-2030 (kilotons, and extrapolated data shown with a pattern fill):

In Figure 14, we also observe considerable yearly differences between the availability of demolition waste and the demand for construction materials. The planned construction of buildings during the period 2019-2023 can be expected to generate a yearly material demand of 90 - 180 kilotons per year. The availability of secondary materials has a larger variability per year. Based on the available data for the period 2019-2023, demolition can be expected to generate between 10 – 90 kilotons of secondary material.

The overall trend in Figure 14 shows that the construction material demand during the period 2019-2030 exceeds the availability of secondary materials. This means that it is harder to match the material demand with the available secondary material supply from demolition, but in the long term, the high construction rate increases the recycling potential for the demolition waste within the boundaries of our case study. Between 2019 and 2030, 585,483 m² of building floor area is planned to be demolished, while 995,480 m² floor area is scheduled for construction. The material losses in the collection and recycling of demolition waste further increase the deficit between the secondary materials availability and the construction material demand.

4.3.3. Recycling potential and mismatch for secondary material flows resulting from demolition

On average, secondary materials can supply around 41% of the demand for construction materials in our case study city. Furthermore, around 66% of the available demolition waste within our case study can be recycling in the construction of new buildings for the period 2019-2030 (EOL recycling rate, the calculation in Appendix AIII.III, table A3.6 & A3.7). Within the theoretical limits of our chosen case study, meeting the material demand across all materials with secondary supply varies from 29% for bitumen up to 76% for cast iron. As shown in Figure 15, none of the materials surpasses the potential recycled content limits, allowing for a considerable recycling potential of materials. A downside of this situation is that there will remain a considerable demand for primary materials. For concrete, brick and gypsum, the recycled content limit could prove to be a limitation in a situation where construction and demolition are more evenly matched.

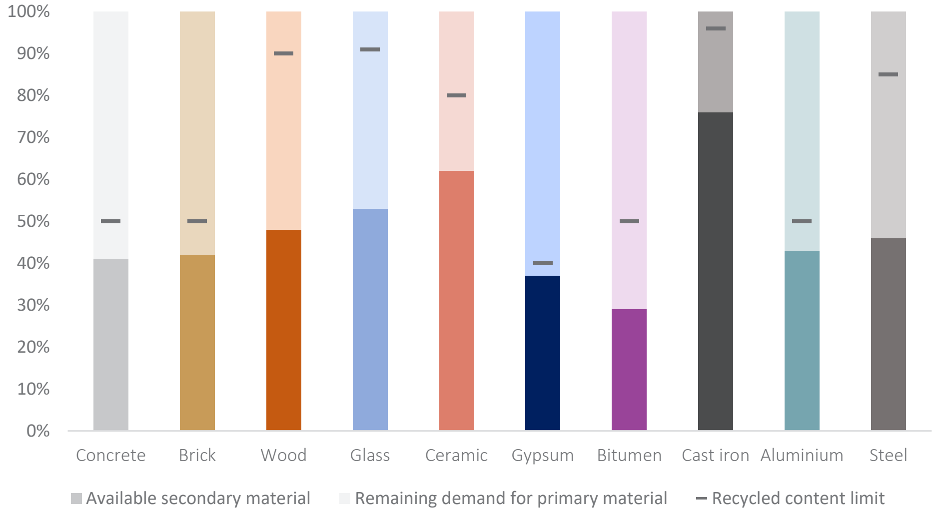

Figure 15. matching construction material supply and demand for Leiden including potential recycled content limits from 2019 to 2030:.

Of the available demolition waste, 20% cannot be recycled due to mismatches in the yearly demand and supply of demolition waste. Another 14% is collected during demolition as material not suitable for recycling (see Appendix AIII.III for the calculation). Matching the timing of demolition and construction projects could be considered to alleviate part of the problem of a mismatch between material supply and demand.

The results show that the Dutch policy goal of reducing primary material demand by 50% is not achieved. In a situation with a lower construction material demand, it will be even harder to recycle the available supply of secondary materials. However, a situation with more demolition would increase the number of secondary materials that could replace the primary material demand, especially since the share of recycled content in our case study could still be increased.

4.4 Discussion

Achieving a 50% reduction in primary material demand for the Dutch construction sector will require significant changes in the current processing of demolition waste. This study provides an analysis of building stocks and flows over time, showing the potential of Urban Mining in reducing primary material demand for the Dutch construction sector. A key innovation is that we used the real-world demolition and construction agenda of the municipality of Leiden to quantify and match building material flows on a year-to-year basis.

Our findings indicate a considerable potential for the recycling of demolition waste. The yearly demand for construction materials in our case study can be lowered by around 41% with the use of demolition waste, falling just short of the Dutch policy goal of 50%. Furthermore, around 66% of the generated demolition waste can be recycled and implemented in the construction of new buildings at its EOL. In our case study city, however, the demand for building materials was higher than the supply of secondary materials, enabling higher recycling rates. Crucially, we found that 20% of the demolition waste could not be recycled due to a mismatch in time, where construction material demand occurred in one year and suitable secondary material supply in another.

The results of this study illustrate the mismatch between the yearly supply of recyclable demolition waste and the demand for building materials. We found that in our municipal-wide case study, the material surpluses and deficits vary strongly per year. Overall, we found that the supply of secondary material is not enough to meet the demand for construction materials. The material losses in the collection and recycling of demolition waste further increase the deficit between the secondary materials availability and the construction material demand. Nevertheless, in some years, for some materials, there were more secondary materials available than required for local construction. We also found that the recycled content potential of construction materials can be a limitation for the recycling of some demolition waste (concrete, brick, gypsum and aluminium) in a situation where building demolition and construction are more evenly matched than in our case study.

While most Dutch municipalities do not have the local capacity to recycle their demolition waste, they can ensure the proper processing of this waste. Policy goals on the recycling of demolition waste are set by the Dutch national government, whereas the demolition waste is recycled by commercial companies, leaving the municipalities in an intermediary position. For example, in tenders with construction companies, municipalities can specify requirements regarding the use of secondary materials. Furthermore, the reduction in primary material demand can be used by municipalities as an indicator for circularity. However, a potential alternative measure of the local recycling of demolition waste could focus more on quantifying the recycling of the municipal-wide produced demolition waste. For municipalities, the challenge is to align the interests of the construction and demolition companies to ensure the proper processing of demolition waste, and to increase the demand for recycled materials.

All this implies that it will be challenging to fully close the Dutch construction and demolition waste cycle. Besides the potential mismatch in building material supply and demand, historically the extent of construction has generally exceeded the extent of demolition. Furthermore, the increasing demand for more floor space per capita further increases the average material demand for each resident. Even in a situation without additional building stock growth, the collection and recycling process cannot recycle 100% of the generated demolition waste, leading to continued demand for primary materials.

Dutch legislation for construction materials should be considered as another limiting factor in the recycling of demolition waste is the current. While it is useful to ensure quality standards for new materials, the current legislation never considered the recycling of old demolition waste on a significant scale. Therefore, construction companies regard the use of demolition waste as secondary materials as a potential risk (M. Baars, personal communication, March 2, 2020). New governmental policies are required to focus on retaining material quality while allowing further use of recycled materials as building materials.

A limitation of this study is the uncertainty of demolition and construction planning. We also assumed that the material composition of buildings will remain the same in the next decade, while some future developments will influence the size and composition of these materials stocks. The growing population of the Netherlands will increase the need for housing and consequently all materials. Also, the energy transition drives higher demand for metals and insulation, while bio-based building techniques will increase the share of bio-based materials (Kleijn et al., 2011; Ostermeyer et al., 2018).

4.5 Conclusion

In conclusion, our results show that the current processing of demolition waste in the Netherlands will require significant improvements to achieve the Dutch government's goal of reducing its construction sectors primary material consumption by 50%. This goal can only be reached if there is enough secondary material supply in comparison with the construction material demand. Our case study shows a deficit of demolition waste, enabling high recycling rates. Besides the recycling of demolition waste, new governmental policies are required to stimulate the use of secondary materials in the construction of buildings. For municipalities, the challenge is to specify requirements for their construction and demolition tenders to ensure proper processing and use of the construction materials. This study may provide a starting point for a country-wide analysis of material stocks and flows and the potential recycling of demolition waste as secondary materials.

A natural progression of this work is to analyse the impact of future building material composition on the recycling of demolition waste. More broadly, a comparison of the material supply and demand in multiple cities or municipalities could help generate further insight into building stocks and flows, and clarify on which scale a circular economy of building materials can operate.

Acknowledgements
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Chapter 5

Transitioning to Low-Carbon Residential Heating: The Impacts of Material-Related Emissions

Teun Johannes Verhagen
Ester van der Voet
Benjamin Sprecher

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Abstract

To achieve climate neutrality, future urban heating systems will need to use a variety of low-carbon heating technologies. The transition towards low-carbon heating technologies necessitates a complete re-structuring of the heating system, with significant associated material requirements. However, little research has been done into the quantity and environmental impact of the required materials for this system change. We analyzed the material demand and environmental impact of the transition towards low-carbon heating in the Netherlands across three scenarios based on the local availability and capacity for sources of low-carbon heat. A wide range of materials is included, covering aggregates, construction materials, metals, plastics and critical materials. We find that while the Dutch policy goal of reducing GHG emissions by 90% before 2050 can be achieved if only direct emissions from the heating system are considered, this is no longer the case when the cradle-to-gate emissions from the additional materials, especially insulation materials, are taken into account. The implementation of these technologies will require 59 to 63 megatons of materials in the period 2021-2050, leading to a maximum reduction of 62%.

5.1 Introduction

The worldwide heating demand for buildings and associated greenhouse gas (GHG) emissions has in recent years been increasing at a rapid pace, currently accounting for 6% of global GHG emissions. The annual global heat consumption of buildings has increased from 26 EJ in 2000, to 32 EJ in 2020 (Isaac & van Vuuren, 2009; Planbureau voor de Leefomgeving, 2019). In line with the Paris agreement, the Dutch government set the goal to reduce its national heating-related GHG emissions by 90% before 2050 (compared with 1990) (Rijksoverheid, 2017). The Dutch heating system is predominantly natural-gas based, unlike in many other countries, making it an interesting contemporary case study (Xining & Steubing, 2021). To achieve the goal of the Dutch government, it is crucial to transition the Dutch natural-gas based heating system to low-carbon heating technologies, which we will refer to as the heating transition ("*warmtetransitie*" in Dutch).

The heating transition is one element of the larger energy transition, which has been studied extensively from the perspective of material intensity and the materials required for building up the renewable energy system and associated infrastructure (van Oorschot et al., 2022; Zhang et al., 2021). For example, the material stock of the electricity system will increase significantly with the development towards a renewable energy system (Deetman et al., 2021; van Oorschot et al., 2022). The implementation of low-carbon electricity technologies also increases the demand for metals, which have a considerable environmental impact (Kleijn et al., 2011). The energy transition will decrease the operational GHG emissions of energy generation, but at the cost of an increased material intensity (Sprecher & Kleijn, 2021). This could also be true for the heating transition, but this has not been researched yet.

While previous studies have shown that operational heating-related GHG emissions can be considerably reduced by the use of low-carbon heating technologies, such as heat pumps and heating networks (Francisco Pinto & Carrilho da Graça, 2018; Verhagen et al., 2020), the transition to a low-carbon heating system also has consequences for the existing heating system and its material composition. The current Dutch heating system operates on natural gas, utilizing a country-wide gas transmissions network. This existing heating system, including in-house heating, infrastructure, and energy production, will have to be adapted to accommodate low-carbon heating technologies that operate on different sources of heat. Low-carbon heating technologies such as low-temperature (LT) and high-temperature (HT) heating networks utilize a network of underground pipes for heat transmission, while heat pump technologies are dependent on the electricity grid and will require additional grid capacity (Love et al., 2017). The implementation of these low-carbon heating technologies requires additional - and different - materials compared to the current heating system (Deetman et al., 2018; Elshkaki, 2019; Elshkaki & Graedel, 2013; Kleijn et al., 2011; Love et al., 2017; Seck et al., 2020).

It has been well established that part of the operational GHG emission reductions achieved by low-carbon heating technologies could be undone by the increased emissions related to the production of the materials required for these technologies (Greening & Azapagic, 2012; Heeren et al., 2013; Kleijn et al., 2011; Koezjakov et al., 2018; Oliver-Solà et al., 2009b). However, to the best or our knowledge, no research has been done on the system-wide influence of the material-related emissions of this heating transition. In particular, no research has been done to assess the combined material demand of the production of low-carbon heat, the material demand of the necessary adjustments to residential buildings, and the material demand related to the energy infrastructure required for the implementation of low-carbon heating technologies.

This work assesses the material-related cradle-to-gate emissions of the future Dutch heating system, and integrate this assessment with the outcomes of previous work on the operational emissions of the future Dutch heating system. We analyse the feasibility of the Dutch policy goal with three future development pathways of the Dutch heating system, based on the local availability and capacity for sources of low-carbon heat.

5.2 Method and data

Four low-carbon heating technologies commonly found in the literature and policy documents were selected. We searched grey and scientific literature for information on the quantities of materials required for the implementation of these four low-carbon heating technologies in residential buildings in the Netherlands, supporting infrastructure and the corresponding production of electricity or heat. The BAG, a Dutch governmental dataset with information on building types and floor area was used to determine the number of residential buildings and dwellings in the Netherlands (Kadaster, 2021). Subsequently, this information was then used to calculate the materials required for each low-carbon heating technology per residential building.

Three scenarios of the material stock and inflow for the future Dutch heating system were modelled with a dynamic stock model. These are based on the scenarios by Berenschot, (2020) (Berenschot, 2020a). For the in- and outflow of materials, we used lifetime distributions from literature for each subcomponent of low-carbon heating technologies (see section 5.2.5 and Table A4.3 in the SI for the detailed overview). The three scenarios also include assumptions on the composition of the future electricity grid, which we included in our model. Next, the cradle-to-gate emissions in CO_2-equivalent (CO_2-eq) of the materials were calculated for each scenario. Lastly, these emissions have been integrated with the operational emissions in CO_2-eq of the heating system, that we assessed in a previous publication (Verhagen et al., 2020), to arrive at an estimate for total emissions in CO_2-eq related to Dutch residential heating. In addition, we compared the system-wide emission impact of this transition towards low-carbon heating with the operational emissions of the current natural gas-based system. The conceptual outline of the model is given in Figure 16. The material intensity values for the implementation of each heating technology can be found in Appendix AIV.

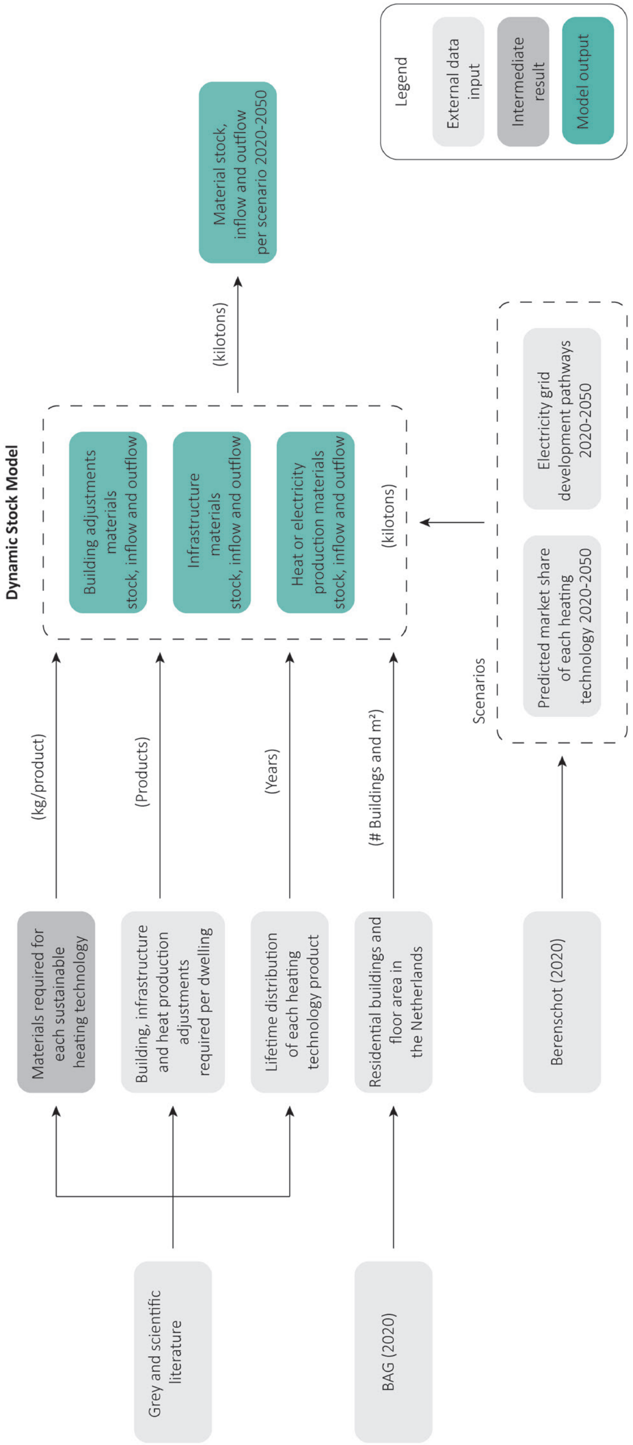


Figure 16, the conceptual outline of the model:

5.2.1 Low-carbon heating technologies and model assumptions

The following technologies are analysed in this research: high-temperature (HT) heating networks, low-temperature (LT) heating networks, heat pumps and hybrid heat pumps. We based this selection on our earlier study Verhagen et al., (2020) and added hybrid heat pumps (Verhagen et al., 2020). We analysed three subcomponents of the Dutch heating system: the required building adjustments (for example, the heat pump, insulation, floor heating and low-temperature radiators), the infrastructure required (heating network, electricity grid, etc) and the heat and electricity production (geothermal district heating, solar panels, windmills, biogas fired power plant). For all technologies except the HT heating networks, we also assumed the installation of floor heating in the buildings. We segregated the residential buildings in the Netherlands into five building types: apartments, corner houses, terraced houses, semi-detached houses, and detached houses. This corresponds to the classification used in the BAG-GIS dataset, which was also used to calculate the number of dwellings and floor area per building type.

For LT and HT heating networks, we based the in-house and infrastructure adjustments on the study by Oliver-Solá et al., (2009) (Oliver-Solà et al., 2009b). We assume the installation of a heat exchanger, in-house distribution pipes for the heating network heat, and the installation of a HT or LT heat network on a neighbourhood scale (Moss et al., 2013; Sullivan, 2010). Based on the report by Berenschot, (2020), the heat production of HT heating networks is assumed to be the waste heat from a biogas-fired power plant, while for LT heating networks we assumed the use of geothermal heat (Basosi et al., 2020). In the Netherlands, geothermal heat is extracted from wells reaching a depth of 2000 meters (Ecofys, 2018). For the production of HT waste heat, we assumed that gas-fired power plants operate on biogas or hydrogen in the future, and that these power plants have a consistent material composition (Spath & Mann, 2000; Vestas, 2019; Weinzettel et al., 2009) .

The most widely implemented heat pump technology in the Netherlands is the air-to-water heat pump since its initial investment is lower in comparison with water-to-water heat pumps (Rijksoverheid, 2018a). We used the study by Greening, B. & Azapagic, A (2012), for our material inventory of a 10 kW air-to-water heat pump (Greening & Azapagic, 2012). For every building type except apartments, we assume the installation of a heat pump for each separate dwelling. For apartments, we assume a heat pump for every 150 m^2 of floor area, as a heat pump can be shared across multiple dwellings in an apartment building. The use of air-to-water heat pumps influences the composition of the electricity grid (Harrison et al., 2010; Jorge et al., 2012), which we further discuss in section 5.2.2.2. For the electricity used by the heat pumps, we assumed a combination of biogas-fired power plants, onshore and offshore windmills and PV panels as specifief by Berenschot, (2020) (Berenschot, 2020b).

For the material inventory of hybrid heat pumps, we also used the study by Greening & Azapagic, (2012). We scaled down the material inventory from the 10 kW heat pump used in the source to a heat pump with a smaller 6 kW capacity used in the hybrid heat pump technology (Greening & Azapagic, 2012). Furthermore, we also included the material inventory of a small CV boiler from the study by Oliver-Solá et al., (2009a) (Oliver-Solà et al., 2009a). Just as our air-to-water heat pump assumptions, the use of a hybrid heat pump influences this grid composition as discussed in section 5.2.2.2. We also modelled an identical composition of electricity production technologies and the shared use of hybrid heat pumps in apartment buildings. For the peak boiler in the hybrid heat pumps, we assumed the use natural gas as the energy source as it is still unclear whether there will be enough future production capacity in the Netherlands of renewable gasses such as hydrogen or biogas (Berenschot, 2020a).

5.2.2 Material demand for the implementation of low-carbon heating technologies.

The material demand for the implementation of low-carbon heating technologies were calculated in kg of material required per dwelling connected to the Dutch heating system (shown in 5.3.1 of the results section). This includes the building adjustments, infrastructure extensions and the additional required heat or electricity production. An overview of the materials included in the model is given in table A4.5 of Appendix AIV.II.

The sources of the required materials for the implementation of low-carbon heating technologies range from scientific literature to grey literature and the Ecoinvent database. We used the Ecoinvent database and literature to assess the materials included in, for example, a heat pump, or geothermal district heating. For each technology and subcomponent, we calculated their cradle-to-gate emissions in CO_2-eqbased on their material composition. The packaging materials were excluded from our material inventory. An overview of the materials included and quantified in our model is given in Appendix AIV.II, and the detailed specification of materials required per heating technology connection per household is provided in Appendix AIV.III.

For the inclusion of insulation suitable for low-carbon heating technologies in Dutch buildings we used the study by Koezjakov et al., (2018) (Koezjakov et al., 2018). We included expanded and extruded polystyrene (ground floor and foundation), mineral wool (roof and walls), polyurethane foam (ground floor and façade) and wood fibreboard (foundation and façade). For the heating network technologies, we included the foundation, façade, roof and wall insulation options. For the (hybrid) heat pump technologies we included all the mentioned insulation materials as heat pumps require a higher degree of insulation to operate efficiently. These materials were also calculated in kg of material required per dwelling connected to the Dutch heating system for each technology.

5.2.3 Consequences of the heating transition for the electricity demand

This transition towards low-carbon heating technologies in the Netherlands results in an increased consumption of electricity. The existing electricity grid will have to be reinforced to accommodate the additional load of heat pumps and hybrid heat pumps.

To calculate the impact of the heat pump and hybrid heat pump integration into the electrical grid, we modelled a case study in a typical European low voltage (lv) grid. First, we calculated the current demand in the grid by modelling the average electricity consumption of households within a theoretical city district. This model provides the basis for the operating conditions of the electrical grid before the electrification of heating systems. Next, we started integrating heat pumps into the grid and analyzed the changes in the demand and operating conditions of the grid. We calculated the materials for the addition of the heat pumps technologies based on the required increase in lv grid capacity. In Appendix AIV.I, we discuss the steps of this analysis of the electricity demand development and the results in detail.

5.2.4 Development pathways of the Dutch heating system

We included three scenarios on the composition of the future Dutch heating system in our analysis: a mixed scenario with mainly LT heating networks and heat pumps, a high heat pump scenario, and a high hybrid heat pump scenario. Our scenarios are based on the *warmtescenario* report by Berenschot (2020), which explores multiple heating system pathways for the Netherlands from 2020-2050 (Berenschot, 2020a). In their analysis, the local availability and capacity for sources of low-carbon heat were considered. Even though each scenario has a different dominant technology, their market share composition does not differ that much (overview in Table A4.4a in Appendix AIV.II). For each of our three scenarios, we varied the electricity generation composition to simulate different developments based on the *klimaatneutrale energiescenarios*, or climate-neutral energy scenarios report by Berenschot (overview in Table A4.4b in Appendix AIV.II) (Berenschot, 2020b). In the absence of time series information, we assumed a linear increase in low-carbon heating technologies market share over time to replace the existing natural gas heating system. The scenarios only explore the composition of the future Dutch heating system. In the Berenschot report, no variation in the total heating demand between different scenarios is assumed. Although having variations in heating demand might have made the scenarios more differentiated, we chose to not adapt the scenarios for our work, as that would negatively influence the ability of policy makers to consider our work together with the outcomes of the Berenschot report.

5.2.5 Dynamic stock modelling

In this section, we describe how we estimated the stocks, in-and outflow of materials for each heating technology. They are based on the number of dwellings using a low-carbon heating technology, the materials required for the implementation of the low-carbon technologies per dwelling, and their expected lifetime. The Dutch population growth expectation from 2021-2050 was used to estimate the increase in dwellings over time (2021). With a stock-driven dynamic stock model we calculated the material demand (inflow), outflow (waste) and in-use stock over time related to the Dutch heating system, from 2020-2050, for each heating technology subcomponent (building adjustments, infrastructure and heat or electricity production) (Pauliuk, 2018). Based on the stock, we determined the in-and outflow with a distributed life span (L) using a Weibull function. In the model, for the calculation of a stock (S), in and outflow at certain years (t) the following function was used

$$Inflow\ (t) = S(t) - S(t-1) + Outflow\ (t) \tag{1}$$

For the calculation of the material stock over time, we multiplied the number of dwellings utilizing low-carbon heating technologies with the materials required for each heating technology subcomponents (buildings adjustments, infrastructure, and energy production). The sum of these three subcomponents is the total amount of materials required per dwelling for a low-carbon heating technology. The subcomponents of a system get only replaced based on their own lifetimes. The in-and outflow of materials for each year was calculated based on the subcomponents and their average lifetime distribution with the dynamic stock model, resulting in the following formula

$$Outflow(t) = S(t) \times L(t, t') \tag{2}$$

The inflow was calculated as the difference between the addition to the stock, and the calculated outflow in a year. Where Weibull distribution parameters where not available, we used standard Weibull distribution values based on the average lifetime distributions of the subcomponents of the heating system. Stock accumulation models are mainly sensitive to the average lifespan, and almost insensitive to the choice of lifespan distribution function (Miatto et al., 2017). In Table A4.3 of Appendix AIV.II, an overview of the mean lifetimes and source for each low-carbon heating technology subcomponent is given.

5.2.6 Operational and cradle-to-gate emissions of low-carbon heating technologies

For the system-wide analysis of the Dutch future heating system, we quantified the operational - and the cradle-to-gate GHG emissions measured in kg CO_2-eq of the material inflow over time from 2021-2050. To calculate the cradle-to-gate impact of the materials, we used the EcoInvent 3.4 database and CMLCA 6.1 software. We only looked at the impact of the production of the materials present in a product, but not at the production of the product itself.

The operational greenhouse gas (GHG) emissions were based on Verhagen et al., (2020), and reported in kg of annual CO_2-eq per heating technology. This impact includes the emissions from electricity, that replace natural gas-based emissions. We used the average heat consumption in kWh per dwelling in the Netherlands in 2020. We also included improvements from insulation, lowering the average energy demand for space heating in a dwelling by 60%. The total emissions produced by a low-carbon heating technology for the production of a kWh of heat are calculated in a CO_2 intensity value. The CO_2 intensity value includes transportation losses from infrastructure and the production of heat from the corresponding sources as described in section 5.2.2. As a result, the annual operational CO_2 emissions per dwelling were calculated as follows:

$$CO_2\ emissions_i \left(\frac{kg}{year}\right) = average\ heat\ demand \left(\frac{kWh}{year}\right) \times CO_2\ inter \tag{3}$$

Based on the market share and number of dwellings for each low-carbon heating technology (i), the total operational emissions per scenario were calculated. In section 5.3.5 we assess the cradle-to-gate and operational emissions from 2021-2050 We also included the operational emissions in CO_2-eq of natural-gas based heating systems based on the paper by Oliver-Solà, J., Gabarrell, X. & Rieradevall, J, (2009) as a Business As Usual (BAU) scenario (Oliver-Solà et al., 2009a). For this scenario, we assumed that 95% of the Dutch households keep utilizing the natural gas-based heating system.

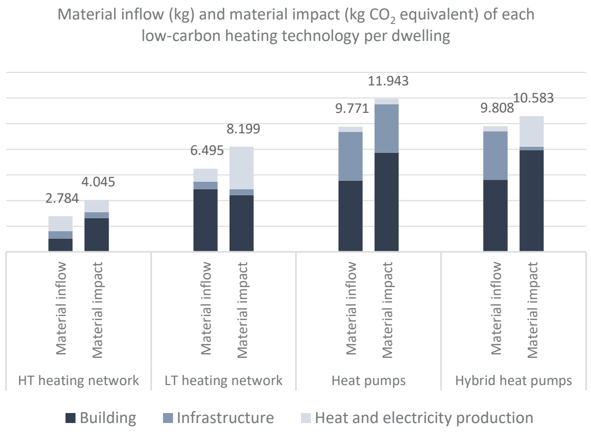
5.3 Results

5.3.1 Material requirements and cradle-to-gate emissions of low-carbon heating technologies per dwelling

The most material-intensive technologies are the heat pump and hybrid heat pump technologies. For these two technologies, the majority of the material requirements is due to the infrastructure and building adjustments, while a small fraction of their material requirements results from heat and energy production. For the LT and HT heating network technologies, the largest share of their material requirements is generated by building adjustments and the required heat production. The material requirements of HT heating networks are substantially lower than the material demand of the other technologies due to the absence of floor heating. Overall, the aggregate material requirements for implementing low-carbon heating technologies per dwelling varies from 2,784 kg for HT heating networks to 9,808 kg for hybrid heat pumps (Figure 17).

For the cradle-to-gate impact of the material requirements, we found 2,784 kg CO$_2$-eq for the HT heating technologies, 8,199 kg CO$_2$-eq. for the LT heating networks, 10,583 kg CO$_2$-eq for the hybrid heat pumps and 11,943 kg CO$_2$-eq for the heat pumps. For all the low-carbon heating technologies, the required installation results in a significant share of their cradle-to-gate impact.

The materials with the highest emission impact are steel, insulation materials, aluminium, and silicon. The heat production for LT heating networks has a relatively high cradle-to-gate impact due to the amount of steel used in geothermal district heating. Furthermore, the infrastructure category has the lowest material impact of all technologies. The highest emissions are not always generated by the materials with the highest inflow. The largest share of the material requirements is generated by limestone, sand and concrete, while the highest share of the emissions is caused by steel, insulation materials, aluminium and silicon. For example, LT heating networks and hybrid heat pumps technologies have a comparable material impact (8,199 up to 10,583 kg CO$_2$-eq.) per dwelling, while the LT heating network technology has a 40% lower total material requirement in comparison with the heat pump technology (6,495 vs 9,808 kg).



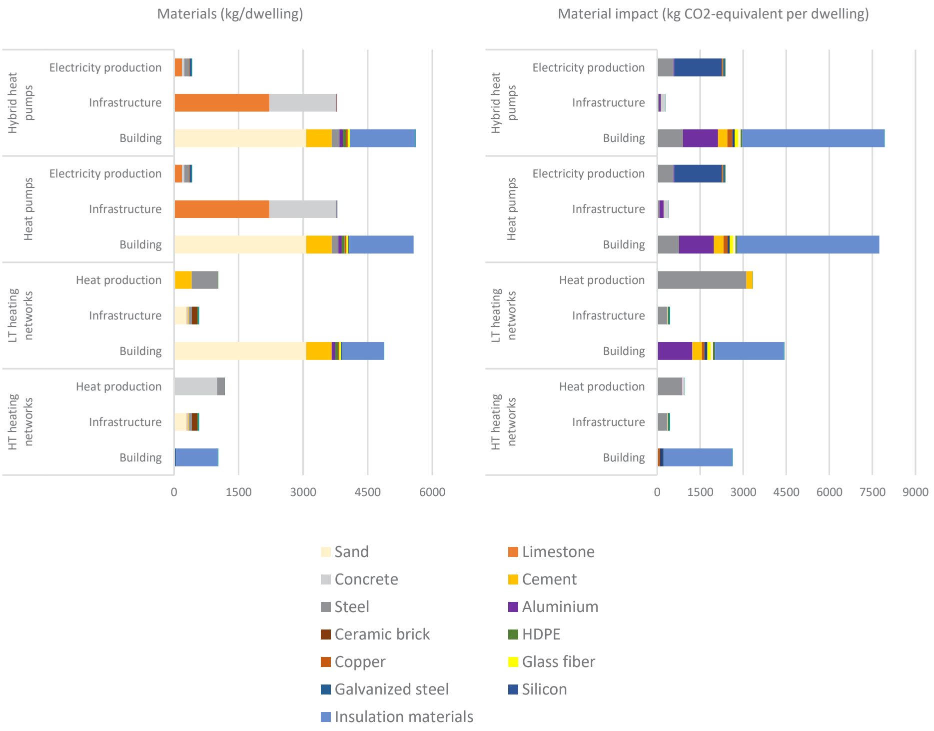


Figure 17, Low-carbon heating technology material demand (left) and cradle-to-gate emissions (right) per dwelling.

5.3.2 Material stock and composition of the Dutch heating system in 2050

In 2050, the material stock of the Dutch heating system varies per scenario from 58,727 kilotons for scenario 1 (Mix LT + HP), and 59,603 in scenario 3 (High HHP) to 63,020 kilotons for scenario 2 (High HP). The largest material category with 31,639 up to 34,445 kilotons in the Dutch heating system composition in 2050 is aggregates (sand, gravel). The second-largest category of materials with 12,509 up to 13,929 kilotons are concrete brick and cement. The insulation materials range from 9,152 - 9.912 kilotons per scenario. Metals and plastics are a smaller material category in the future Dutch heating system with 3,855 to 4,497 kilotons for metals and 880 to 931 kilotons for plastics. Overall, between scenarios, there is only a slight variation in the material stock (figure 18).

A large share of the material stock in each scenario originates from the heat pumps and hybrid heat pumps. Most of the material stock comes from the sand, insulation materials, concrete and cement in the in-house floor heating, insulation requirements and the transformer buildings for heat pumps and hybrid heat pumps. The largest material demand in scenarios 1 and 2 and the highest share of metal demand in every scenario originates from the LT heating networks. This results from the steel intensity of the geothermal heat source for the LT heating networks. We included all the material stock values per technology and scenario in Appendix AIV.III.

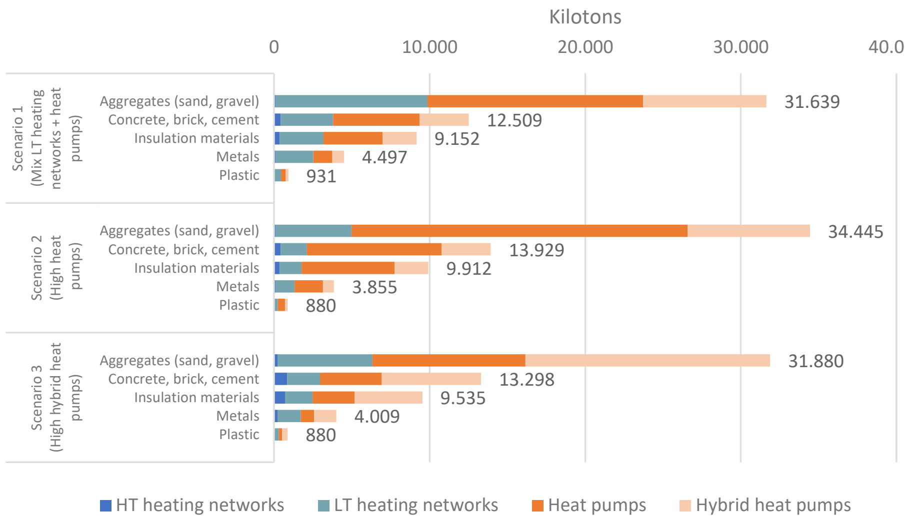


Figure 18, Material stock of the Dutch heating system in 2050 for each scenario and material category.

5.3.3 Material inflows related to the Dutch heating transition from 2020-2050

Overall, the share of materials in the inflow only differs slightly between each scenario, as illustrated by Figure 19. The annual material inflow of the low-carbon Dutch heating system is expected to increase from 1,248 to 1,476 kilotons in 2020 up to 3,137 to 3,285 kilotons in 2050 across the three heating technology scenarios.

The major material inflows result from sand, limestone, cement, concrete, insulation materials, steel, aluminium and HDPE. Smaller inflows consist of copper, glass fibre, etc with an inflow of around 30 up to 80 kilotons per year. The annual material inflow is generally comparable in weight and composition for each scenario. The higher relative share of steel and aluminium in scenario 1 is due to the higher share of LT heating networks in this scenario. The other inflows will largely remain the same across the scenarios. More detailed information on all materials inflows can be found in Appendix AIV.III.

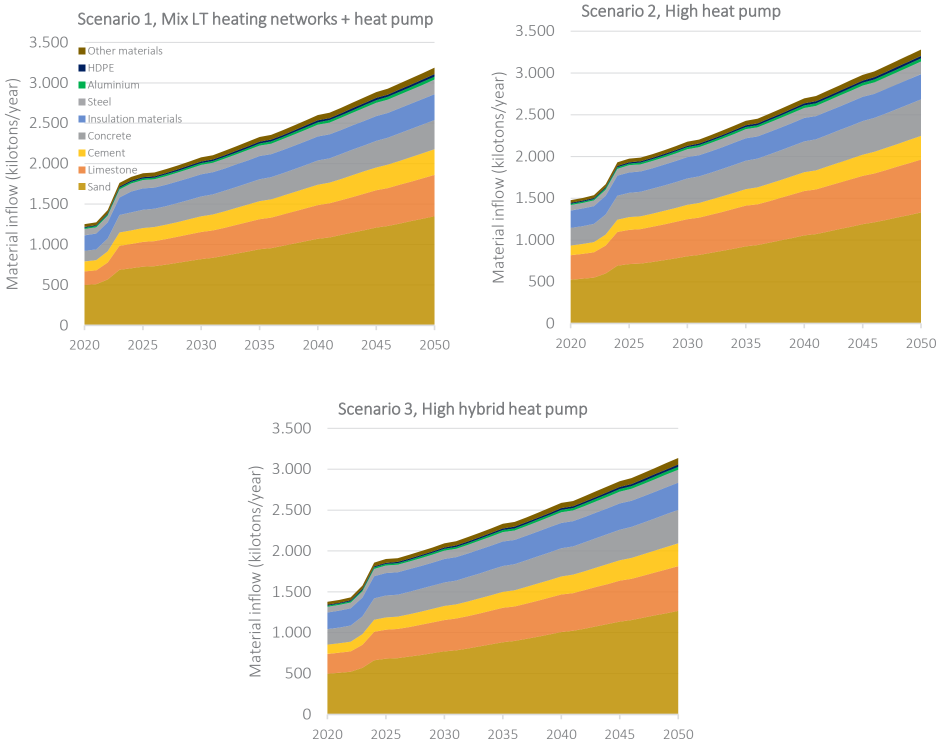


Figure 19, Annual material inflow and inflow composition of the Dutch heating system until 2050.

5.3.4 Cumulative cradle-to-gate GHG emissions of low-carbon heating technologies from 2020-2050

Due to the high material inflow of scenario 3, this scenario is the most GHG intensive option with 70.8 megatons of cradle-to-gate emissions in CO_2-eq. The GHG emissions of the other scenarios range from 59.7 megatons of CO_2-eq for scenario 2, up to 67.0 megatons CO_2-eq for scenario 1. The highest cradle-to-gate impact is generated by building adjustments, and electricity and heat production, while the infrastructure adjustments have the lowest impact.

A trend can be observed among the heat pump and heating network technologies: most of the heat pump technologies impact is generated by the building adjustment category resulting from the installation of a (hybrid) heat pump and insulation requirements, while the heating network technologies impact is largely determined by its heat production (Figure 20). Also, the steel intensity of the LT heating networks technology heat production is reflected in its emissions, as steel has a relatively high cradle-to-gate impact.

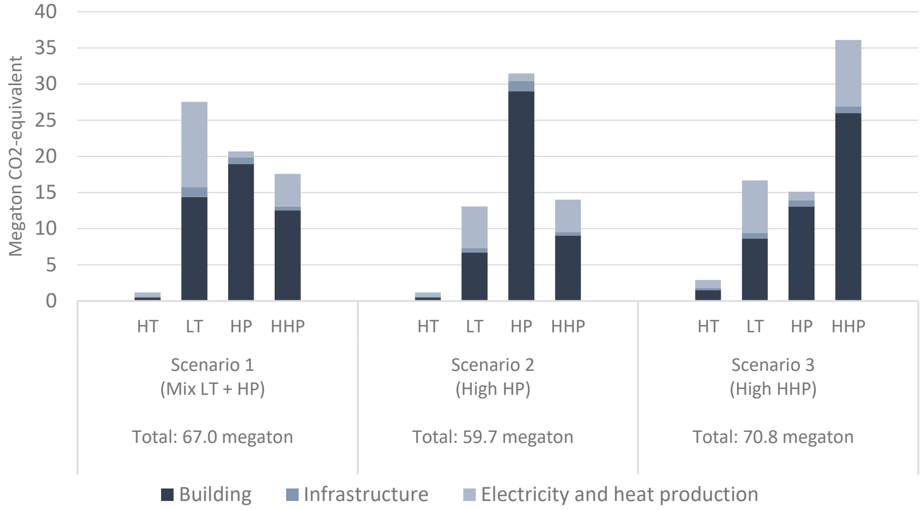


Figure 20 The cumulative cradle-to-gate emissions of low-carbon heating technologies material inflow for each scenario in the period 2020 to 2050.

5.3.5 System-wide GHG emission reduction of the Dutch heating system

Figure 21 shows that the highest annual net CO_2-eq impact reduction with 15,115 kilotons in 2050 can be achieved with scenario 2 (High heat pump). In comparison with the operational emissions of the Dutch heating system in 1990, this translates into a reduction of 64%. Scenario 1 has the second-highest annual emission reduction in 2050 with 14,976 kilotons, and scenario 3 has the lowest annual net CO_2-eq impact reduction with 14,514 kilotons. In comparison with the operational emissions of the Dutch heating system in 1990, this translates into a 62%-64% reduction. Furthermore, in 2050, the total cradle-to-gate impact of the in-use material stock is between 3,223 and 3,329 kilotons and will generate around 40% of the GHG-emissions of the Dutch heating system. After 2050, the build-up of the Dutch low-carbon heating system is assumed to be complete. The material inflow and corresponding cradle-to-gate impact will be reduced and largely consist of stock maintenance.

Overall, the market share of heating technologies and electricity grid development does not differ much between scenarios. Consequently, the system-wide emissions change little between the scenarios. The system-wide CO_2 emissions are still largely determined by the operational emissions, even in 2050. Still, the share of material-related emissions will increase over time in comparison with the operational emissions.

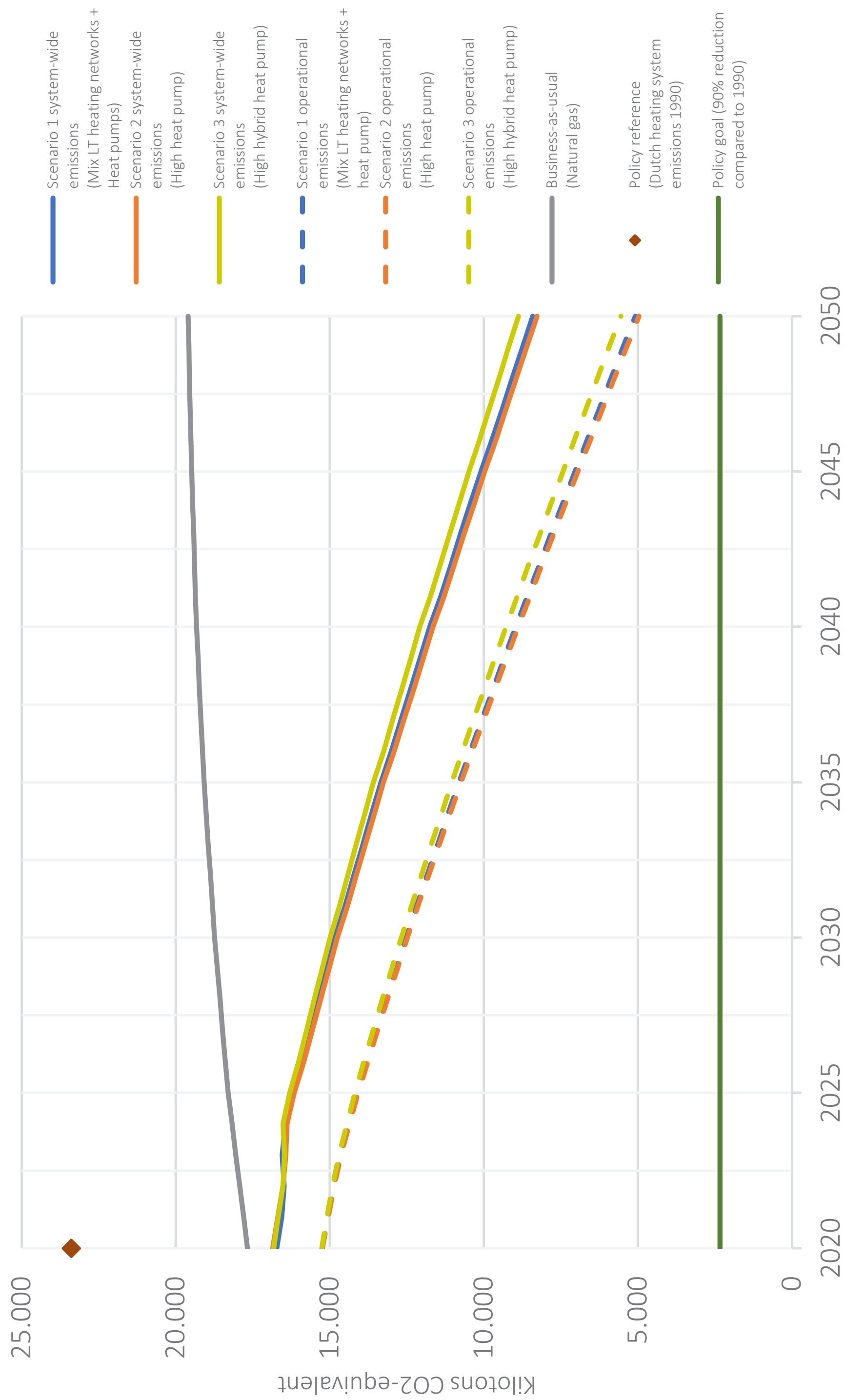


Figure 21 Annual Dutch heating system GHG-emissions for each scenario in the period 2020 to 2050.

5.4 Discussion & conclusion

This work quantifies the material demand and stock as well as the cradle-to-gate CO_2 emissions resulting from the implementation of low-carbon heating technologies in the Netherlands. We compare this to the Dutch climate goal of reducing CO_2 emissions by 90% before 2050 from the 1990 baseline. We used three future scenarios based on the local availability and capacity of low-carbon heat. This research is a continuation of earlier work, which assessed the operational emissions of the future Dutch heating system, allowing for a comparison of both the operational and cradle-to-gate emissions (Verhagen et al., 2020).

Taking into account emissions related to materials has major consequences for the achievability of the Dutch climate goals. Across all three scenarios of a future Dutch heating system, an operational emissions-only point of view would lead to the conclusion that an 80% reduction will be achieved. However, the additional material requirements negate part of the emission reduction benefits of the heating transition, to the point that a reduction in system-wide GHG-emissions of no more than 62% to 64% is achievable.

The stated policy goal of reducing urban heating related GHG-emissions by 90% in 2050 is achievable, but only with the right combination of heating technologies and sources of heat (Verhagen et al., 2020). Furthermore, the heating system will have to be designed with technologies that have a significantly lower material demand. In comparison with the existing heating system, some parts of the low-carbon heating system are less-material intensive. For example, older residential buildings in the Netherlands use heavy iron piping systems, radiators and boilers for the distribution of heat. More modern solutions allow the utilization of lightweight polymer-based distribution systems, smaller radiators and smaller boilers. Insulation materials with lower overall life-cycle impacts must be developed. Innovation and dematerialization of heating systems could alleviate some of the material demand and corresponding environmental impact of this transition towards low-carbon heating.

The material inflows and associated cradle-to-gate GHG-emissions of the Dutch low-carbon heating system will decrease after 2050, as the stock will transition from a growth state to a maintenance state. Still, we find that the share of material-related emissions will increase to 40% of the heating system-wide emissions in 2050. These results are similar to those of Yang et al (2021) and Koezjakov et al (2018), who found that the embodied emissions of building materials will increase from 10-12% in the current situation to 36-46% of the total lifetime emissions in energy-efficient homes (Koezjakov et al., 2018) (Xining & Steubing, 2021).

Contrary to expectations, this study did not find a significant difference in the material demand between the different scenarios planned by the Dutch government, due to the comparable material demand of the low-carbon heating technologies. Therefore, the choice of a combination of low-carbon heating technologies will have to be based on other considerations, such as the availability of sources of heat.

The overall amount of materials invested in the heating system 2020 and 2050 is 60-70 megatons. The materials with the highest share of the cradle-to-gate CO_2 emissions are insulation materials, steel, aluminium and silicon, while in terms of weight sand, limestone and concrete constitute a large share of the annual material demand. Critical materials included in our research amounted to less than 0.1% of the material mass and less than 1.5% of the cradle-to-gate impact. Floor heating for low temperature space heating requires a considerable amount of sand and concrete, while geothermal heat plants are steel-intensive methods for heat production.

The Dutch heating system is estimated to have a stock of around 3.3 up to 4.2 million tons of steel in 2050, and an annual metal inflow of 180 up to 250 kiloton per year. This means that the Dutch heating system is 4 to 5 times less metal-intensive than the future Dutch electricity system, which will comprise a material stock of around 14,300 to 25,800 kiloton of steel in 2050 and an annual metal inflow of 800 up to 1,600 kiloton per year (van Oorschot et al., n.d.). Furthermore, we found an annual inflow of concrete in the Dutch low-carbon heating system of around 254 up to 679 kilotons per year, or an order of magnitude less than concrete inflow of the Dutch building sector, which according to a study by Zhang et al (2021), amounts to around 2,800 up to 4,800 kilotons per year (Zhang et al., 2021).

Uncertainty exists over the future composition of the Dutch low-carbon heating system. Several scenarios were used to address this uncertainty. While the differences in market share between the different low-carbon heating technologies in these scenarios are limited, the material flows will remain largely the same even with a different composition of the market share of these technologies. This is due to the comparable material demand of the low-carbon heating technologies. There is also uncertainty over the average lifetime distributions for the subcomponents of the future Dutch heating system. The choice of lifetime distribution function has little influence on stock accumulation models (Miatto et al., 2017). On the other hand, the size of the material inflow and the generation of waste streams is sensitive to the average lifespan of these subcomponents. Therefore, the use of different lifetime distributions for the subcomponents of the heating system will influence the size of the material inflow and the cradle-to-gate impact.

The modelling of the electricity system carries more uncertainties. Besides the transition towards low-carbon heating technologies, the future electricity grid capacity will also be influenced by other developments such as the energy transition, increased cooling demand and further adoption of electric cars (Blagoeva et al., 2016). We modelled an increase in low-voltage and medium-voltage grid capacity based on the additional grid load and corresponding materials necessary for the implementation of heat pumps. It is possible that we overallocated the share of this material demand for the transition towards low-carbon heating in our research due to potential overlap of the additional grid capacity with the other developments. Furthermore, heat pumps can also provide cooling. With an increasing demand for residential cooling in the Netherlands, the utilization of heat pumps could prevent or replace independent cooling solutions and the corresponding materials.

A limitation of this research is the use of a cradle-to-gate impact assessment rather than a full lifecycle assessment. Due to the broad variety of materials used in the model, it was not possible to include the full lifecycle of all the included materials. Furthermore, there is a limited number of available sources on the material data of the low-carbon heating technologies used in this research. With more data on materials in low-carbon heating systems, it would have been easier to model the material demand scenarios more accurately.

In this paper, we have explored the material requirements for a new, renewables-based heating system. Another related topic would be to investigate the old, fossil fuel-based heating system which will become obsolete over time. We could explore possible end-of-life pathways, to see in what way we could make the best use of this urban mine.

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Chapter 6

Discussion

6.1 Introduction

In this thesis, the energy and material related impacts of the transition towards low-carbon heating in the Netherlands was explored. As a starting point, the size of the current Dutch natural-gas based heating system, and its potential use in a circular economy was analysed in chapter 2. In chapter 3, the development pathways of the Dutch heating system and the operational emissions over time were quantified in the context of the Dutch climate goals (reducing heating-related CO_2 emissions by 90% before 2050). Next, chapter 4 presented the share of primary material demand that could be replaced with secondary materials in the Dutch construction sector in relation to the Dutch circularity goals (reducing primary material demand by 50% before 2030). Finally, based on the results from chapter 3, chapter 5 showed the impact of the transition towards low-carbon heating on the material and operational GHG-emissions of the Dutch heating sector.

This thesis contributes to understanding the transition towards low-carbon heating in the Netherlands, in the context of the Dutch climate and circular policy goals by: 1) showing the stock and flow size of the current and future Dutch heating system; 2) providing a comparison of operational and material-related GHG-emissions over time of this system change; 3) providing an understanding of the impact of this transition on both climate and circular economy policy goals.

This dissertation aimed to answer the following research questions:

1. What is the size of the material stock of the current Dutch natural-gas based heating system, and can this material be used in a circular economy?
2. What are the possible development pathways of the Dutch heating system and operational GHG-emissions towards 2050?
3. What are the consequences of the heating transition for the use of materials and how can this transition contribute to the circular economy transition?
4. What is the impact on GHG-emissions of the transition towards a low-carbon heating system from 2021-2050?

In the following sections 6.2-6.6, we first answer and discuss the research questions. After this, the limitations and future research are discussed in section 6.7. Finally, in section 6.8 the implications of this dissertation are discussed for research and society.

6.2 Material stock of the Dutch-natural-gas based heating system and its application in a circular economy

In total, we find a stock of 1,080 kilotons of materials in the heating boilers, natural gas production installations and gas pipelines for 2020, consisting of mostly steel, PVC, cast iron and copper. Because of the transition towards low-carbon heating, this natural-gas-based heating system will become obsolete over time. Part of this heating system will go into hibernation, part of it will be recovered and recycled while another part could be reused for the distribution of hydrogen or green gas.

Our results in chapter 2 shows that between 1,782 and 2,078 kilotons will flow out from the in-use stock between 2020-2050. Without further action, most of the material stock of the Dutch natural-gas infrastructure will most likely go into hibernation after the use phase, as the recovery of underground obsolete material stocks is often considered unprofitable (Krook et al., 2011). Active policy measures are required from the Dutch government to incentivize collection of these material stock by the network operators.

The future production capacity of hydrogen or green gas will mainly determine the extent to which this gas network can be reused. Generating hydrogen on such a scale that 45% of the Dutch residential buildings could be supplied with heat may also cause problems with the availability of metals, and the significant investment of materials may cancel out part of the intended emission reduction (Kleijn & van der Voet, 2010). In any case, the capacity of the current natural-gas-based heating system will be scaled down in the future, which means that at least part of this heating system will become available for recovery and recycling in a circular economy.

In total, the Dutch natural-gas-based heating system is a valuable urban mine that is comparable to the size of the Dutch electricity grid. Based on current plans, it is likely that only part of the Dutch natural gas infrastructure will be reused for the distribution of hydrogen. The remaining out of-use materials underground are a valuable urban mine of mainly steel, PVC cast iron and copper. Recycling and reusing materials from the natural-gas-based heating system can alleviate some of the material impact of the build-up of the more material-intensive low-carbon heating system.

6.3 Development pathways and operational GHG-emissions of the Dutch heating system towards 2050

We found that attaining the Dutch climate goal of achieving a 90% reduction in operational CO_2 emissions before 2050 requires a drastic change in the current Dutch heating system. With the use of a combination of LT-heating networks and (hybrid) heat pumps, the climate goal is attainable. This will require an increased LV-capacity of the Dutch electricity grid, a renewables-based electricity system, investments in heating network distribution infrastructure and the utilization of low-carbon sources of heat. With the use of HT-heating network, the Netherlands could reach the 2030 climate goal (50% reduction of CO_2 emissions) but would significantly limit further reductions. This is because of the relatively high CO_2 emissions per kWh of urban heat of the HT-heating networks.

Several scenarios of the Berenschot heating scenario report were used to address the uncertainty on the future composition of the low-carbon Dutch heating system. As shown in the findings in chapter 3, the differences in market share of low-carbon heating technologies between the scenarios are relatively small. The market share of heat pump technologies ranges from 55-75%, while the LT heating networks have a 20-40% market share depending on the scenario. Because of these small differences, the operational emissions reduction variation between the scenarios are also limited. In future research, scenarios in which one low-carbon heating technology is dominant should also be explored to cover more varied development pathways of the future Dutch heating system.

Our findings in chapter 3 underline the importance of the sources of heat and electricity in reducing the CO_2 impact of residential heating. Replacing heating technologies is not sufficient on its own, and more low-carbon sources of heat and electricity need to be utilized to achieve significant CO_2 reductions before 2050. We also found that when the heating technology market share of the Berenschot scenarios is used, an operational CO_2 emissions reduction of only 80% can be achieved before 2050. While most of the heating technology market share in these scenarios consist of LT-heating networks and (hybrid) heat pumps, the remaining share of HT-heating networks prevents attaining the Dutch climate goals of 2050.

6.4 Consequences of the heating transition for the use of materials and its potential contribution to the circular economy transition

In chapter 5, we found that the build-up of the Dutch low-carbon heating system will require a material demand of 1,200-3,300 kilotons per year, resulting in a material stock of between 58,000 and 60,000 kilotons in 2050. This material demand is mainly a result of the in-house adjustments required for low-carbon heating such as heat pumps, additional insulation and floor heating, and the material-intensive generation of low-carbon heat.

We compared the material stock of both the natural-gas-based and low-carbon heating system over time for a selection of materials in chapter 2, and found that the low-carbon heating system is more material intensive, and especially more metal-intensive. Because of the increased material intensity, it is important to recover and recycle as much of the soon-to-be obsolete natural-gas-based heating system and the existing buildings as possible.

In chapter 4, we explored to what extent secondary materials generated through urban mining could replace the primary material demand in the Dutch construction sector. We found that with the current construction and demolition plans in the Netherlands, 41% of the primary material demand can be replaced by using secondary materials. In addition, we found that 66% of the generated demolition waste could be recycled. This means that the 2030 circular economy goals are already difficult to attain and that primary material extraction will remain necessary for the construction sector. The recycled content potential is the biggest obstacle in reducing the primary material demand, and using secondary materials are currently seen as a risk by construction companies. New policies are required to focus on retaining material quality while allowing further use of recycled materials as building materials.

The heating system change towards low-carbon heating technologies can also stimulate the transition to a circular economy. The material demand of the heating transition negatively influences the system-wide GHG-emissions reduction, while at the same time it results in a significant release of materials from the old natural-gas-based heating system. The material-related impacts, increased primary material demand and the availability of these significant urban mines can stimulate recycling practices and the use of secondary materials. It is therefore essential for the Dutch government to utilize the out of use natural-gas-based heating system as an urban mine and stimulate recovery and recycling practices. For the build-up of the new low-carbon heating system, the use of secondary could reduce the material-related impacts.

6.5 The impact on GHG-emissions of the transition towards a low-carbon heating system from 2021-2050

Taking into account emissions related to materials has major consequences for the achievability of the Dutch climate goals. Across all three scenarios in the Berenschot scenarios of a future Dutch heating system, an operational emissions-only point of view would lead to the conclusion that an 80% reduction will be achieved. However, the additional material requirements negate part of the emission reduction benefits of the heating transition, to the point that a reduction in system-wide GHG-emissions of no more than 62% to 64% is achievable.

The stated policy goal of reducing urban heating related GHG-emissions by 90% in 2050 is achievable, but only with the right combination of heating technologies and sources of heat (Verhagen et al., 2020). We find that the share of material-related emissions will increase to 40% of the heating system-wide emissions in 2050. Policy is needed from the Dutch government to reduce this material impact. For example, stimulating the use of secondary materials for the build-up of the low-carbon heating system. Furthermore, the heating system will have to be designed with technologies that have a significantly lower material demand. Innovation and dematerialization of heating systems could alleviate some of the material demand and corresponding environmental impact of this transition towards low-carbon heating.

Another strategy to compensate part of the material-related emissions is the accelerated build-up of the low-carbon heating system. Sooner or later, there will be a significant material demand required for the build-up of the low-carbon heating system. By transitioning towards a low-carbon heating system on a more ambitious timeframe, the operational, and therefore cumulative GHG-emissions of the Dutch heating system can be reduced.

6.6 The energy and material-related impacts of the transition towards low-carbon heating

Based on the previous chapters, we can now discuss the main research question: *How is the Dutch heating system expected to change towards 2050, and how does this affect the Dutch policy goals related to climate change and the circular economy?*

In chapter 3 we have shown that to achieve the Dutch climate target of reducing operational CO_2 emissions of urban heating by 90% in 2050, a new low-carbon heating system has to be built up. For this, the electricity grid has to be expanded with additional LV capacity for heat pumps, and heating networks will have to be installed on a large scale. Existing residential buildings will have to be adapted to accommodate low-temperature heating and require increased levels of insulation. In addition, the available sources of low-carbon heat in the Netherlands have to be carefully surveyed as these are essential in achieving the climate target.

The construction of a separate low-carbon heating system has a significant material demand, and is even more material-intensive than the current natural gas-based heating system (chapter 2 & 5). In the second chapter of this thesis, we have also shown that the current natural-gas based heating system will become largely obsolete in the future. This means that a large urban mine of materials can be recovered and recycled for use as secondary materials in the circular economy. The use of secondary materials as a substitution for primary material demand can stimulate recycling practices and reduce material-related impacts.

The associated material demand for this transition to low-carbon heating ensures that the climate target will not be achieved. Even after the build-up of the low-carbon heating system, there will still be a significant material impact from the maintenance of this system. Still, in comparison with the natural-gas-based heating system, considerable operational emissions reductions can be achieved. In order to achieve the Dutch climate target of 2050 after the build-up of the low-carbon heating system, considerable reductions in material-related impacts will have to be realised.

The transition towards low-carbon heating requires adjustments to residential buildings, which also generates a considerable material demand. Chapter 4 shows that it is very challenging to close the Dutch construction and demolition waste cycle. Even in a situation without additional building stock growth, the collection and recycling process cannot recycle 100% of the generated demolition waste, leading to continued demand for primary materials. Achieving the 2030 circular economy policy goal of decreasing primary material demand by 50% will require significant improvements to the current processing of (demolition) waste and recovered materials.

The adjustments required to buildings and the heating system will lead to an increase in material demand, especially for metals. At the same time, the release of a large urban mine in the form of the old natural gas-based heating system and the demolition of buildings offers opportunities for the circular economy. In this situation it could become more attractive to use secondary materials and to invest more in circular economy practices such as recovery, recycling and reuse. In addition, the increased demand for materials offers a chance to use secondary materials to a greater extent. The energy transition, of which the heating transition is part of, could also reduce the impact of material recycling, as this if often an energy-intensive process. Applying circular economy practices in the build-up of the new low-carbon heating system can decrease the material-related impacts, bringing the Netherlands closer to achieving its 2050 climate and circular economy policy goals.

Insight into the impact of this transition towards low-carbon heating on energy and material use is essential to make targeted policy through which both policy goals will be achieved, and the efforts of one do not nullify the efforts of the other.

6.7 Limitations and future research

Method

A limitation of this research is that it does not cover the variety in how much material could become available annually from the old material stocks until 2050. In our analysis, we modelled a linear increase and market share and corresponding material flows due to a lack of data on this topic. In reality, the adoption of low-carbon heating technologies can go a lot faster due to for example, financial stimulus through subsidies. This would cause the increased obsolescence of the natural-gas-based heating system and availability of its material stock for potential urban mining, and could create a mismatch in material demand and secondary material availability over time. The material demand for the build-up of the low-carbon heating could reach its peak well before enough secondary materials are recycled to replace part of the primary demand.

Berenschot scenarios were used to cover the uncertainty about the future composition of the Dutch heating system. All the scenarios describe a combination of multiple low-carbon heating technologies in use for 2050. More extreme scenarios in which the composition of the future heating system tends more towards one dominant heating technology should also be explored. The current heating system in the Netherlands is predominantly natural-gas-based, and therefore one-sided heating technology scenarios ought to not remain completely unexplored.

Data

Another limitation of this research is that at this moment there is a limited number of available sources on the material data of the low-carbon heating technologies. With more data on materials in low-carbon heating systems, it would have been easier to model the material demand scenarios more accurately. Furthermore, for heating networks technologies, implied data was used due to a lack of information. Especially the infrastructure prices of the heating networks are generally unspecified.

Recommendations for future research

A recommendation for further research would be on the combined heating and cooling demand of the future Dutch heating system. With an increasing demand for residential cooling in the Netherlands, the utilization of heat pumps could prevent or replace independent cooling solutions and the corresponding materials. It is also important to research to what extent the use of low-carbon electricity can reduce the impact of recycling and reuse processes.

Other recommendations for future research include a further exploration of the materials and corresponding environmental impact of the current fossil-fuel based energy system. In this dissertation we included the natural gas system in the Netherlands, while the overall fossil fuel system that a low-carbon heating system could replace is more complex and extensive. Only after analyzing both systems with completely equal system boundaries can we determine if the low-carbon heating (and energy) system is more material-intensive. Furthermore, it is also worth exploring what the impact is of the transition towards low-carbon heating on the critical material demand. While we included critical materials, it was not the main focus of the research. Further quantification of critical materials in this system change would most likely result in higher stocks in the energy system, but more importantly would highlight a potential strategic importance for the Netherlands to acquire a secure supply. In existing stocks of the currently used heating system, most other materials are already present, but for critical materials a stock still has to be built-up in the form of a new low-carbon energy system.

The development of this transition towards low-carbon heating could also be influenced by energy storage solutions. At present, the use of energy storage is limited, but in the future, this could have a strong influence on the system (Petrović & Karlsson, 2016). Phase change materials (PCM's), improvements in battery technology and localized hydrogen storage present a potentially disruptive development for the overall energy grid (heat and electricity). The material demand for such a large-scale transition of an energy system could also influence, or even disrupt critical material supply chains (Sprecher et al., 2017). These developments should be considered in future research on this topic.

6.8 Implications

Implications for research

This research has shown that the transition towards low-carbon heating, just as with the energy transition, leads to an increased use of materials and corresponding material impacts. These results are valid for our used case study of the Netherlands, and are potentially applicable to neighbouring countries in the EU that also heavily utilize natural-gas for space heating.

Assuming the outcomes of our study are also valid for the rest of the world, this means that:

- A global transition towards low-carbon heating will contribute to an increased demand for materials, especially for metals and insulation materials. Potential shortages in material availability could stimulate circular economy practices such as recovery, recycling and reuse.
- Buildings and legacy heating systems could be used as a source of secondary materials through urban mining. With the increasing material demand and the environmental impacts of primary material production, secondary material extraction will most likely play an increasingly important role.
- Energy transition and circular economy policy goals will need to be further integrated to achieve considerable emission reductions. Accounting for potential trade-offs while incorporating both policy goals is something that has to incorporated in climate research and policy making.
- The total environmental impact of urban heating will first increase as a result of the material-related impacts. After the build-up of the low-carbon heating system, the environmental impact of urban heating can decrease significantly.

In reality, the comparison between the Netherlands and other countries, especially ones outside the EU becomes more difficult, as other built environments can have an increased level of insulation, and utilize different heating technologies. Furthermore, the demand for heating outweighs the demand for cooling in the Netherlands, while in other countries such as China and India the cooling demand is more important for the energy use of buildings. Because of these differences it is also important to externally validate these outcomes with studies on the heating system and the transition towards low-carbon heating (and cooling) in other countries (Flyvbjerg, 2006).

Implications for society

Climate and CE-policy are inextricably linked. With the build-up of the low-carbon heating system, an increased material intensity must be taken into account. Promotion of CE practices by the Dutch government could help to reduce the material-related impacts of the low-carbon heating system.

The low-carbon heating system will be further integrated in the electricity sector than the natural-gas-based heating system. After the transition there will be a considerable overlap between the electricity and heating system due to the application and use of heat pump technologies. This could mean that policy directed to change one part of this energy system can also impact the other parts as these are more integrated than before.

Wide-scale implementation of financial incentives for home-owners can accelerate this transition towards low-carbon heating. Sooner or later, there will be a significant material demand required for the build-up of the low-carbon heating system, generating a considerable environmental impact in the form of material-related emissions. Accelerating the transition towards low-carbon heating on a more ambitious timeframe can reduce the cumulative system-wide GHG-emissions of the Dutch heating sector.

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Summary

Summary

The almost unsatiable demand for energy of our modern society has created a strong reliance on fossil fuels. Of all the greenhouse gases produced in the world, energy production is responsible for 72% (IEA, 2020). To reduce emissions and adapt to the impacts of climate change, 196 countries signed the Paris agreement in 2015. In this agreement, countries aim to achieve a climate neutral world by 2050, and therefore completely abolish the use of fossil fuels. For the energy sector, this has resulted in the energy transition; the shift from fossil-based systems of energy production and consumption to renewable energy sources.

Energy transition research has mainly focussed on the electricity sector and transport fuels (Liang et al., 2022; Tang et al., 2021). Up to now, very little attention has been paid to the heating sector. This thesis fills that gap by exploring a critical piece of the energy transition: the transition towards fossil-free urban heating. Buildings are responsible for 40% of the global energy demand, of which most is used for space heating. Three-quarters of this energy demand is met by using fossil fuels (IEA, 2021).

The existing heating system, including in-house heating, infrastructure, and energy production, will have to be adapted to accommodate low-carbon heating technologies that operate on different sources of heat. Furthermore, to realize the transition towards a low-carbon heating system, many changes will have to be made to buildings. All the changes required for the transition towards low-carbon heating to buildings, infrastructure and energy production will over time lead to: 1) the obsolescence of the current Dutch natural-gas-based heating system and; 2) the build-up of a separate low-carbon heating system. At the same time, it is unknown how much material the build-up of this low-carbon heating system will require, and if this transition towards low-carbon heating will make the Dutch 2050 climate goal of reducing heating-related GHG emission by 90% attainable.

The aim of this thesis is to investigate the transition towards low-carbon heating in the Netherlands, in the context of the Dutch climate and circular policy goals. This results in the following **main research question**: *How is the Dutch heating system expected to change towards 2050, and how does this affect the Dutch policy goals related to climate change and the circular economy?*

We use the Netherlands as a contemporary case study as its heating system is heavily reliant on the use of natural gas. In 2017, the political decision was taken to transition towards fossil-free urban heating, on a very ambitious time-schedule: heating-related CO2

emissions should be reduced by 50% before 2030, and 90% before 2050 (Rijksoverheid, 2017). For the existing Dutch building stock, this means that more than 80% are to be renovated. Besides the transition towards low-carbon heating, the Dutch government also formulated circular economy policy to reduce the country-wide use of primary materials (minerals, metals, and fossil fuels) by 50% before 2030, and become fully circular by 2050.

For the development scenarios of the composition of the Dutch heating system, we mainly use the heating scenarios report by Berenschot (Berenschot, 2020a). This report explores multiple heating system pathways for the Netherlands from 2020-2050 based on the local availability of sources of heat.

To answer the main research question, chapter 1 to 5 offered answers to each of the research questions mentioned below:

1. What is the size of the material stock of the current Dutch natural-gas based heating system, and can this material be used in a circular economy?

In chapter 2, we found a stock of 1,080 kilotons of materials in the heating boilers, natural gas production installations and gas pipelines for 2020, consisting of mostly steel, PVC, cast iron and copper. Because of the transition towards low-carbon heating, this natural-gas-based heating system will become obsolete over time. Part of this heating system will go into hibernation, part of it will be recovered and recycled while another part could be reused for the distribution of hydrogen or green gas. Recycling and reusing materials from the natural-gas-based heating system can alleviate some of the material impact of the build-up of the more material-intensive low-carbon heating system.

2. What are the possible development pathways and operational GHG-emissions of the Dutch heating system towards 2050?

In chapter 3 we found that attaining the Dutch climate goal of achieving a 90% reduction in operational CO_2 emissions before 2050 requires a drastic change in the current Dutch heating system (Verhagen et al., 2020). With the use of a combination of LT-heating networks and (hybrid) heat pumps, the climate goal is technically attainable. This will require an increased LV-capacity of the Dutch electricity grid, a renewables-based electricity system, investments in heating network distribution infrastructure and the utilization of low-carbon sources of heat. With the use of HT-heating network, the Netherlands could reach the 2030 climate goal (50% reduction of CO_2 emissions) but would significantly limit further reductions. This is because of the relatively high CO_2 emissions per kWh of urban heat of the HT-heating networks.

We also found that when the heating technology market share of the Berenschot scenarios is used, an operational CO_2 emissions reduction of only 80% can be achieved before 2050. While most of the heating technology market share in these scenarios consist of LT-heating networks and (hybrid) heat pumps, the remaining share of HT-heating networks prevents attaining the Dutch climate goals of 2050.

3. What are the consequences of the heating transition for the use of materials and how can this transition contribute to the circular economy transition?

In chapter 5, we found that the build-up of the Dutch low-carbon heating system will require a material demand of 1,200-3,300 kilotons per year, resulting in a material stock of between 58,000 and 60,000 kilotons in 2050. This material demand is mainly a result of the in-house adjustments required for low-carbon heating such as heat pumps, additional insulation and floor heating, and the material-intensive generation of low-carbon heat. In chapter 4 we also found that with the current construction and demolition plans in the Netherlands, 41% of the primary material demand can be replaced by using secondary materials. In addition, we found that 66% of the generated demolition waste could be recycled. This means that the 2030 circular economy goals are already difficult to attain, and that primary material extraction will remain necessary for the construction sector.

We compared the material stock of both the natural-gas-based and low-carbon heating system over time for a selection of materials in chapter 2 and found that the low-carbon heating system is more material intensive, and especially more metal-intensive. Because of the increased material intensity, it is important to recover and recycle as much of the soon-to-be obsolete natural-gas-based heating system and the existing buildings as possible.

4. What is the impact on GHG-emissions of the transition towards a low-carbon heating system from 2021-2050?

Taking into account emissions related to materials has major consequences for the achievability of the Dutch climate goals. In chapter 4, we found that across all three scenarios in the Berenschot scenarios of a future Dutch heating system, an operational emissions-only point of view would lead to the conclusion that an 80% reduction will be achieved. However, the additional material requirements negate part of the emission reduction benefits of the heating transition, to the point that a reduction in system-wide GHG-emissions of no more than 62% to 64% is achievable. We find that the share of material-related emissions will increase to 40% of the heating system-wide emissions in 2050.

Overall, chapters 2 to 5 showed that the associated material demand for this transition to low-carbon heating ensures that the climate target will not be achieved. Even after the build-up of the low-carbon heating system, there will still be a significant material impact from the maintenance of this system. Still, in comparison with the natural-gas-based heating system, considerable operational emissions reductions can be achieved. In order to achieve the Dutch climate target of 2050 after the build-up of the low-carbon heating system, considerable reductions in material-related impacts will have to be realised.

The adjustments required to buildings and the heating system will lead to an increase in material demand, especially for metals. At the same time, the release of a large urban mine in the form of the old natural gas-based heating system and the demolition of buildings offers opportunities for the circular economy. In this situation it could become more attractive to use secondary materials and to invest more in circular economy practices such as recovery, recycling, and reuse. For example, the possibility of reusing the existing Dutch natural gas grid for the distribution of renewable gasses such as hydrogen or biogas. In addition, the increased demand for materials offers a chance to use secondary materials to a greater extent. The energy transition, of which the heating transition is part, could also reduce the impact of material recycling, as this if often an energy-intensive process. Applying circular economy practices in the build-up of the new low-carbon heating system can decrease the material-related impacts, bringing the Netherlands closer to achieving its 2050 climate and circular economy policy goals.

Assuming the outcomes of our study are also valid for the rest of the world, this means that:

- A global transition towards low-carbon heating will contribute to an increased demand for materials, especially for metals and insulation materials. Potential shortages in material availability could stimulate circular economy practices such as recovery, recycling, and reuse. Legacy heating systems could be used as a source of secondary materials through urban mining.
- The total environmental impact of urban heating will first increase as a result of the material-related impacts. After the build-up of the low-carbon heating system, the environmental impact of urban heating can decrease significantly.

In reality, the comparison between the Netherlands and other countries, especially ones outside the EU becomes more difficult. Other built environments can have an increased level of insulation and utilize different heating technologies. Furthermore, the demand for heating outweighs the demand for cooling in the Netherlands, while in other countries such as China and India the cooling demand is more important for the energy use of buildings. Because of these differences it is also important to externally validate these outcomes with studies on the heating system and the transition towards low-carbon heating (and cooling) in other countries (Flyvbjerg, 2006).

This dissertation has shown that both policy goals do not only go hand in hand, but also influence each other (where possibly also negatively). The transition towards a low-carbon heating system is essential to achieve the 2050 climate targets. At the same time, the build-up of a low-carbon heating system increases primary material extraction, making it more difficult to achieve the Dutch Circular Economy policy goals. The energy transition however, of which the heating transition is part of, could also reduce the negative environmental impact of material recycling, as this if often an energy-intensive process.

Insight into the impact of this transition towards low-carbon heating on energy and material use is essential to make targeted policy through which both policy goals will be achieved, and the efforts of one do not nullify the efforts of the other.

Samenvatting

Samenvatting

De bijna onverzadigbare vraag naar energie van onze moderne samenleving heeft geleid tot een sterke afhankelijkheid van fossiele brandstoffen. Van alle broeikasgassen die in de wereld worden geproduceerd, is energieproductie verantwoordelijk voor 72% (IEA, 2020). Om de uitstoot te verminderen en zich aan te passen aan de gevolgen van klimaatverandering, ondertekenden 196 landen in 2015 het akkoord van Parijs. In dit akkoord streven landen naar een klimaat neutrale wereld in 2050 en daarmee het gebruik van fossiele brandstoffen volledig af te schaffen. Voor de energiesector heeft dit geleid tot de energietransitie; de transitie van op fossiele brandstoffen gebaseerde systemen voor energieproductie en -verbruik naar hernieuwbare energiebronnen.

Onderzoek naar energietransitie heeft zich voornamelijk gericht op de elektriciteitssector en transportbrandstoffen (Liang et al., 2022; Tang et al., 2021). Tot nu toe is er zeer weinig aandacht besteed aan de verwarmingssector. Deze dissertatie vult dit gat op door een kritiek onderdeel van de energietransitie te onderzoeken: de overgang naar fossielvrije stadsverwarming. Gebouwen zijn verantwoordelijk voor 40% van de wereldwijde energievraag, waarvan het grootste deel wordt gebruikt voor ruimteverwarming. Driekwart van deze energievraag wordt gedekt door het gebruik van fossiele brandstoffen (IEA, 2021).

Het bestaande warmtesysteem, met inbegrip van de verwarming binnenshuis, de infrastructuur en de energieproductie, zal moeten worden aangepast om geschikt te zijn voor lage-emissie warmtetechnologieën die op verschillende warmtebronnen werken. Bovendien zullen er, om de overgang naar een lage-emissie warmtesysteem te realiseren, veel veranderingen in gebouwen moeten worden doorgevoerd. Alle veranderingen die nodig zijn voor de overgang naar een lage-emissie verwarming van gebouwen, infrastructuur en energieproductie zullen na verloop van tijd leiden tot: 1) het in onbruik raken van het huidige Nederlandse warmtesysteem op basis van aardgas en; 2) de opbouw van een apart lage-emissie warmtesysteem. Tegelijkertijd is het onbekend hoeveel materiaal de opbouw van dit lage emissie warmtesysteem zal vragen, en of deze overgang naar lage emissie verwarming de Nederlandse klimaatdoelstelling voor 2050 (90% reductie van warmte-gerelateerde emissies) haalbaar zal maken.

Het doel van dit proefschrift is om de transitie naar een lage-emissie warmtesysteem in Nederland te onderzoeken, in de context van de Nederlandse klimaat- en circulaire beleidsdoelen. Dit resulteert in de volgende **hoofdonderzoeksvraag**: Hoe verandert het Nederlandse warmtesysteem naar 2050 toe, en hoe beïnvloedt dit de Nederlandse beleidsdoelen op het gebied van klimaatverandering en de circulaire economie?

We gebruiken Nederland als een hedendaagse case study, omdat het warmtesysteem sterk afhankelijk is van het gebruik van aardgas. In 2017 is het politieke besluit genomen om over te gaan op fossielvrije stadsverwarming, met een zeer ambitieus tijdschema: de warmte-gerelateerde CO_2-uitstoot moet voor 2030 met 50% en voor 2050 met 90% zijn verminderd (Rijksoverheid, 2017). Voor de bestaande Nederlandse gebouwenvoorraad betekent dit dat meer dan 80% gerenoveerd moet worden. Naast de transitie naar een lage-emissie warmtesysteem heeft de Nederlandse overheid ook beleid voor de circulaire economie geformuleerd om het landelijke gebruik van primaire materialen (mineralen, metalen en fossiele brandstoffen) vóór 2030 met 50% te verminderen en in 2050 volledig circulair te zijn.

Voor de ontwikkelingsscenario's van de samenstelling van het Nederlandse warmtesysteem maken we voornamelijk gebruik van het rapport Warmtescenario's van Berenschot (Berenschot, 2020a). Dit rapport verkent meerdere ontwikkelingspaden van het Nederlandse warmtesysteem 2020-2050 op basis van de lokale beschikbaarheid van warmtebronnen.

Om de hoofdonderzoeksvraag te beantwoorden, boden hoofdstuk 1 tot en met 5 antwoorden op elk van de onderstaande onderzoeksvragen:

1. Hoe groot is de materiaalvoorraad van het huidige Nederlandse gas-gebaseerde warmtesysteem en is dit materiaal toepasbaar in een circulaire economie?

In hoofdstuk 2 vonden wij voor 2020 een voorraad van 1.080 kiloton aan materialen in de verwarmingsketels, aardgasproductie-installaties en gasleidingen, bestaande uit voornamelijk staal, PVC, gietijzer en koper. Door de transitie naar lage-emissie verwarming zal dit warmtesysteem op aardgas op termijn overbodig worden. Een deel van dit warmtesysteem gaat in hibernation, een deel wordt teruggewonnen en gerecycled en een ander deel kan worden hergebruikt voor de distributie van waterstof of groen gas. Recycling en hergebruik van materialen van het op gas-gebaseerde warmtesysteem kan een deel van de materiële impact van de opbouw van het meer materiaal intensieve lage-emissie warmtesysteem verlichten.

2. Wat zijn de mogelijke ontwikkelingstrajecten en operationele broeikasgasemissies van het Nederlandse warmtesysteem richting 2050?

In hoofdstuk 3 hebben wij laten zien dat het behalen van de Nederlandse klimaatdoelstelling om vóór 2050 90% reductie van de operationele CO_2-uitstoot te bereiken een drastische verandering van het huidige Nederlandse verwarmingssysteem vereist. Met de combinatie van LT-warmtenetten en (hybride) warmtepompen is het klimaatdoel haalbaar. Dit vereist een grotere laagspanning capaciteit van het Nederlandse elektriciteitsnet, een op hernieuwbare energie gebaseerd elektriciteitssysteem, investeringen in de distributie-infrastructuur van warmtenetten en het gebruik van lage-emissie warmtebronnen. Met de inzet van HT-warmtenetten kan Nederland de klimaatdoelstelling voor 2030 halen (50% reductie CO_2-uitstoot) maar verdere reducties aanzienlijk beperken. Dit komt door de relatief hoge CO_2-uitstoot per kWh warmte van de HT-warmtenetten.

Ook constateerden wij dat bij gebruik van de Berenschot-scenario's voor de samenstelling van het warmtesysteem in 2050, een operationele CO_2-emissiereductie van slechts 80% gerealiseerd kan worden. Het grootste deel van het marktaandeel van de verschillende warmtetechnieken in deze scenario's bestaat uit LT-warmtenetten en (hybride) warmtepompen, het resterende aandeel HT-warmtenetten verhindert het halen van de Nederlandse klimaatdoelen van 2050.

3. Wat zijn de gevolgen van de warmtetransitie voor het materiaalgebruik en hoe kan deze transitie bijdragen aan de transitie naar circulaire economie?

In hoofdstuk 5 hebben wij geconstateerd dat de opbouw van het Nederlandse lage-emissie warmtesysteem een materiaalvraag van 1.200-3.300 kiloton per jaar zal vergen, resulterend in een materiaalvoorraad van tussen de 58.000 en 60.000 kiloton in 2050. Deze materiaalvraag is voornamelijk het gevolg van de aanpassingen die nodig zijn voor lage-emissie warmte zoals warmtepompen, extra isolatie en vloerverwarming, en de relatief materiaal intensieve opwekking van lage-emissie warmte. In hoofdstuk 4 hebben wij ook geconstateerd dat met de huidige bouw- en sloopplannen in Nederland 41% van de primaire materiaalvraag kan worden vervangen door secundaire materialen. Daarnaast vonden wij dat 66% van het gegenereerde sloopafval kon worden gerecycled. Dit betekent dat de doelstellingen voor de circulaire economie voor 2030 nu al moeilijk te halen zijn en dat de winning van primaire materialen noodzakelijk blijft voor de bouwsector.

Wij vergeleken de materiaalvoorraad van zowel het op aardgas gebaseerde als het lage-emissie warmtesysteem in de tijd voor een selectie van materialen in hoofdstuk 2, en ontdekten dat het lage-emissie warmtesysteem materiaal intensiever is, en vooral meer metaalintensief. Vanwege de verhoogde materiaalintensiteit is het belangrijk om het binnenkort verouderde gas-gebaseerde warmtesysteem en de bestaande gebouwen zoveel mogelijk terug te winnen en te recyclen.

4. Wat is de impact op de uitstoot van broeikasgasemissies van de overgang naar een lage-emissie warmtesysteem van 2021-2050?

Rekening houden met broeikasgasemissies gerelateerd aan materialen heeft grote gevolgen voor de haalbaarheid van de Nederlandse klimaatdoelen. In hoofdstuk 4 ontdekten wij dat over alle drie de Berenschot-scenario's van een toekomstig Nederlands warmtesysteem in 2050, de operationele emissies met 80% kunnen worden verminderd. De extra materialen om dit lage-emissie systeem op te bouwen doen echter een deel van de operationele emissiereductie van de warmtetransitie teniet. Het meerekenen van de materiaal-gerelateerde emissies zorgt ervoor dat een reductie van de systeem brede broeikasgasemissies van maximaal 62% tot 64% haalbaar is. Het aandeel materiaal-gerelateerde emissies in 2050 zal toenemen tot 40% van de systeem brede emissies van het Nederlandse warmtesysteem.

In totaal is uit de hoofdstukken 2 tot en met 5 gebleken dat de materiaalvraag voor deze overgang naar een lage-emissie warmtesysteem ervoor zorgt dat de klimaatdoelstellingen niet zullen worden gehaald. Zelfs na de opbouw van het lage-emissie warmtesysteem zal er nog een aanzienlijke materiële impact zijn van het onderhoud van dit systeem. Toch kan er in vergelijking met het gas-gebaseerde warmtesysteem aanzienlijke operationele emissiereducties worden bereikt. Om na de opbouw van het lage-emissie warmtesysteem de Nederlandse klimaatdoelstelling voor 2050 te halen, zullen aanzienlijke reducties in materiaal gerelateerde impacts moeten worden gerealiseerd.

De aanpassingen die nodig zijn aan gebouwen en het warmtesysteem zullen leiden tot een toename van de materiaalvraag, vooral naar metalen. Tegelijkertijd biedt het vrijkomen van een grote urban mine in de vorm van het oude warmtesysteem op gas en de sloop van gebouwen kansen voor de circulaire economie. In deze situatie kan het aantrekkelijker worden om secundaire materialen te gebruiken en meer te investeren in circulaire-economie toepassingen zoals terugwinning, recycling en hergebruik. Denk hierbij bijvoorbeeld aan de mogelijkheid om het bestaande Nederlandse aardgasnet te hergebruiken voor de distributie van hernieuwbare gassen zoals waterstof of biogas. Daarnaast biedt de toegenomen vraag naar materialen een kans om secundaire materialen in grotere mate te gebruiken. De energietransitie, waar de warmtetransitie deel van uitmaakt, zou ook de impact van materiaalrecycling kunnen verminderen, aangezien dit vaak een energie-intensief proces is. Het toepassen van circulaire economie praktijken bij de opbouw van het nieuwe lage-emissie warmtesysteem kan de materiaal gerelateerde impacts verminderen, waardoor Nederland dichter bij het bereiken van zijn 2050 klimaat- en circulaire economie beleidsdoelen komt.

Ervan uitgaande dat de uitkomsten van onze studie ook gelden voor de rest van de wereld, betekent dit dat:

- Een wereldwijde overgang naar lage-emissie stadswarmte zal bijdragen aan een grotere vraag naar materialen, vooral naar metalen en isolatiematerialen. Mogelijke tekorten in de beschikbaarheid van materialen kunnen circulaire economie-praktijken zoals terugwinning, recycling en hergebruik stimuleren. Verouderde verwarmingssystemen kunnen worden gebruikt als bron van secundaire materialen door urban mining.
- De totale milieu-impact van stadsverwarming zal eerst toenemen ten gevolge van de materiaal vraag. Na de opbouw van het lage-emissie warmtesysteem kan de milieu-impact van stadsverwarming aanzienlijk afnemen.

In werkelijkheid wordt de vergelijking tussen Nederland en andere landen, met name landen buiten de EU, moeilijker. Andere gebouwde omgevingen kunnen een hoger isolatieniveau hebben en gebruik maken van andere warmtetechnologieën. Bovendien is in Nederland de vraag naar warmte groter dan de vraag naar koeling, terwijl in andere landen zoals China en India de vraag naar koeling belangrijker is voor het energiegebruik van gebouwen. Vanwege deze verschillen is het ook van belang om deze uitkomsten extern te valideren met studies naar het warmtesysteem en de overgang naar lage-emissie warmte (en koeling) in andere landen (Flyvbjerg, 2006).

Dit proefschrift heeft aangetoond dat beide beleidsdoelen niet alleen hand in hand gaan, maar elkaar ook beïnvloeden (waar mogelijk ook in negatieve zin). De overgang naar een lage-emissie warmtesysteem is essentieel om de klimaatdoelstellingen voor 2050 te halen. Tegelijkertijd leidt de opbouw van een lage-emissie warmtesysteem tot een toename van de winning van primaire materialen, waardoor het moeilijker wordt om de Nederlandse beleidsdoelen voor de circulaire economie te realiseren. De energietransitie, waar de warmtetransitie deel van uitmaakt, kan echter ook de negatieve milieueffecten van materiaalrecycling verminderen, aangezien dit vaak een energie-intensief proces is. Inzicht in de effecten van deze overgang naar een lage-emissie warmte op het gebied van energie- en materiaalgebruik is essentieel om gericht beleid te kunnen maken waarmee beide beleidsdoelen worden bereikt en de inspanningen van de een de inspanningen van de ander niet tenietdoen.

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Not everyone is given the opportunity to pursue a PhD. I am well aware of this and am deeply grateful to have been given this chance. There was a point in my life where I was doubting if I would be able to complete my bachelor's degree, making this PhD journey even more meaningful.

During this journey I have noticed that I am intrinsically driven, and that I want to contribute something positive to the world. This drive has resulted in the dissertation you are currently reading, and I aim to keep incorporating this positive contribution to the world in my career.

I was able to learn a lot from my supervisors, Ester van der Voet and Benjamin Sprecher. First of all, I would like to thank Benjamin for hiring me as a researcher at the CML and thereby bringing out my scientific interest. You taught me a lot about systems-thinking, writing and the ins and outs of the scientific world. Ester, thank you very much for your patience, knowledge, and wise words. You have proven to be a razor-sharp thinker and pragmatic at the right moments.

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To my wife Kaveri, who has taught me so much about the important things in life, thank you for supporting me through all the ups-and downs of a PhD. I promise I will return the favour with your PhD journey that started this year.

Curriculum Vitae

Curriculum Vitae

Teun Johannes Verhagen was born on the 14th of March 1992 in Zwolle, the Netherlands. After completing high school in 2010 at the Thorbecke Scholengemeenschap Zwolle, he went to study Industrial Design Engineering at the Delft University of Technology (TU Delft). He discovered his passion for sustainability with the minor Sustainable Energy Technologies. Shortly after, he joined the TU Delft Solar Boat Team to help design the solar array for the 2014 race. After completing the bachelor's degree, his thesis was selected for the TU Delft Best Graduate Award of 2016. The two-year master programme Industrial Ecology at Leiden University was for him the next logical step. During this master, he worked at the Rotterdam University of Applied Sciences as a policy advisor sustainability, and as a student assistant for the Resilient Cities Hub. In his master thesis, he analysed the trade-offs of low-carbon residential heating within the region of Leiden. Teun was then offered a research position in the field of Industrial Ecology at the Institute of Environmental Sciences (CML) to further pursue the topic of his master thesis. After one year, this position was converted into a full PhD. His research has been focussed on understanding the energy and material related impacts of the transition towards low-carbon heating in the Netherlands. He also contributed to multiple Circular Economy reports of the Dutch Planbureau voor de Leefomgeving (PBL).

List of publications

List of publications

Verhagen, Teun Johannes, Ester van der Voet, and Benjamin Sprecher. 2020. 'Alternatives for Natural-Gas-Based Heating Systems: A Quantitative GIS-Based Analysis of Climate Impacts and Financial Feasibility'. Journal of Industrial Ecology n/a(n/a). doi: 10.1111/jiec.13047.

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Berghe, Karel, **Verhagen, Teun Johannes**. 2021 'Making it concrete: analyzing the locations of concrete plants in achieving, or failing, urban circular policy goals' Frontiers in Built Environment, section Urban Science

Appendix I

Based on supplementary information provided with chapter 2:

Verhagen, T. J., Nielen, S. van, Voet, E. van der, & Sprecher, B. (2022). Legacy residential natural-gas infrastructure: urban mine or hydrogen infrastructure? *Resources conservation & Recycling*, *n/a*(n/a). (In review)

AI.I – Network provider data

Table A1.1, network operators and their infrastructure length extracted from the GIS-datasets, for Rendo and Coteq the numbers are based on Netbeheer Nederland and are marked in italics:

Network operator	Gas infrastructure length (km)	Number of pipeline segments
Stedin	23,345	555,368
Liander	63,585	5,675,329
Enexis	49,431	968,147
Enduris	3,924	57127
Westland infra	6	248
Rendo	*3,492*	N.a.
Coteq	*4,389*	N.a.
Total	**148,172**	**7,256,219**

AI.II – Natural gas production installations:

Table A1.2, kg of material required for the production of a m3 of natural gas (EcoInvent, 2010):

	Steel	Cement	Concrete
Onshore natural gas well	4.24E-04	4.04E-04	
Pipeline infrastructure	1.00E-03		
Natural gas processing plant	2.00E-03		9.29E-04
Total:	3.42E-03	4.04E-04	9.29E-04

With an annual onshore production of 7.77+E09 Nm3 of natural gas in the Netherlands for 2020, we calculated the following material stock for the natural gas production installations:

	Steel (ton)	Cement (ton)	Concrete (ton)
Total:	2.66E+04	3.14E+03	7.22E+03

AI.III – Eindhoven case study data

Table A1.3, residential buildings in the GIS dataset of Eindhoven:

All residential buildings in Eindhoven	Residential buildings built before 1965	Residential buildings built before 1948
73,138	32,829	14,869
100%	45%	20%

Table A1.4, materials in the natural gas infrastructure around residential buildings in Eindhoven.

	All residential buildings (tonnes)	Residential buildings built before 1965 (tonnes)	Residential buildings built before 1949 (tonnes)
Steel	6,930	5,180	2,060
PCV + SPVC	2,880	1,160	573
PE	36	13	6
Grey iron + ductile iron	2,140	1,520	1,340
Asbestos cement	21	8	1
Total	12,000	7,880	3,980

Figure A1.1, natural gas infrastructure in Eindhoven in 2020 (left), the situation in 2050 with 45% of buildings still connected to the gas grid (middle) and the situation in 2050 with 20% of buildings connected to the gas grid (right):

AI.IV – Lifetime distributions & material intensity per dwelling

Table A1.5, Weibull distribution parameters used in the Dynamic Stock Model:

	Scale	Shape	Source
Natural gas boilers	2	17	(Oliver-Solà et al., 2009a)
Pipelines	2	38	(Mukherjee et al., 2015)
Natural gas production installations	2	32	(Rijksoverheid, 2021)

Table A1.6, materials intensity of the natural-gas-based heating system per dwelling:

	Steel	(S)PVC	Copper	Cast iron	Concrete	Cement	Brass	PE	Bronze	Total
Natural gas production installations	4.2	0.0	0.0	0.0	1.1	0.5	0.0	0.0	0.0	5.8
Infrastructure	57.7	42.5	0.0	11.3	0	0	0.0	3.6	0.0	115.1
CV-boilers	27.3	6.6	8.4	0.2	0.0	0.0	1.9	0.0	0.3	44.6

AI.V – Pipelines suitable for the distribution of hydrogen

Table A1.7, materials in the Dutch natural-gas infrastructure deemed suitable for the distribution of hydrogen by the Dutch network providers:

Material	(S)PVC	Steel	PE	Cast iron	Asbestos cement	Total
Stock (kilotons)	277.0	376.5	23.7	73.8	1.4	752.5
Length (km)	103,188	22,449	18,732	3,462	245	148,172
Mass percentage	37%	50%	3%	10%	0%	100%
Length percentage	69.8%	15.2%	12.5%	2.3%	0.2%	100%
Suitable for hydrogen distribution	Yes	Yes	Yes	No	No	

Appendix II

Based on supplementary information provided with chapter 3:

Verhagen, T. J., Voet, E. van der, & Sprecher, B. (2020). Alternatives for natural-gas-based heating systems: A quantitative GIS-based analysis of climate impacts and financial feasibility. *Journal of Industrial Ecology*, *n/a*(n/a). https://doi.org/10.1111/jiec.13047

AII.I – Model variables

Table A2.1, variables used in the model:

Variable	Value	Unit	Source
2018 price per m3 gas	0.67	Euro	(Milieu centraal, 2019)
2018 price per kWh electricity	0.21	Euro	(Milieu centraal, 2019)
2018 price per kWh network heat	0.065	Euro	(Milieu centraal, 2019)
Cost insulation per kWh/m2	1.47	Euro	Supplementary data 4
Kg CO_2 per kWh gas	0.178	Kg	
Lifetime heat pump	15	Years	(Technische Unie, 2018)
Lifetime heat exchangers	15	Years	(RVO, 2014)
Lifetime CV	15	Years	(RVO, 2014)
Infrastructure cost heat pumps	10000	Euro	(Rijksoverheid, 2018c)
Infrastructure cost heating networks	12800	Euro	(Province of Zuid-Holland, 2018)
Cost heat pump	10000	Euro	(Rijksoverheid, 2018c)
Cost heat exchanger	850	Euro	(RVO, 2014)
Cost boiler	2000	Euro	(RVO, 2014)
COP heat pump	3.5	kWh heat / kWh of the system	(Greenhome, 2017)
COP low temperature	0.88	kWh heat / kWh of the system	(Lund et al., 2014)
COP high temperature	0.76	kWh heat / kWh of the system	(Lund et al., 2014)
CO_2 intensity heat pumps	2.14	kg CO_2 per kWh	Supplementary data 1
CO_2 intensity LT	0.468	kg CO_2 per kWh	Supplementary data 1
CO_2 intensity HT	0.674	kg CO_2 per kWh	Supplementary data 1

AII.II – Investment per building and insulation

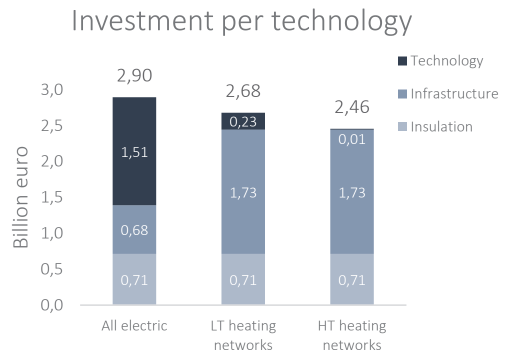

Figure A2.1, investment per building and technology in the baseline scenario for the whole case study:

AII.III – Insulation calculations

Table A2.2, overview of the investment and energy reduction of a Dutch residential building (Milieu centraal, 2018):

	Investment	Annual reduction kWh/m2	Euro per kWh/m2
Wall insulation (5-8cm)	€ 817.00	44.82	18.23
Wall insulation (8-10cm)	€ 4,388.00	4.37	1004.36
Floor insulation (8-10cm)	€ 1,165.00	14.08	82.76
Floor insulation (13-20cm)	€ 503.00	4.69	107.19
Roof insulation (8-10cm)	€ 3,692.00	19.74	187.02
Roof insulation (13-20cm)	€ 950.00	9.87	96.25
HR++ glass living rooms	€ 2,307.00	8.09	285.15
HR ++ glass bedrooms	€ 1,912.00	6.80	281.34
Total:	**€ 15,734.00**	**112.46**	**139.91**

95 m2

1.47 euro/kWh/m2 energy reduction

AII.IV – Case study GIS-maps

Figure A2.2, reduction of CO2 emissions with different heating technologies in the case study:

AII.V – CO_2 emissions per building

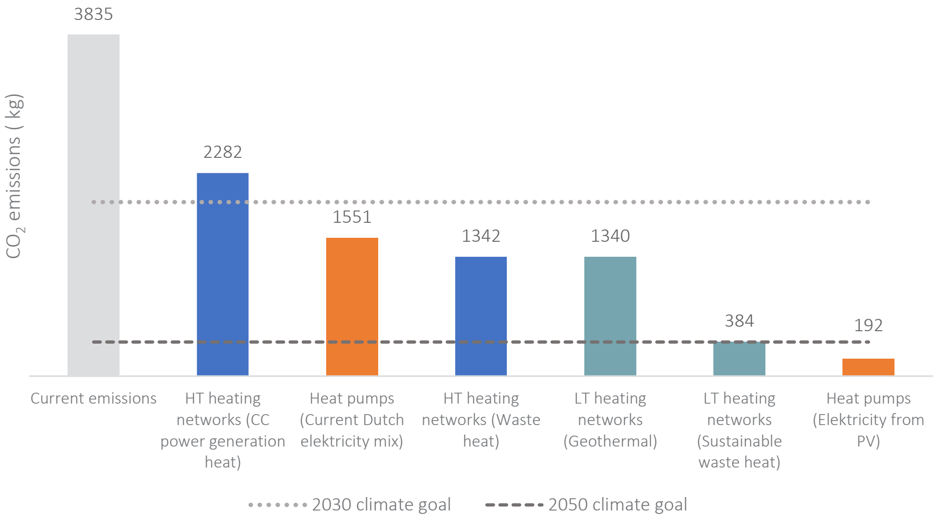

Figure A2.3, average annual urban heating CO_2 emissions per building and technology:

2030 climate goal - 50% reduction in heating-related CO_2 emissions

2050 climate goal - 90% reduction in heating-related CO_2 emissions

Appendix III

Based on supplementary information provided with chapter 4:
Verhagen, T. J., Sauer, M. L., van der Voet, E., & Sprecher, B. (2021). Matching
Demolition and Construction Material Flows, an Urban Mining Case Study.
Sustainability, 13(2), 653. https://doi.org/10.3390/su13020653

AIII.I – Construction and demolition in Leiden for the 2020-2030:

Table A3.1, planned demolition in m2 for the municipality of Leiden, 2020-2030:

	Row house	Offices	High rise	Commercial	Other	Detached	Apartment
2019	0	1,845	52,613	0	22,706	1,831	14,511
2020	4,096	1,590	52,114	0	3,796	1,298	48,733
2021	12,082	1,321	978	15,124	32,317	0	2,340
2022	0	41,122	35,755	0	50,443	0	2,725
2023	0	6,115	0	2,747	48,875	0	0
2024	0	0	0	0	13,468	0	0
2025	0	18,249	0	0	31,542	97	16,599
2026	2,311	10,035	20,209	2,553	29,021	461	12,130
2027	2,311	10,035	20,209	2,553	29,021	461	12,130
2028	2,311	10,035	20,209	2,553	29,021	461	12,130
2029	0	0	0	0	11,925	0	0
2030	0	0	0	0	35,526	0	0

Table A3.2, planned construction in m2 for the municipality of Leiden, 2020-2030:

	Row house	Offices	High rise	Commercial	Other	Detached	Apartment
2019	0	0	23,080	0	25,890	1,640	11,760
2020	7,600	1,440	60,910	0	5,860	1,760	32,400
2021	13,120	7,200	3,520	10,240	95,920	0	3,280
2022	0	68,160	26,300	0	75,560	0	0
2023	0	52,920	0	4,000	95,880	0	0
2024	0	0	0	0	48,300	0	0
2025	0	40,000	0	0	32,300	49,280	32,000
2026	2,960	24,246	16,259	2,034	54,244	7,526	11,349
2027	2,960	24,246	16,259	2,034	54,244	7,526	11,349
2028	2,960	24,246	16,259	2,034	54,244	7,526	11,349
2029	0	0	0	0	65,160	0	0
2030	0	0	0	0	100,000	0	0

Total demolition: 814,640 m2
Total construction: 1,351,331 m2

AIII.II – Construction and demolition waste in Leiden

Table A3.3, demolition waste supply per year (tonnes):

	Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
2019	80,838	26,734	5,539	1,269	642	1,133	1,931	1,572	1,087	984	338	347
2020	119,258	41,645	7,229	278	700	567	2,222	2,282	789	1,468	521	154
2021	44,605	11,570	3,000	2,520	531	1,853	1,431	541	1,518	1,063	75	587
2022	97,802	21,724	5,513	4,731	1,054	3,490	3,183	1,219	2,669	1,595	189	1,109
2023	43,104	9,725	2,084	2,983	516	2,118	1,373	254	1,650	796	-	678
2024	10,112	2,474	481	696	120	493	309	59	393	171	-	158
2025	62,330	15,585	2,834	2,573	548	1,888	1,615	575	1,475	1,028	82	600
2026	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
2027	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
2028	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
2029	8,954	2,190	426	616	107	436	273	52	348	151	-	140
2030	26,675	6,525	1,268	1,836	317	1,300	815	156	1,036	451	-	417

Table A3.4, construction material demand per year (tonnes):

	Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
2019	55,949	18,063	3,537	1,338	455	1,073	1,310	889	964	740	179	335
2020	103,818	36,222	7,109	377	695	619	2,194	2,212	813	1,272	503	173
2021	96,705	23,948	5,495	5,857	1,135	4,228	3,048	921	3,408	1,875	98	1,349
2022	125,109	23,653	6,513	7,426	1,446	5,365	4,355	1,190	3,990	2,230	129	1,711
2023	113,084	20,658	5,330	7,895	1,366	5,611	3,925	672	4,190	2,180	0	1,796
2024	36,266	8,871	1,724	2,496	431	1,767	1,108	213	1,409	613	0	567
2025	152,889	57,208	16,781	3,736	1,147	2,978	3,572	2,050	2,462	2,309	398	921
2026	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
2027	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
2028	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
2029	48,925	11,968	2,326	3,367	582	2,384	1,494	287	1,901	827	0	765
2030	75,085	18,367	3,570	5,167	893	3,659	2,293	440	2,917	1,269	0	1,175

Table A3.5, material supply from demolition and demand from construction per year (tonnes):

		Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
2019	Supply	80,838	26,734	5,539	1,269	642	1,133	1,931	1,572	1,087	984	338	347
	Demand	55,949	18,063	3,537	1,338	455	1,073	1,310	889	964	740	179	335
	Balance	24,889	8,670	2,002	-69	187	60	621	683	123	245	159	12
2020	Supply	119,258	41,645	7,229	278	700	567	2,222	2,282	789	1,468	521	154
	Demand	103,818	36,222	7,109	377	695	619	2,194	2,212	813	1,272	503	173
	Balance	15,440	5,424	120	-99	5	-52	27	69	-24	196	17	-19
2021	Supply	44,605	11,570	3,000	2,520	531	1,853	1,431	541	1,518	1,063	75	587
	Demand	96,705	23,948	5,495	5,857	1,135	4,228	3,048	921	3,408	1,875	98	1,349
	Balance	-52,100	-12,378	-2,495	-3,338	-605	-2,375	-1,617	-380	-1,890	-812	-22	-762
2022	Supply	97,802	21,724	5,513	4,731	1,054	3,490	3,183	1,219	2,669	1,595	189	1,109
	Demand	125,109	23,653	6,513	7,426	1,446	5,365	4,355	1,190	3,990	2,230	129	1,711
	Balance	-27,307	-1,929	-1,000	-2,695	-391	-1,875	-1,172	29	-1,321	-635	60	-603
2023	Supply	43,104	9,725	2,084	2,983	516	2,118	1,373	254	1,650	796	-	678
	Demand	113,084	20,658	5,330	7,895	1,366	5,611	3,925	672	4,190	2,180	0	1,796
	Balance	-69,980	-10,933	-3,246	-4,912	-850	-3,493	-2,553	-418	-2,540	-1,384	-	-1,117
2024	Supply	10,112	2,474	481	696	120	493	309	59	393	171	-	158
	Demand	36,266	8,871	1,724	2,496	431	1,767	1,108	213	1,409	613	0	567
	Balance	-26,154	-6,398	-1,244	-1,800	-311	-1,275	-799	-153	-1,016	-442	-	-409
2025	Supply	62,330	15,585	2,834	2,573	548	1,888	1,615	575	1,475	1,028	82	600
	Demand	152,889	57,208	16,781	3,736	1,147	2,978	3,572	2,050	2,462	2,309	398	921
	Balance	-90,559	-41,623	-13,947	-1,163	-599	-1,089	-1,957	-1,475	-987	-1,282	-316	-322
2026	Supply	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Balance	-32,253	-8,452	-2,830	-2,011	-366	-1,443	-1,064	-235	-1,094	-588	-15	-460
2027	Supply	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Balance	-32,253	-8,452	-2,830	-2,011	-366	-1,443	-1,064	-235	-1,094	-588	-15	-460
2028	Supply	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Balance	-32,253	-8,452	-2,830	-2,011	-366	-1,443	-1,064	-235	-1,094	-588	-15	-460
2029	Supply	8,954	2,190	426	616	107	436	273	52	348	151	-	140
	Demand	48,925	11,968	2,326	3,367	582	2,384	1,494	287	1,901	827	0	765
	Balance	-39,971	-9,778	-1,901	-2,751	-476	-1,948	-1,221	-234	-1,553	-676	-	-625
2030	Supply	26,675	6,525	1,268	1,836	317	1,300	815	156	1,036	451	-	417
	Demand	75,085	18,367	3,570	5,167	893	3,659	2,293	440	2,917	1,269	0	1,175
	Balance	-48,410	-11,842	-2,302	-3,331	-576	-2,359	-1,478	-284	-1,881	-818	-	-757

AIII.III – Annual collected and recycled demolition waste in Leiden

Table A3.6, material recycling per material and year (tonnes, extrapolated values in dark blue):

		Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
	Collection rate (%)	85%	95%	95%	0%	95%	95%	95%	95%	95%	50%	95%	100%
	Recycled content (%)	50%	50%	90%	0%	50%	85%	91%	80%	40%	50%	96%	0%
2019	Supply	68,712	25,397	5,262	-	610	1,077	1,835	1,493	1,032	492	321	347
	Demand	55,949	18,063	3,537	1,338	455	1,073	1,310	889	964	740	179	335
	Recycled content limit	27,974	9,032	3,183	-	228	912	1,192	711	386	370	172	-
	Recycled	27,974	9,032	3,183	-	228	912	1,192	711	386	370	172	-
2020	Supply	101,369	39,563	6,867	-	665	538	2,111	2,167	750	734	495	154
	Demand	103,818	36,222	7,109	377	695	619	2,194	2,212	813	1,272	503	173
	Recycled content limit	51,909	18,111	6,398	-	348	526	1,997	1,770	325	636	483	-
	Recycled	51,909	18,111	6,398	-	348	526	1,997	1,770	325	636	483	-
2021	Supply	37,914	10,991	2,850	-	504	1,761	1,359	514	1,442	532	72	587
	Demand	96,705	23,948	5,495	5,857	1,135	4,228	3,048	921	3,408	1,875	98	1,349
	Recycled content limit	48,352	11,974	4,945	-	568	3,594	2,773	737	1,363	937	94	-
	Recycled	37,914	10,991	2,850	-	504	1,761	1,359	514	1,363	532	72	-
2022	Supply	83,132	20,637	5,238	-	1,002	3,315	3,024	1,158	2,536	797	179	1,109
	Demand	125,109	23,653	6,513	7,426	1,446	5,365	4,355	1,190	3,990	2,230	129	1,711
	Recycled content limit	62,554	11,826	5,862	-	723	4,560	3,963	952	1,596	1,115	124	-
	Recycled	62,554	11,826	5,238	-	723	3,315	3,024	952	1,596	797	124	-
2023	Supply	36,638	9,239	1,980	-	490	2,012	1,304	241	1,568	398	-	678
	Demand	113,084	20,658	5,330	7,895	1,366	5,611	3,925	672	4,190	2,180	-	1,796
	Recycled content limit	56,542	10,329	4,797	-	683	4,769	3,572	538	1,676	1,090	-	-
	Recycled	36,638	9,239	1,980	-	490	2,012	1,304	241	1,568	398	-	-
2024	Supply	8,596	2,350	457	-	114	468	293	56	373	85	-	158
	Demand	36,266	8,871	1,724	2,496	431	1,767	1,108	213	1,409	613	-	567
	Recycled content limit	18,133	4,436	1,552	-	216	1,502	1,008	170	564	306	-	-
	Recycled	8,596	2,350	457	-	114	468	293	56	373	85	-	-

Table A3.6, Continued

		Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
2025	Supply	52,980	14,806	2,693	-	520	1,794	1,534	546	1,402	514	78	600
	Demand	152,889	57,208	16,781	3,736	1,147	2,978	3,572	2,050	2,462	2,309	398	921
	Recycled content limit	76,444	28,604	15,103	-	573	2,531	3,251	1,640	985	1,155	382	-
	Recycled	52,980	14,806	2,693	-	520	1,794	1,534	546	985	514	78	-
2026	Supply	55,620	17,569	3,621	-	558	1,566	1,637	882	1,300	508	163	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Recycled content limit	48,844	13,473	5,977	-	477	2,628	2,537	931	985	801	179	-
	Recycled	48,844	13,473	3,621	-	477	1,566	1,637	882	985	508	163	-
2027	Supply	55,620	17,569	3,621	-	558	1,566	1,637	882	1,300	508	163	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Recycled content limit	48,844	13,473	5,977	-	477	2,628	2,537	931	985	801	179	-
	Recycled	48,844	13,473	3,621	-	477	1,566	1,637	882	985	508	163	-
2028	Supply	55,620	17,569	3,621	-	558	1,566	1,637	882	1,300	508	163	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Recycled content limit	48,844	13,473	5,977	-	477	2,628	2,537	931	985	801	179	-
	Recycled	48,844	13,473	3,621	-	477	1,566	1,637	882	985	508	163	-
2029	Supply	7,611	2,081	404	-	101	415	260	50	330	76	-	140
	Demand	48,925	11,968	2,326	3,367	582	2,384	1,494	287	1,901	827	-	765
	Recycled content limit	24,463	5,984	2,094	-	291	2,027	1,360	229	760	413	-	-
	Recycled	7,611	2,081	404	-	101	415	260	50	330	76	-	-
2030	Supply	22,673	6,199	1,205	-	301	1,235	774	148	984	225	-	417
	Demand	75,085	18,367	3,570	5,167	893	3,659	2,293	440	2,917	1,269	-	1,175
	Recycled content limit	37,542	9,183	3,213	-	447	3,110	2,087	352	1,167	635	-	-
	Recycled	22,673	6,199	1,205	-	301	1,235	774	148	984	225	-	-

Table A3.7, summarized recycling of materials (tonnes):

	Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
Supply	586,487	183,970	37,817	-	5,983	17,315	17,405	9,022	14,318	5,377	1,634	5,747
Demand	1,100,894	299,796	72,309	50,141	11,011	36,960	31,661	12,366	29,441	18,122	1,867	11,731
Recycled	455,383	125,053	35,269	-	4,760	17,138	16,648	7,636	10,865	5,156	1,418	-

Supply of demolition waste: 1,033,029 metric tonnes
Supply of demolition waste after collection: 885,074 metric tonnes

Demand: 1,676,298 metric tonnes
Recycled: 679,327 metric tonnes
66% of demolition waste recycled as secondary materials, 41% lower primary material demand
14% material of demolition waste not suitable for collection, 20% mismatch

Appendix IV

Based on supplementary information provided with chapter 5:
Verhagen, T. J., Cetinay, H. I., van der Voet, E., & Sprecher, B. (2022). Transitioning to Low-Carbon Residential Heating: The Impacts of Material-Related Emissions. *Environmental Science & Technology.* https://doi.org/10.1021/acs.est.1c06362

In this document, we included the consequences of the heating transition for the electricity demand in detail (I), the input data used in the model (II), excluded materials (III), and the output data of the model per scenario (IV).

AIV.I – Consequences of the heating transition for the electricity demand

Figure A4.1 represents a typical low voltage grid in a neighbourhood in Europe (IEEE, 2020). The network has $N = 906$ lv connections (nodes), that are connected by $L = 905$ lv cables (links) and 1 mv/lv transformer. Figure is the graphical representation of the grid, where the nodes represent the lv connections and the links are the cables between the connections.

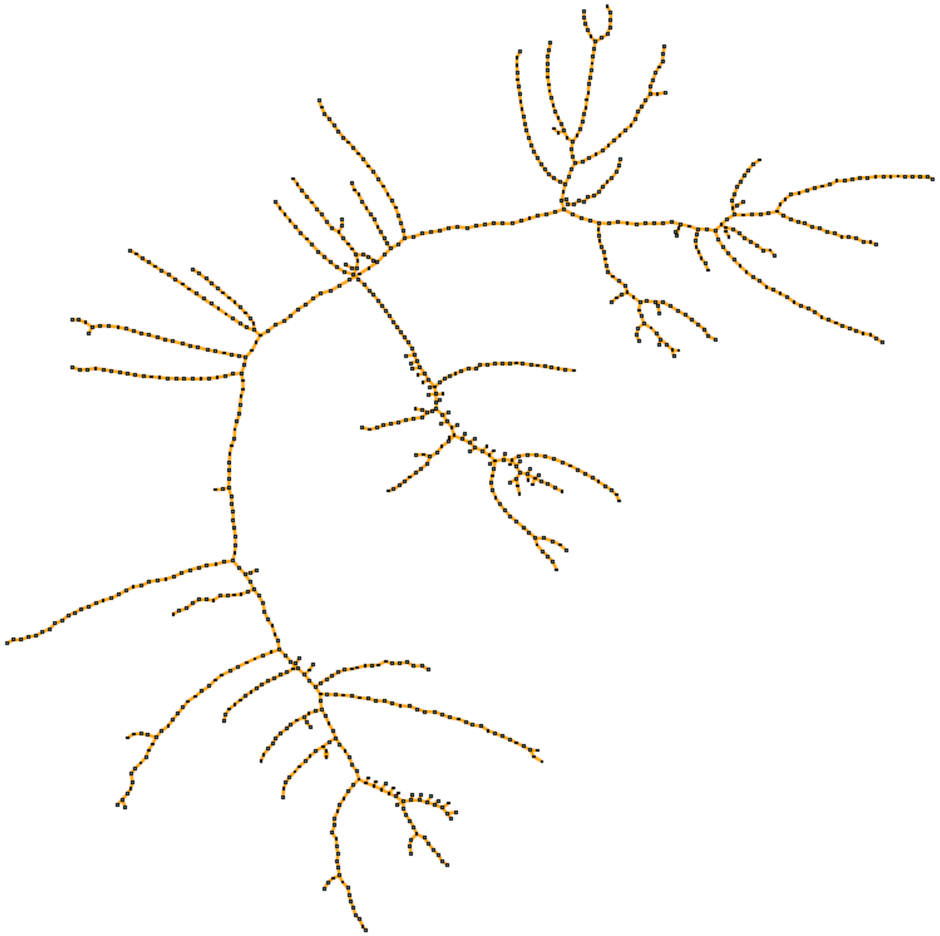

Figure A4.1. European low voltage grid with N = 906 nodes and L = 905 links. The grid is a tree network, in other words, there are no loops. The network starts from the low voltage side of the distribution transformer (node 1).

We use electricity consumption behavior profiles from the vereniging Nederlandse Energie-Data Uitwisseling (NEDU), which is as an umbrella organization of the Dutch electricity companies, to represent an average lv connection in the Netherlands (NEDU, 2020). We use the profile E1A profile, which represent a lv connection smaller than 3x25A. A typical household electricity consumption in the Netherlands is taken as 6000 kwh. The planning for the electricity grid investments are mainly based on the peak-load conditions, in other words when the electricity consumption demand is maximum. According to the NEDU profile, the peak load happens at the first week of January with the maximum peak load of 1.55 kw per household as shown in Figure A4.2.

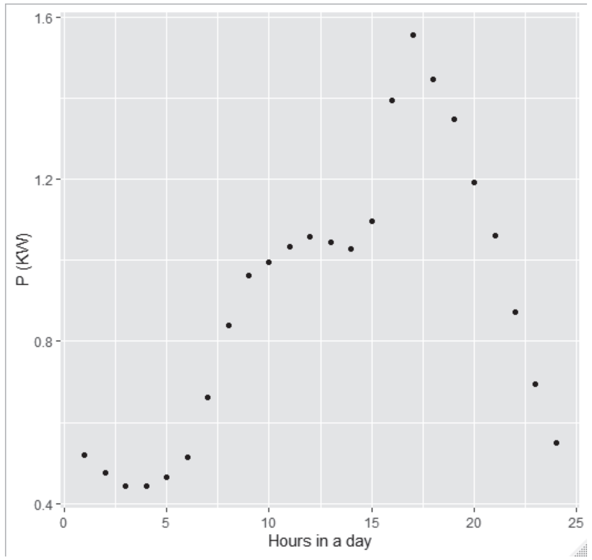

Figure A4.2. The electricity consumption of an average household at the peak day. The x axis represent the hours in a day whereas the y axis in the electricity demand in kw.

We will use the linearized DC power flow equations to find the flow of each link in network at the peak load conditions (Cetinay, Kuipers, et al., 2018). Following (Cetinay, Soltan, et al., 2018). we assume that the thermal capacity c_i of a link *l* is $c_l = \min\{\text{mean(flows)}, (1+\alpha) \times f_l\}$ and an investment decision is made when the flow f_i of a link is higher than its thermal capacity c_i. In this paper we take $\alpha = 0.5$.

We assume that in our test grid, initially, there are no houses with heat pumps, i.e. the number of total heat pumps is zero. Next, we add the heat pump load on the regular house hold electricity demand. We choose a heat pump of size 4 kw. Focusing at the peak day, we assume that the heat pump will work on a full capacity with COP=1 making the electrical load of a heat pump 4 kw (Nyers & Nyers, 2011). We take the simultaneity factory of the heat pumps as 1, meaning that most people are likely have heat pump working at this winter peak day. If we the probability that a house hold getting a heat pump is h_i , the total load of a household with heat pump P_{max}^{HP} becomes

$$P_{i,max}^{HP} = P_{i,max}^{0} + h_i \times s_i$$

where S_i is the size of the heat pump at connection (node) *i* and $P_{max}^{0} = 1.55$ is the initial peak load of the connection *i*.

We assume a uniform distribution of the heat pump among the houses, in other words, every house has an equal probability h_i to obtain a heat pump. Under these assumptions, we re-solve the dc power flow again to calculate the flow of each link in the network and we compare these new flows of the links with their thermal capacities to find the overloaded links. In addition, using the lengths of the cables in the datasets, we also calculate the total length of the overloaded links.

In order to calculate the average additional investment of lv cables and the number of distribution transformers per household in this example neighborhood, we normalize the heat pump integration effects with the number of households *N*. For the distribution transformers, we see that it becomes overloaded when $h_i = 0.2$ thus its investment decision becomes a step function. Table presents the average investments per customer in the example grid. To assess the whole Netherlands, we can scale up this average neighborhood for each city and their ambition for the heat pump integration.

Table A4.1 Average investment length of lv cables and distribution transformers per household versus the probability of integration of heat pumps

Probability of integration of heat pumps h_i	Additional investment length of lv cables (m)	Additional investment of distribution transformers (units)
0	0	0
0.1	0.04	0
0.2	0.42	0.0011
0.3	0.42	0.0011
0.4	0.44	0.0011
0.5	0.45	0.0011
0.6	0.47	0.0011
0.7	0.48	0.0011
0.8	0.5	0.0011
0.9	0.51	0.0011
1	0.52	0.0011

A similar analysis has been done also for the hybrid heat pumps, with the assumption that the heat pump peak load is 3 kw (due to the switching to gas). Compared to the full electric heat pumps, we see the transformer is overloaded when h_i = 0.3 and the additional investments in the lv cables are slightly lower.

Table A4.2 Average investment length of lv cables and distribution transformers per household versus the probability of integration of hybrid heat pumps

Probability of integration of hybrid heat pumps h_i	Additional investment length of lv cables (m)	Additional investment of distribution transformers (units)
0	0	0
0.1	0.01	0
0.2	0.05	0
0.3	0.42	0.0011
0.4	0.42	0.0011
0.5	0.44	0.0011
0.6	0.45	0.0011
0.7	0.45	0.0011
0.8	0.47	0.0011
0.9	0.47	0.0011
1	0.49	0.0011

AIV.II – Model input data

Table A4.3a, mean lifetimes for each low-carbon heating technology subcomponent (years):

	Building adjustments	Insulation materials	Infrastructure	Electricity and heat production	Sources
HT heating networks	25	75	50	20	(Oliver-Solà et al., 2009b; Sullivan, 2010)
LT heating networks	25	75	50	30	(Basosi et al., 2020; Oliver-Solà et al., 2009b)
Heat pumps	25	75	40	25	(Greening & Azapagic, 2012; Jorge et al., 2012; Spath & Mann, 2000; Vestas, 2019)
Hybrid heat pumps	25	75	40	25	(Greening & Azapagic, 2012; Jorge et al., 2012; Spath & Mann, 2000; Vestas, 2019)

Table A4.3b, Weibull function parameters used in the Dynamic Stock Model based on the mean lifetimes from Table A4.3a:

	Building adjustments		Insulation materials		Infrastructure		Electricity and heat production	
	Scale	Shape	Scale	Shape	Scale	Shape	Scale	Shape
HT heating networks	2	28	67	2	2	57	2	23
LT heating networks	2	28	67	2	2	57	2	34
Heat pumps	2	28	67	2	2	45	2	28
Hybrid heat pumps	2	28	67	2	2	45	2	28

Table A4.4a, distribution of market share of low-carbon heating technologies for the Dutch built environment in 2050, based on the *warmtescenario* report by Berenschot (Berenschot, 2020a):

	Scenario 1 (Mix LT+ heat pump)	Scenario 2 (High heat pump)	Scenario 3 (High hybrid heat pump)
HT heating networks	5 %	5 %	10 %
LT heating networks	40 %	20 %	25 %
Heat pumps	35 %	55 %	25 %
Hybrid heat pumps	20 %	20 %	40 %

Table A4.4b, electricity generation composition for each scenario in 2050, based on the *klimaatneutrale energiescenarios* report by Berenschot (Berenschot, 2020b), (PBL, 2019; Rijksoverheid, 2017):

	Scenario 1 (Mix LT + heat pump)	Scenario 2 (High heat pump)	Scenario 3 (High hybrid heat pump)
Biogas power plant	26 %	35 %	31 %
Wind onshore	10 %	7 %	12 %
Wind offshore	26 %	20 %	21 %
Solar power (PV)	38 %	38 %	36 %

Table A4.5a and A4.5b are input data used from from our previous paper for the calculation of the operational emissions over time (Verhagen et al., 2020).

Table A4.5a, CO_2 intensity per kWh of supplied heat for heating networks and heat pumps sources (MRA & TNO, 2017) (Stimular, 2016):

	Gram CO_2/GJ	gram CO_2/ kWh heat	CO_2 intensity (natural gas = 1)	Temperature
Natural gas		192.8	1	N/A
Biomass	13000	46.8	0.24	LT
Waste heat without additional burning	8800	31.7	0.16	LT
Geothermal	25050	90.1	0.47	LT
Heat from burning waste	26000	93.6	0.49	HT
Waste heat Tata Steel	26000	93.6	0.49	HT
Waste heat from gas fired power plant	32000	115.2	0.60	HT
Waste heat from coal fired power plant	45000	162.0	0.84	HT

Table A4.5b, CO_2 intensity per kWh of supplied heat for heat pumps (COP = 3.5):

	Gram CO_2/ kWh electricity	gram CO_2/ kWh heat	CO_2 intensity (natural gas = 1)
PV	50	14.3	0.07
'Grey' electricity	365.83	104.5	0.54

Table A4.6, materials included and quantified in the model:

Other materials	Metals	Plastics
Cement	Aluminium	ABS
Ceramic brick	Brass	HDPE
Concrete	Bronze	PE
Limestone	Cast iron	Polyurethane (foam)
Sand	Copper	PVC
Wood fibreboard	Galvanized steel	Synthetic rubber
Mineral wool	Stainless steel	Glass fiber
	Steel	Polystyrene
	Nickel	
	Manganese	
	Chromium	
	Molybdenum	
	Tungsten	
	Niobium	
	Vanadium	
	Titanium	
	Cobalt	
	Tantalum	
	Neodymium	