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

Verhagen, T.J.

Chapter 2

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

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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:

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

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:

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

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
EOL-options	**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.

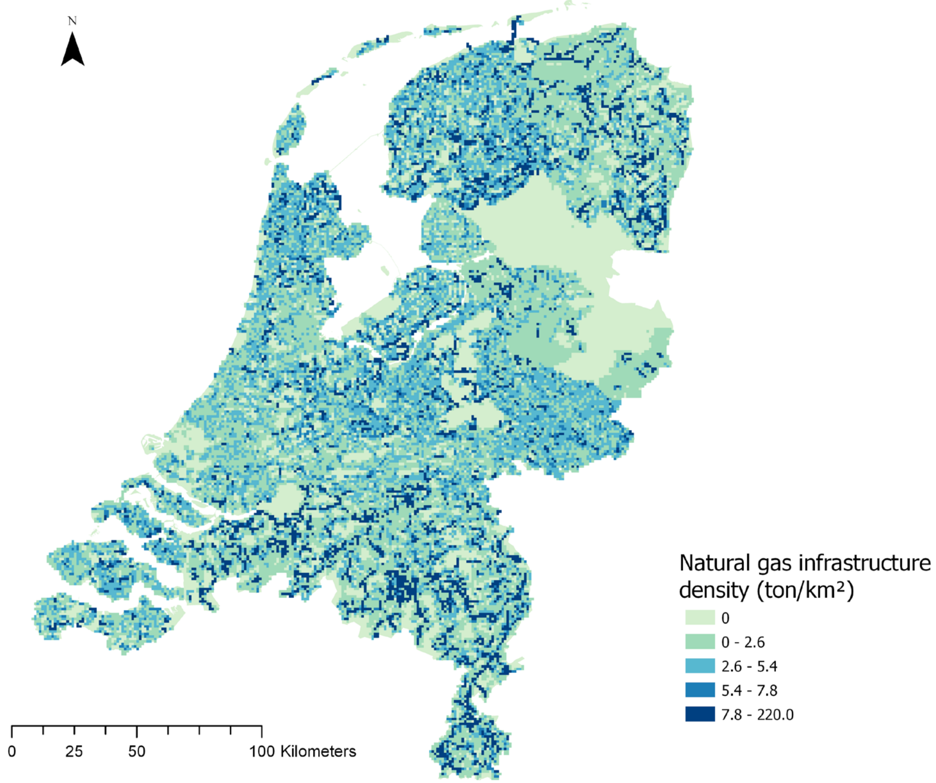

Figure 1, the material density of the Dutch natural gas pipeline infrastructure in 2020 in ton/km2:

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.

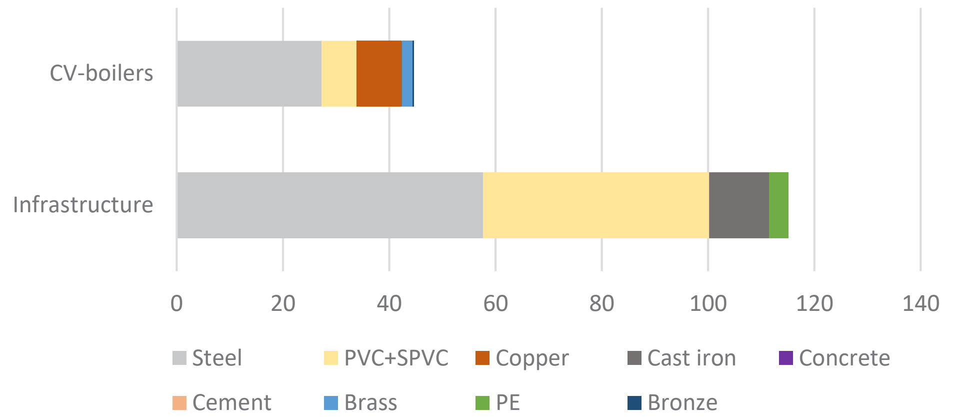

Figure 2, the material intensity in the natural-gas-based heating system in 2020 in kg per dwelling:

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.

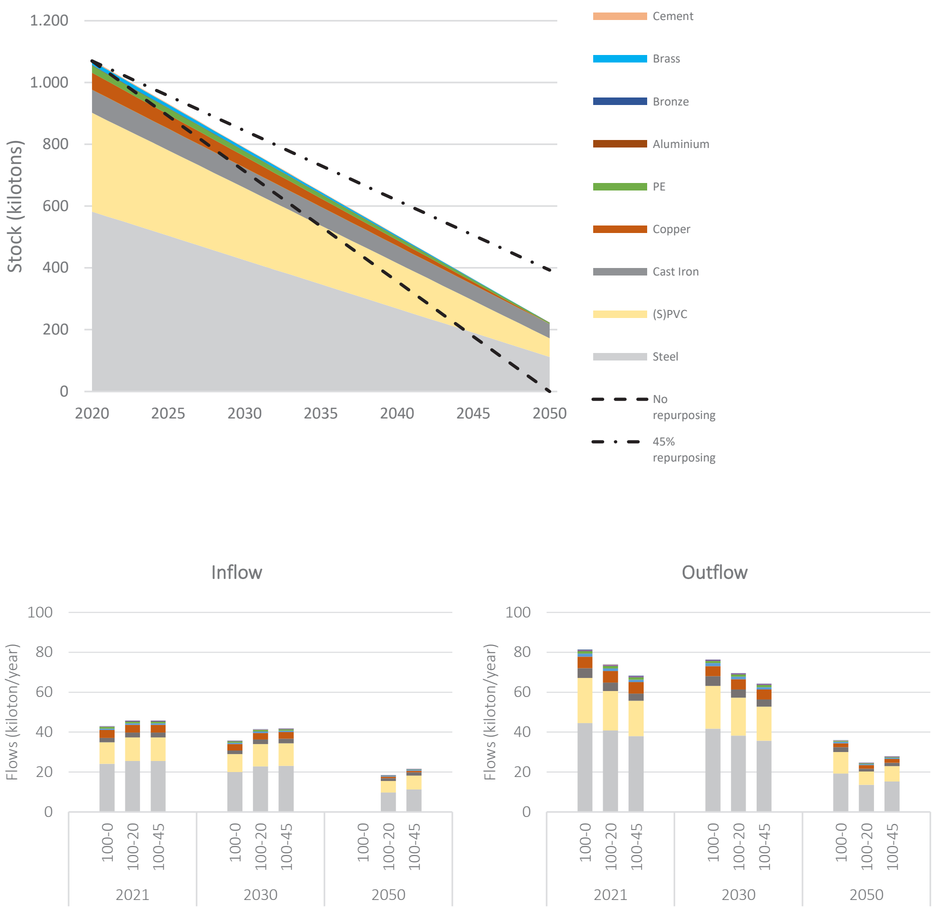

Figure 3, in-use material stock (top) and flows (bottom) of the natural-gas-based heating system for 2021, 2030 and 2050 for the development pathways. The top figure shows the material stock of the 20% repurposing development pathway (100-20), with the no repurposing (100-0) pathway as the lower limit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

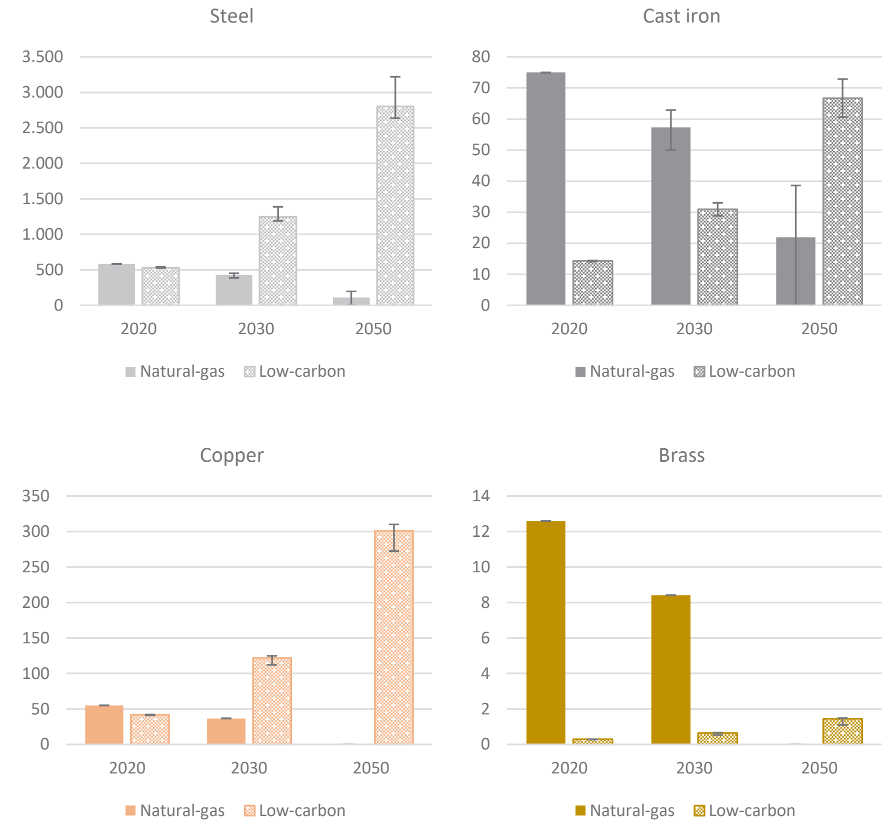

Figure 4a, in-use material stock of metals in the natural-gas-based heating system and the low-carbon heating system in 2020, 2030 and 2050 (kilotons). The different development pathways for both systems are shown with the error bars.

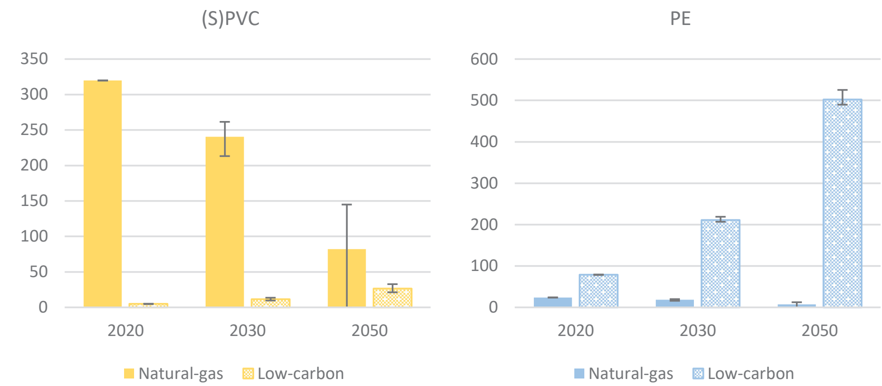

Figure 4b, in-use material stock of plastics in the natural-gas-based heating system and the low-carbon heating system in 2020, 2030 and 2050 (kilotons). The different development pathways for both systems are shown with the error bars.

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
EOL-options	**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.