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

Verhagen, T.J.

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).