A circular economy in 2050
A look at the stocks and flows of electricity cables in the Netherlands

A thesis presented by

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For the master program

Industrial Ecology

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Delft, The Netherlands
August 19, 2020

Executive summary

Creating a ‘circular economy’ is a hot topic these days. One of the countries with specific goals for creating a circular economy is the Netherlands. A program that aims for a Dutch circular economy by 2050 has been initiated by the Dutch government in 2016 (Ministerie van Infrastructuur en Milieu, 2016).

In order to create a circular economy, it is important to know what materials are already contained in society. One of the sectors in society containing large amounts of materials is the electricity system. If the Dutch government wants to recycle the materials contained in the electricity system as secondary materials, it is relevant to know which materials the system contains, and in which quantities. It is also relevant to know how the materials are currently recycled, and whether improvements could be made to increase the material outflows of the electricity system and reduce the inflows. To support the Dutch circular economy, this thesis has analyzed the metals in the cables of the electricity system, with the help of the following research question:

How will the metal stocks and flows of electricity cables in the Netherlands develop for different energy transition scenarios, and how can the outflows re-enter the circular economy?

To uncover the stocks and flows of electricity cables in the Netherlands, a Material Flow Analysis (MFA) has been conducted on aluminium, copper, and steel, and the current process of recycling cables has been studied through expert interviews.

To predict the possible development of the stocks and flows, I used four scenarios on the energy transition which were created by CE Delft (2017b). The scenarios are based on the level of steering of the energy transition, and the following levels have been used: regional steering, national steering, international steering, and generic steering (2017b). The scenarios have been created to show all 'corners of the playing field' of the energy transition to the Dutch government(2017b), and the actual energy transition will likely find itself somewhere in the middle of these scenarios.

For all four scenarios, the electricity grid needs to expand significantly until 2050. For these expansions, large metal inflows are needed, which are shown in Figure 1.

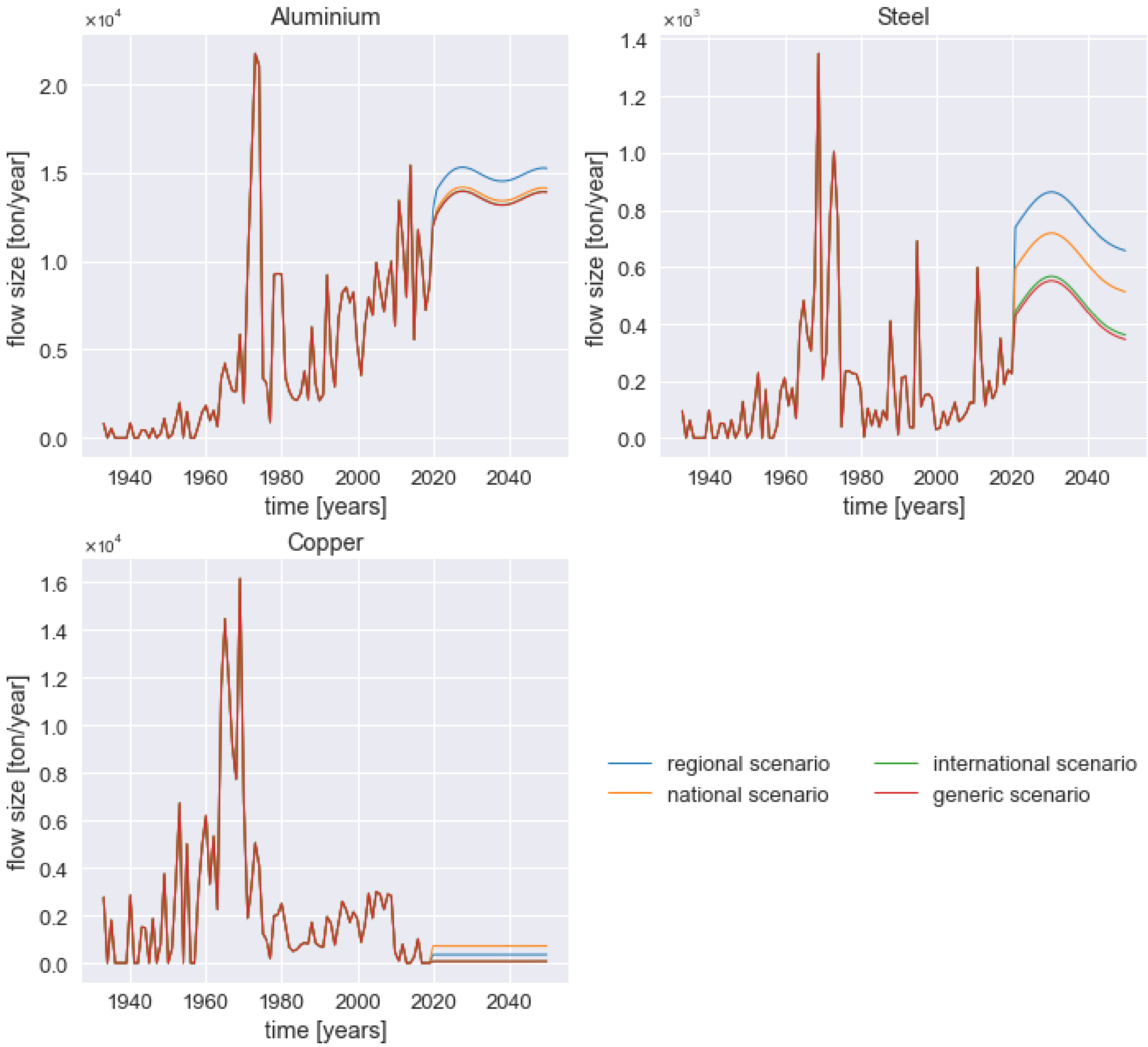

Figure 1. Material inflows per year, for both expansion of the electricity grid and replacement of EoL cables. The scale changes for each graph.

Although a difference is visible between the inflows for the four scenarios, the aluminium and steel inflows become quite high after 2020 for all scenarios. But even though these inflows will need to be high, similar high amounts of inflows have already been achieved around 1970, so the inflows should be possible to achieve. The inflows of copper look significantly different, they decrease instead of increase. The reason for this is that copper, which was used for the cores of cables in the past, has in recent years mainly been replaced by aluminium.

The outflows also change interestingly. In Figure 2, the in- and outflows of the metals are compared.

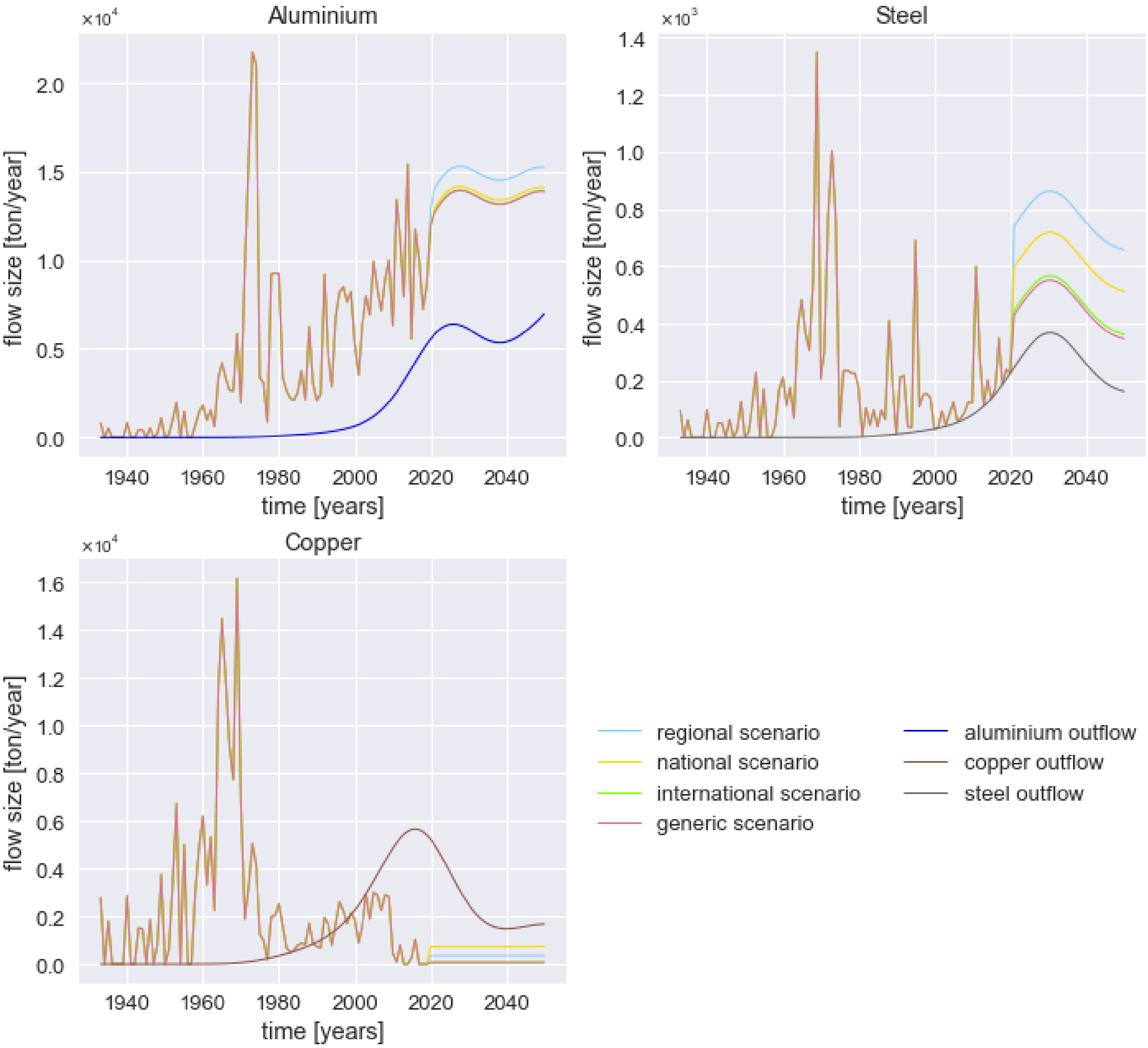

Figure 2. Material inflows for all scenarios and outflows of EoL cables. The graphs have different orders of magnitude.

The outflow of aluminum has increased largely since 2000 and it is visible that it will stay high until 2050. But compared to the inflow of aluminium, the outflow is significantly lower than the needed inflow. The outflows of copper currently just passed a high peak. Currently, significant amounts of copper become available for recycling, but it will decrease until 2040, after which the outflow will become fairly stable. What can be seen is that the copper outflow is higher than the needed inflow of copper for each year. The steel outflow will reach a peak in 2030, but as the aluminium flows, the inflow of steel will always be higher than the outflow. This means that for aluminium and steel, there is always more material inflow needed than the outflows could provide, so new material needs to be added into the system. However, in cables in the Netherlands, a very high degree of material purity is needed for the aluminum and copper inflows, to meet the current requirements on the materials for cables. This means that although the EoL cables are recycled and their metals are re-used as secondary material, the requirements on the purity of the metals make it undesirable to use secondary material for new cables. The reason for this is that metals from EoL cables are smelted in a batch with multiple alloys. Because of this, many other material particles are found in secondary metals, which decreases the purity of the material greatly. Thus, new cables cannot be made of secondary aluminium or copper, and only virgin metals will be used for the inflows into the electricity cables. However, the concept of a circular economy not only focusses on reducing waste, but it also aims to reduce the inflows in the economy. So only being able to use virgin metals for new cables is not favorable for the Dutch circular economy. It would be very beneficial if the aluminum and copper from EoL cables can be reused in new cables, as this specific secondary aluminium and copper already has the necessary purity for cables. As shown before, the copper outflows could fully supply the demand for new copper, so if it is possible to reuse that copper for new cables, no virgin copper would need to be added to the circular economy. However, when looking at aluminium, until 2050 the inflows are higher than the outflows, so even if the aluminium of EoL cables could be reused in new cables, still a large part of virgin aluminium would need to enter the economy. In order to truly obtain a circular economy, it might be needed to lower the requirements on metal purity for new cables, making it possible to use secondary material from all kinds of sectors instead of only from EoL cables.

Unfortunately, not all metal outflows of EoL cables do re-enter the economy as secondary material. A large part of the underground cables is left behind in the ground at their end of life, instead of being excavated by Distribution System Operators (DSOs). The main part of the electricity consists of underground cables, which means that this has a large influence on the actual recovered secondary material flow. There can be multiple reasons why cables are left behind, but they can be aggregated into two categories: it is too expensive to get them out of the ground, or there is not enough stakeholder support. The EoL cables that remain in the ground form a hibernating stock. Exact data on the percentage of EoL cables entering the hibernating stock in the Netherlands was unfortunately not found, it was only found that it is a large part. To show how the hibernating stock could develop three hibernation percentages for EoL cables have been analyzed. The hibernating stock and the associated recovery flow of copper and aluminium of these hibernation percentages are shown in Figure 3 and Figure 4 respectively.

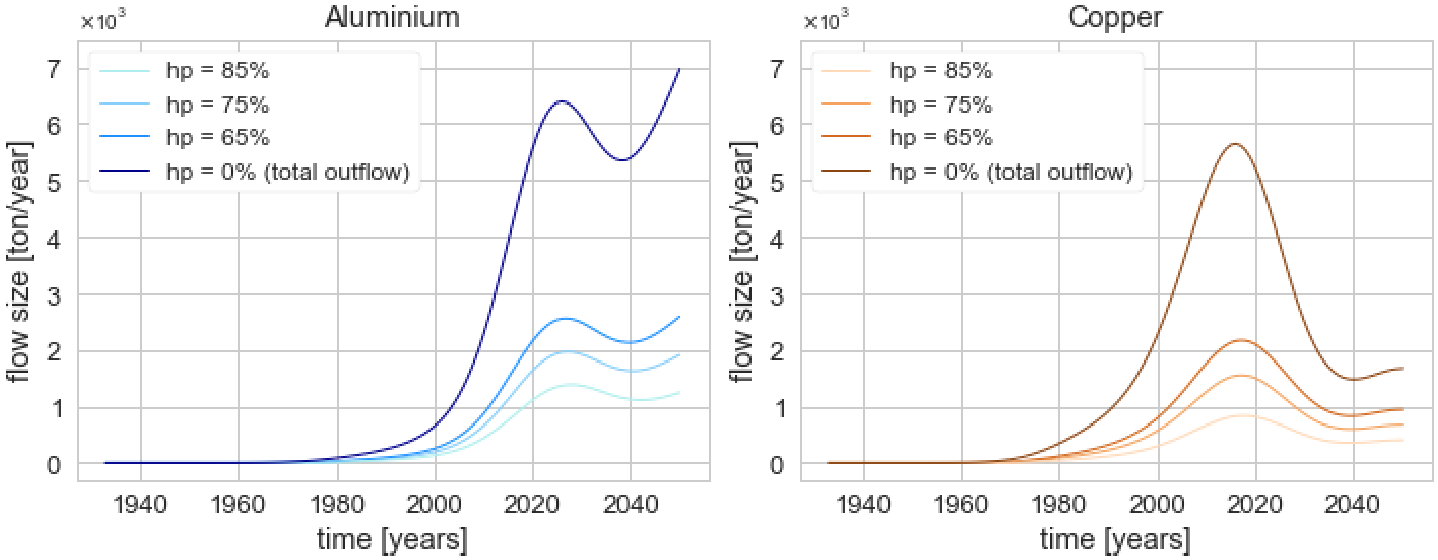

Figure 3. The recovered aluminium and copper flows, as they would be for different hibernation percentages (hp).

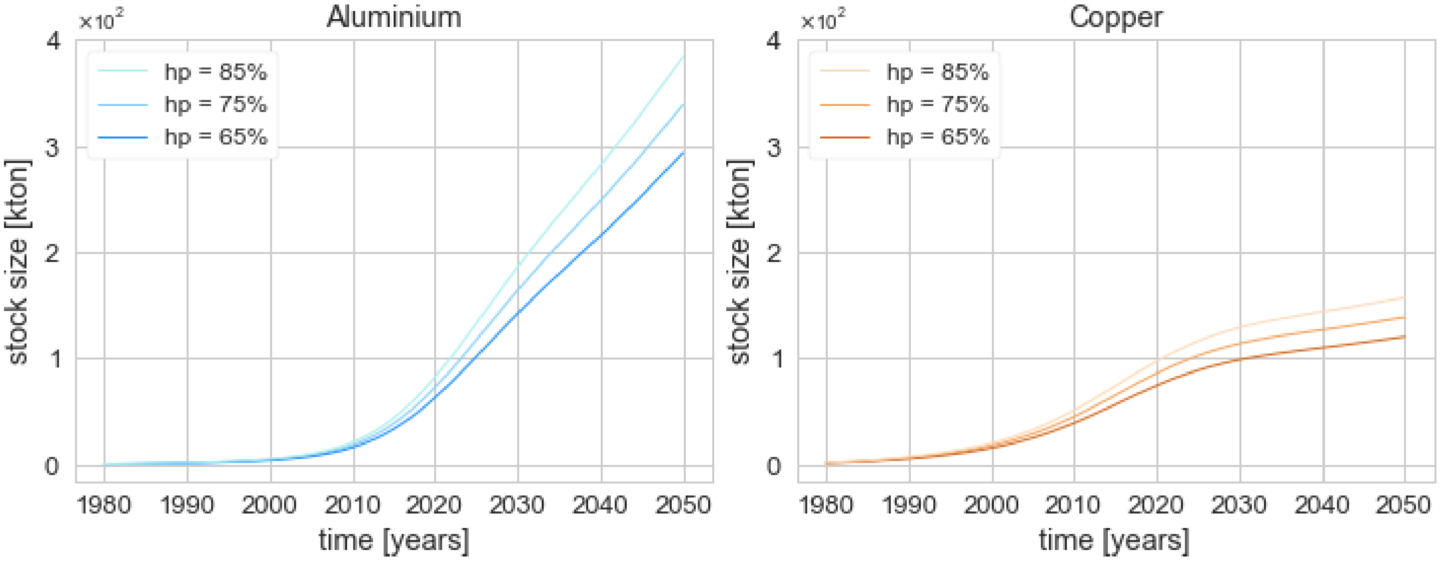

Figure 4. The size of the hibernating stock, as it would be for different hibernation percentages.

The hibernation percentages in these graphs denote what percentage of EoL cables in one year enters the hibernating stock. As visible in the figures, the model has shown that if indeed a large part of the cables remain underground, a huge hibernating stock will generate over the coming years, even though it is currently still relatively small. Since the Netherlands aims to create a circular economy, it is a huge waste of all possible secondary materials that are in EoL cables, and measures should be taken to stimulate the DSOs to remove the cables from the ground.

After all, the electricity grid contains large quantities of aluminum, copper, and steel, which could certainly be used for the circular economy, if only they are seen as a valuable material source and are treated accordingly.

Based on the discussed conclusions I would like to make four recommendations.

First of all, there is a large data gap on what shares of underground cables are excavated or left behind, and I would recommend researching further what these shares would exactly be. The model used in this research has made an educated assumption on these shares and thus has gotten a general idea of what the hibernating stock could become. But gathering this data will provide much more specific knowledge on how large the hibernating stock will be in reality, and thus the exact amounts of material which can be taken from the hibernating stock for the purpose of the circular economy. As this data is currently not available I would also recommend to record the data on what exactly happens to EoL cables more thoroughly.

Secondly, to keep the hibernating stock as small as possible, and thus recover as much secondary material of EoL cables as possible, I recommend the government to implement instruments which entice DSOs to remove EoL cables from the ground. Two examples would be to simply oblige DSOs to excavate EoL cables, or to implement a ‘precario’-tax (precariobelasting) on cables which are out of use but left behind in the ground.

Thirdly, to keep the inputs of virgin aluminium and copper into the economy as low as possible I would recommend the government to implement financial instruments that incentivize cable producers to increase their use of secondary materials for new cables. Because it is currently much cheaper to get virgin metals at a high enough purity as is needed for cable conductors, using secondary metals for the conductors is not a valid business case. To change this for example a tax on the use of virgin materials could be implemented, or a subsidy for using secondary materials.

And lastly, I would greatly recommend the cable producers and DSOs to look at the requirements made on aluminium and copper for new cables and whether they are truly necessary. If the requirements could be slightly lowered, it could be much easier to use secondary metals instead of virgin metals.

Acknowledgements

First of all, I would like to thank my supervisors, Ester van der Voet and Gijsbert Korevaar, and my non-official supervisor Janneke van Oorschot, for all the time they have put into helping me. Thank you so much for all of your feedback and patience, and for all your help and support in general. I enjoyed working together and I have learned a lot from you.

Secondly, I want to thank my parents, Rienco and Marleen Verschelling, who have supported me so much in my study choices and have supported me for them financially, but also in my personal life. You have always supported me throughout my entire life, you encouraged me to learn and to grow, and you have always been there when I needed you.

Then last but absolutely not least, I would like to thank my husband Ivo, with whom I've spent so many hours at the same desk in our working-office which greatly helped motivate me, who has always listened to me when I needed to vent my study struggles, and who has always supported me and told me it was perfectly fine as well to take breaks every once in a while. Because of you I went through my studies without too much stress.

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1 Introduction

Interest in the Circular Economy (CE) concept has grown rapidly around the world: many studies have been executed on the topic in many different countries (Ghisellini et al., 2016). The European Union's interest has grown as well, a '*new Circular Economy Action Plan'* was proposed this year (European Commission, 2020). CE is seen as a new business model that allows the economy to grow but simultaneously decreases resource consumption since resources are recycled and brought back into the economy as secondary materials (Ghisellini et al., 2016). This has the great benefit of reducing environmental impacts at the same time as saving resources since secondary materials often need a lot less energy to be produced. Not only the EU has plans to become circular in the future; the Netherlands is also very aware of the importance of circularity. The Dutch government has initiated a program which aims to direct the Netherlands towards a circular economy in 2050 (Ministerie van Infrastructuur en Milieu, 2016).

In the meantime, the urbanization of the world has greatly increased the demand for metals, which are some of the most important materials for our society (Hu et al., 2010; López et al., 2020). As metals are often (theoretically) infinitely recyclable, research into metal flows and creating a circular loop on metals is especially important for reaching a circular economy (López et al., 2020). One sector where large quantities of metals can be found is the electricity system. For the Dutch government to be able to use the metals contained in the Dutch electricity system for the circular economy, it is important to know which metals can be found there and in which quantities. When the metals are recovered to re-use them in the circular economy, the materials should be recycled correctly to be able to enter the economy as secondary material.

This study will research the metals within the electricity system in the Netherlands and the current process of recycling. In this introduction, I will first quickly introduce the Dutch electricity system, before looking into the existing literature on this topic to find a knowledge gap and define the research question.

1.1 The Dutch electricity system

An electricity system consists of several components. First, electricity has to be produced. In the Netherlands, electricity is produced from fossil fuels, wind energy, solar energy, biomass energy, nuclear energy, waste incineration, and hydropower (Van Oorschot et al., 2020).

The produced energy needs to be transmitted to the users. Historically, the first step of transmissions happens through the 'extra-high voltage' grid (EHV) (Movares Energy, 2017). In the Netherlands, this grid has a voltage of 220 kV or 380 kV (depending on the location) and is used for transport over long distances (Movares Energy, 2017). A high voltage is used for long distances as higher voltages have less electricity losses (HoogspanningsNet, n.d.-b).

After being transported by the EHV grid, the voltage is transformed by a transformer to a lower voltage; 150 kV or 110 kV. These voltages are called the 'high voltage' grid (HV) and the grid is used for further transport over shorter distances (Movares Energy, 2017).

In the Netherlands, the EHV and HV grid consist mainly of overhead cables, but both contain a few underground cables in densely populated areas. Underground cables are also used to connect offshore wind parks with the mainland grid.

After long-distance transport, the electricity is transformed to a lower voltage again, 50 kV for transport over smaller distances or 1 kV - 35 kV for distribution to the users. 1 kV – 50 kV is called 'middle voltage' (MV) and is currently purely used for distribution (Movares Energy, 2017). Large users are supplied by this grid. The management of the MV grid is divided into different market parties. Because the MV grid is divided each party can decide on the voltage that will be used. For this reason, there are many different voltages used in the MV grid (HoogspanningsNet, n.d.-a). The most widely used in the Netherlands is 10 kV (Movares Energy, 2017). Small users are supplied by the 'low voltage' grid (LV) (Movares Energy, 2017). The LV grid contains all voltages lower than 1 kV (Movares Energy, 2017). The MV and LV grids are in the Netherlands entirely positioned underground.

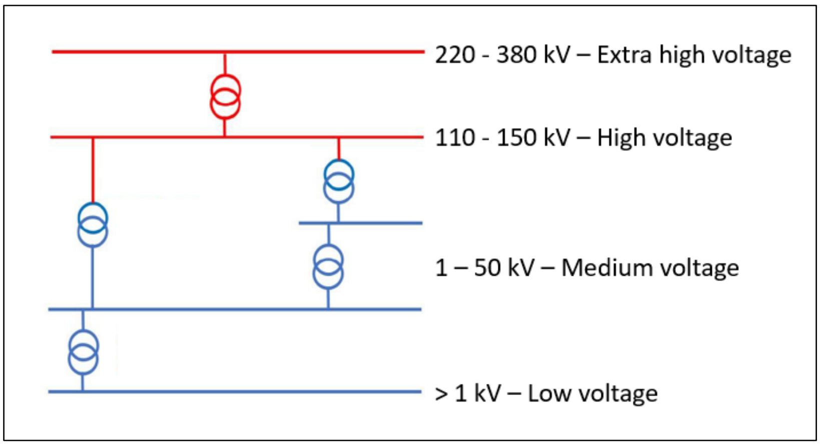

Figure 5. The sections of the Dutch electricity grid. Figure adapted from (Leguijt et al., 2019).

A schematic visualization of the different grids and the connections between them is shown in Figure 5.

1.2 Literature

To find a gap in literature which this research could fill, a literature review has been conducted focused on the available literature on material flows in the electricity system. The existing literature found in this review is discussed here.

Materials in the electricity system

First of all, several studies have been conducted on the material flows of renewable electricity technologies. Elshkaki and Graedel (2013) studied development scenarios of ten different energy technologies, and the metal flows connected to these technologies. Blagoeva et al. (2016) studied the demand for multiple materials needed for the energy transition in the European Union (EU) and potential bottlenecks in the supply chain of these materials. Choi et al. (2016) looked more specifically into the indium flows which arise from the change to clean energy technologies. Deetman et al. (2018) looked into the future global demand of copper, tantalum, neodymium, cobalt, and lithium, resulting from the change to renewable energy technologies. Månberger and Stenqvist (2018) studied the demand of twelve metals as needed for the energy transition, among which the metals needed for renewable energy technologies. Yang et al. (2020) performed a static MFA on wind power in China. Wind power is one of the more often used renewable energy technologies, but it is very material-intensive (Yang et al., 2020). So Yang et al. (2020) studied the material efficiency of wind power over the past. They found that the material efficiency of wind power has gotten better over the years, but still large amounts of concrete and steel are used (Yang et al., 2020). In the Netherlands, Exter et al. (Exter et al., 2018) studied the demand for critical materials which is expected to result from the transition towards electricity production from wind and solar PV.

In addition, several studies have been conducted which focus on one specific material needed for the energy transition. These studies are often also focused on metals needed for renewable energy technologies. Guyonnet et al. (2015) studied the stocks and flows of Rare Earth Elements (REE) in Europe as they play an important role in the energy transition and can relatively easily be recycled. They show that with recycling EoL REE-containing products the available supply should be sufficient in the near future. Rasmussen et al. (2019) studied the global platinum cycle with MFA, as platinum is widely used in the energy transition. They used multiple scenarios to study the development of platinum flows. They have found that when EoL platinum-containing products are collected and recycled more efficiently, the available platinum reserves should be able to fulfill the platinum demand for the energy transition, depending on the scenario (Rasmussen et al., 2019).

However, a lot less research has been performed on material flows of electricity infrastructure as needed for the energy distribution, and even less on flows of specifically electricity cables. Bader et al. (2011) did analyze the copper flows in Switzerland, which included the copper flows in Swiss electricity cables. They found that a large part of EoL copper ends up in landfills and that there is a large number of losses. These losses cannot completely be reduced through increasing the recycling rate, as many losses are from diffusion, and an important solution would be to substitute copper with another material with similar characteristics (Bader et al., 2011). Daigo et al. (2009) has performed research into the flows of copper in Japan. The electricity grid is one of the sectors where a large amount of copper is used. Daigo et al. (Daigo et al., 2009) used a population balance model to estimate the copper outflows. For the lifetime of power cables, a Weibull distribution has been used with an average of 17.5 years (Daigo et al., 2009)

The only research specifically focused on material flows of electricity distribution infrastructure is conducted by F. Li et al. (2020). They performed an MFA study on the major construction materials contained in the power infrastructure in China until 2050. The study looks at the infrastructure needed for electricity production, but also at infrastructure for transmission and distribution, the electricity grid (F. Li et al., 2020). A large increase is expected for all studied materials since the energy transition will need a lot of new infrastructures. when looking specifically at electricity cables, a large increase in copper and aluminium demand will be needed in China to stimulate the energy transition (F. Li et al., 2020).

When looking specifically at material flows of electricity cables in the Netherlands, van Oorschot et al. (2020) have created an overview of the current stocks of the electricity system. In this research average cable types for each of the different grids were used in the calculations. With this method, they found that about 90% of all aluminium and 78% of copper of the Dutch electricity system is found in the cables (Van Oorschot et al., 2020). They have also found a significant amount of steel in high voltage cables. The main part of these metals is currently still in use. When cables containing these materials reach their end-of-use they can become available for recycling and renewed entry into the circular economy. Two masters theses looking at copper in Amsterdam have been published, which take power cables into account among other things (de Haes, 2018; Lin, 2016).

An interesting aspect of electricity cables is the so-called 'hibernating stock'. Hibernating stocks refer to products that are not used anymore (Daigo et al., 2015). In the Dutch underground electricity grid these hibernating stocks are already present (Van Oorschot et al., 2020). Often, when new cables are placed, the old ones are not removed but simply left in the ground because direct removal creates too much disturbance (Van Oorschot et al., 2020). Daigo et al. (2015) created an MFA model that can estimate hibernating stocks. The model looks at the difference between outflows of the in-use stocks and data on the known recovered scrap, de difference would be how the hibernating stock changes (Daigo et al., 2015). The schematic model is shown in Figure 6. Daigo et al. (2015) used the model to find the current existing hibernating stock of steel in Japan. Wallsten et al. (2013) performed a similar study on the hibernating stocks of a city in Sweden, including the electricity cables, and found that there is a significant amount of aluminium and copper hibernating stocks.

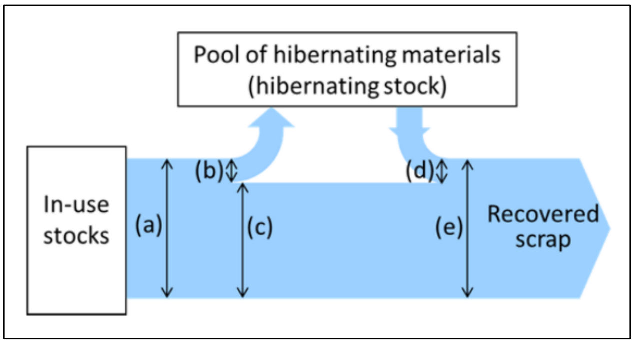

Figure 6. Model for the calculation of hibernating stocks (Daigo et al., 2015).

However, no specific study has been conducted yet on the specific metal flows of electricity cables in the Netherlands, nor on the hibernating stocks belonging to electricity cables.

Recovery of electricity cables

On the topic of recovery of electricity cables, recent studies have mostly been performed on technical recycling processes. Comparisons are made, and new methods are experimented with. L. Li et al. (2017) analyzed the present status of the recycling methods of copper-containing cables. The recycling methods are analyzed, and limitations to these recycling processes are mapped (L. Li et al., 2017). Tanabe et al. (2019) experimented with a specific recovery process for obtaining aluminium and copper from waste cables, as these are valuable materials. Richard et al. (2017) studied a specific type of separator process for separating metals and plastics from electric cable waste for recovery. Martins et al. (2020) compared two recycling methods for metals from EoL cables. Kumar et al. (2020) researched a recovery process for the metal and plastics of electrical wires.

Although a lot of research has been performed on technical recycling processes, little research is done to understand more logistical issues hampering the circularity of the materials in electricity cables, especially in the context of the current Dutch recycling system.

1.3 Knowledge gap and research question

As the Dutch government wants to facilitate both an energy transition and a circular economy, it is both relevant and interesting to study how the material flows of the energy infrastructure will influence the Dutch circular economy. The literature review from the previous section has shown that there are two large knowledge gaps. Firstly, there are few studies found on the material flows or hibernating stocks of electricity cables, and even fewer studies focus on the Netherlands. Van Oorschot et al. (2020) have already studied the materials currently contained in the Dutch electricity infrastructure, but not yet the material flows in the future. This research tries to fill this knowledge gap by studying the material flows and stocks of the Dutch electricity grid until 2050, the year by which the Dutch government aims to be a circular economy. Secondly, neither are logistical issues hampering the circularity of electricity cables been studied in the context of the Dutch recycling system. This thesis will also provide a starting point for filling this second knowledge gap, by studying how cables are currently processed in the Netherlands and through researching the difficulties that the cable industry experiences when aiming for circularity.

To fill these knowledge gaps the following research question has been formulated:

How will the metal stocks and flows of electricity cables in the Netherlands develop until 2050, for different energy transition scenarios, and how can the outflows re-enter the circular economy?

This main research question will be answered with the help of four sub-questions:

1. *What is the magnitude of the stocks and flows of the electricity cables and the metals they contain, and how are they expected to develop over time?*

2. *How do the metal outflows currently re-enter the economy as secondary material?*

3. *How can the metal flows re-entering the economy as secondary material be increased and how can the virgin metal inflows be decreased?*

In chapter 2, the general methodology is first discussed together with the data that is used. Chapter 3 elaborates on the scenarios used in this research and the connected expansions for the future of the electricity grid. Then in chapter 4 the results of the research are given, which are then discussed further in chapter 5. Finally, in chapter 6 conclusions are drawn and recommendations are made based on these conclusions.

2 Methodology and data

This chapter elaborates on the method used in this research and the available data. This study looks into the material flows of electricity cables and the processing of EoL cables. To answer the research question, as introduced in the introduction, a combination is made of quantitative and qualitative research. The quantitative research is in the form of a dynamic Material Flow Analysis (MFA) and quantifies the material flows of the electricity cables. The qualitative research focusses on the processing of EoL cables.

First, the scope of the research will be defined, before explaining the used method for the MFA and the used data. At the end of the chapter, the qualitative research on the processing will shortly be discussed.

2.1 Scope

The technical scope contains the metal flows of electricity cables. This comprises only the electricity cables as managed by the DSOs in the Netherlands. Any cables inside production facilities or buildings are excluded from this scope. In addition, any connections between cables, pylons carrying overhead cables, or transformers between voltage levels, are excluded from the scope. Both land-based and offshore cables are analyzed. The materials analyzed are aluminium, copper, and steel. The aluminium and copper analyzed are the materials needed for the conductors of electricity cables and the steel is used for strength in overhead cables.

The geographical scope is the Netherlands. All cables within the country are analyzed. The only exceptions are several cables that connect the Netherlands to neighboring countries, which are excluded from this research.

The temporal scope consists of the year from which the first data is available on cable building, namely 1933, until 2050 when the Dutch government aims to have reached a circular economy.

2.2 Material Flow Analysis

The approach to the MFA model will be explained in this section.

A stock-based dynamic MFA has been built to calculate the material flows of the electricity grid. The MFA model of this research is based on a model of Müller (2006), who has conducted a dynamic stock-based model for analyzing the in- and outflows of concrete in Dutch housing. The MFA model which he used (Figure 7) is driven by population, concrete intensity of buildings, lifetime of the residential buildings, and lifestyle (Müller, 2006).

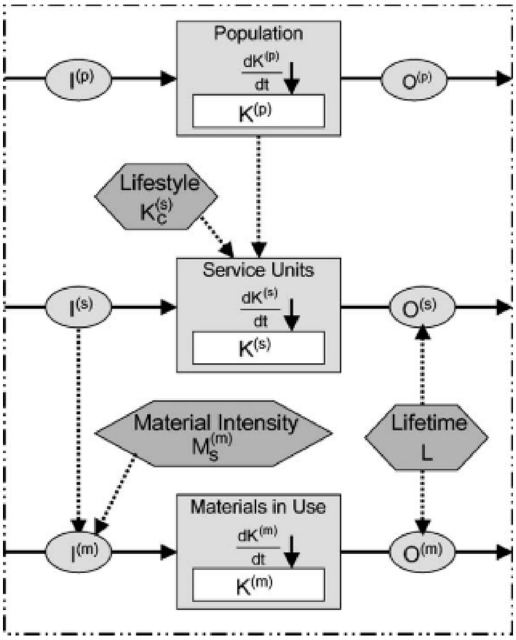

Figure 7. Basic material flow model for in and outflows of one product category. The hexagons provide the drivers of the model. Müller (2006).

The model that I created is shown in Figure 8. The program which was used for modeling is called Spyder, which uses the programming language Python (Spyder, n.d.). I have chosen to use a stock-based model. The dynamic stock model created by Pauliuk (n.d.) has been used as a basis to create the model in python.

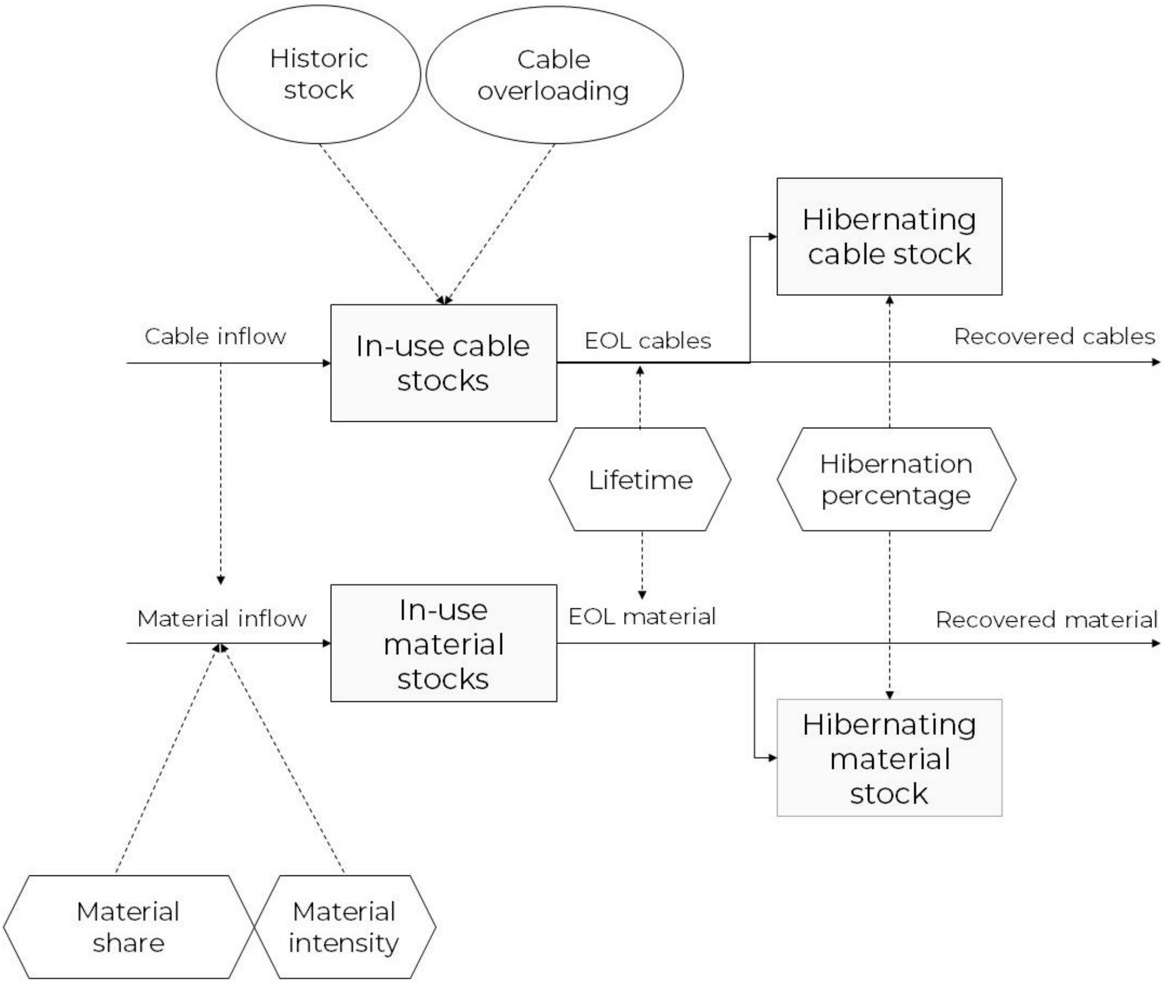

Figure 8. Schematic model for electricity cables. Full arrows portray flows, rectangles portray stocks. Ovals are the model input, polygons are model variables, and dotted arrows show relationships between different elements.

The model is defined through model inputs and model variables. As the model is stock-based, the model inputs are data used to define the in-use stock. Two model inputs have been used: the historic cable stock, and the cable overloading. The data used for the historic stocks are from the period 1933-2019. The period 2020-2050 is defined by the 'cable overloading' input. The cable overloading is used to calculate the in-use stock in the future, the exact calculation method for the stock in the future will be explained further on.

There are four driving forces of the model; lifespan, hibernation percentage, material share, and material intensity. The driving force of lifetime speaks for itself. The hibernation percentage is the share of cables that reach their End Of Life (EoL) in a certain year, but which are not taken out of the ground. The material share gives the proportion of cables with a core of a certain material, as the grid consists of cables with both aluminium and copper cores. And lastly, the material intensity is the amount of material in a specific length of that cable, so for example the amount of aluminium per km of cable containing an aluminium core.

As visible in Figure 8, the model exists out of two parts: the *cable* stocks and flows (the upper part), and the *material* stocks and flows (the lower part). The driving forces mainly drive the cable stocks and flows, and these themselves drive the associated material stocks and flows.

The relationships between the cable stocks and flows have been described very well in formula form by Li et al. (2020):

$$I_{c,t} = S_{c,t} - S_{c,t-1} + O_{c,t} \tag{1}$$

Where: $I_{c,t}$ is the inflow of cables, c, in year t; $S_{c,t} - S_{c,t-1}$ is the difference in the stock between year t and the previous year $t-1$, in the case of this research thus the expansion of the electricity grid in year t; and $O_{c,t}$ is the outflow of cables in year t, which are the cables which reach their end of life and need to be replaced with new cables. The calculation of the outflow is described by Li et al. (2020) as follows:

$$O_{c,t} = \sum_{t_i=t_0}^{t_i=t-1} \left(L(t,t_i) * I_{c,t_i}\right) \tag{2}$$

Where $O_{c,t}$ is the outflow of cables in year t, calculated from the inflow I_{c,t_i} in the year t_i, multiplied by a lifetime distribution $L(t,t_i)$, which calculate how much of the cables built in year t_i reach their end of life in the year t.

This research adds two equations. One for the hibernating stock:

$$HS_{c,t} = \sum_{t=0}^{t} (O_{c,t} * hp_c) \tag{3}$$

Where $HS_{c,t}$ is the hibernating cable stock in year t, $O_{c,t}$ is the outflow in year t, and hp_c is the hibernation percentage.

The last equation used for the cable flows is to calculate the recovered cables flow:

$$R_c = O_t * (1 - hp) \tag{4}$$

Where R_c is the recovered cables flow, which means the cables which are excavated from the ground, and hp is once again the hibernation percentage.

To calculate the material stocks and flows, the cable inflow has been translated to the material inflows with the following equation:

$$I_{m,t} = I_{c,t} * p_{m,t} * mi_m \tag{5}$$

Where $I_{m,t}$ is the inflow of material m in year t, $I_{c,t}$ is the inflow of cables in the year t, $p_{m,t}$ is the percentage of cable inflows with a core of material m in the year t, and mi_m is the material intensity of material m in a cable with a core of material m.

The material stocks and flows are then calculated through inflow-based MFA. The equations of the outflow (2), the hibernating stocks (3), and the recovered flow (4) are the same for the material stocks and flows as for the cable stocks and flows. Equation (1) does change as the material stocks need to be calculated instead of the material inflows. This is the following equation:

$$S_{m,t} = \sum_{t=0}^{t}(I_{m,t} - O_{m,t}) \tag{6}$$

These equations together comprise all relationships used in the MFA model of this research.

2.2.1 Model input

In this section, the data used for the two model inputs and the assumptions made for data gaps are discussed.

2.2.1.1 Historic stock

For all grid sections on land, the stock in the year 2019 is provided by NetbeheerNederland (2019), which is the last year of the historic stock. For ease of communication, this will be called the current stock. The current stocks of the different grid sections are shown in Table 1.

The construction years for all EHV and HV cables have been provided by TenneT (2019). As the model is stock-based, this data has been used to calculate the stocks for each year.

The historic stock of offshore cables is not available in specific data, so an estimation had to be made. Offshore cables are used to connect offshore wind parks to the mainland. The Dutch Enterprise Agency (2020) has provided information on the capacity of the currently existing wind-parks, the years in which they entered use, and the distance from the mainland. I assumed that, for security of supply reasons, each wind park is connected to the mainland with two cables which both have the length of the distance from the park to the mainland. In addition, I assumed that the cables were installed in the same year in which each wind-park was put into use.

No specific data on building years and lengths of cables has been found for the MV and LV grid sections. Therefore, the historic stock for the MV and LV grid is based on assumptions, which are the following: historically, the electricity grid has been built as a distribution grid, where all production facilities were connected to the HV or EHV grids. The electricity then flows from the EHV through the HV and MV grids before arriving at the LV grid for distribution to the consumers. It can thus be reasoned that when the HV grid expands, more electricity will be transported to consumers. The MV and LV grids then also need to expand to transport this increased amount of electricity towards the consumers. For this reason, the assumption has been made that the MV and LV have built up in a similar ratio to the HV grid. This means that when in a certain year 5% of the total HV grid in 2019 has been built, 5% of the current MV and LV grids were also built in this same year. Although the exact historic data of the MV and LV will be slightly different, for the purpose of this research this method of deciding on the historic stock is sufficiently detailed.

	Overhead cables (km)	**Underground cables (km)**
EHV	10898	337
HV	15489	4891
MV	-	108415
LV	-	220629
Offshore	-	269

Table 1. Stocks of all cable sections cables in 2019, in km. Data from NetbeheerNederland (2019).

2.2.1.2 Cable overloading

For the expansion of the stock until 2050 four scenarios are used. These scenarios are focused on the level of steering of the energy transition, and the levels the scenarios use are the following: regional steering, national steering, international steering, and generic steering. The scenarios will be explained more elaborately in chapter 3, in this section I will only discuss the data resulting from these scenarios which are used as model input.

Two studies have been conducted in three Dutch provinces (Groningen, Drenthe and Noord-Holland) to find out what the effects of these scenarios will be on the currently existing Dutch electricity grid. These studies were foundational to this thesis in calculating the expansion of the grid sections (Leguijt et al., 2019; Niet et al., 2019). The studies have found the amount of overloading of the current electricity grid in the three provinces in 2050. This can be understood as follows: the electricity grid has been designed to transport a specific amount of electricity, therefore there is a maximum capacity of electricity that the cables and the transformer-stations can transport. When an amount of electricity higher than the maximum capacity would be transported through a cable, the cable gets overloaded. To accommodate the desired electricity flow when such overloading occurs, the grid must be expanded in some way. Leguijt et al. (2019) and Niet et al. (2019) have provided a list of the expected overloading percentages in 2050 for all EHV and HV cables in Groningen, Drenthe and Noord-Holland, for each of the four scenarios. This database is too large to provide here, so for more information I would like to refer to the reports of Leguijt et al. (2019) and Niet et al. (2019).

For the MV and LV grids, the share of cables which experience overloading by 2050 has only been provided for the provinces Groningen and Drenthe (Niet et al., 2019), and has been shown in Table 2.

	regional	**national**	**international**	**generic**
MV	31%	29%	24%	30%
LV	29%	28%	24%	29%

Table 2. Percentage of MV and LV cables in Groningen and Drenthe which will be overloaded in 2050. Data from (Niet et al., 2019).

The exact manner of calculating the expansion of the cable stocks until 2050 from this data will be explained in chapter 3.

A summary of the model inputs and the data sources used for them is provided in Table 3.

Model input	**Source**
Historic stock	TenneT (2019) NetbeheerNederland (2019a)
Cable overloading	CE Delft (2017b) Niet et al. (2019) Leguijt et al. (2019)

Table 3. Overview of the material inputs and the data sources used for them.

2.2.2 Driving forces

The different driving forces of the model, the data, and the assumptions used to fill data gaps are discussed in this section. To model the driving forces, the electricity grid has been divided into seven grid sections because each of these sections is modeled with slightly different data. The data and assumptions for the driving forces will be discussed for all of these grid sections. The first distinction between the sections is the voltage level, EHV, HV, MV, and LV. The EHV and HV grid sections are both divided between overhead cables and underground cables (MV and LV cables only contain underground cables), and the last grid section is the offshore cables.

The driving forces are modeled through specifically available data, literature, experts, or a combination of those, and often supplied with necessary assumptions. The exact used data and supplementary assumptions for each driving force are explained in the subsections below.

2.2.2.1 Lifetime

The official lifetime of cables sold in the Netherlands is 40 years (P. Soepboer, personal communication, April 9, 2020), but they are generally used for at least 50 years (P. Soepboer, personal communication, April 9, 2020; J. Smit, personal communication, April 30, 2020). Overhead cables can even reach a lifespan of 100 years (J. Smit, personal communication, April 30, 2020).

In literature, a variety of different options can be found for calculating the lifetime of cables. Li et al. (2020) use a normal distribution, with a mean of 40 years and a standard deviation of 8 years. Daigo et al. (2009) use a Weibull distribution with a mean of 17.5 years, and Harrison et al. (2010) use a static lifetime of 40 years instead of a distribution.

In this study, I will use the normal distribution as proposed in the research of Li et al. (2020), as the research of Li et al. (2020) has a high similarity to this research, and as the numbers used for average lifespan come closest to what the Dutch experts say. However, to remain closer to the Dutch experts, the mean lifetime for underground cables will be put at 50 years. As overhead cables have longer lifespans, the mean lifetime for them will be put at 60 years. The standard deviation of 8 years will be used as proposed by Li et al. (2020).

2.2.2.2 Hibernation percentage

In the Netherlands, underground cables are not always recovered after they have reached the end of their lifetime (P. Soepboer, personal communication, April 9, 2020; J. Smit, personal communication, April 30, 2020). The cables that remain underground are no longer part of the in-use stock but become part of the hibernating stock. No specific data has been found available on the share of cables which is recovered from the ground in the Netherlands, nor were the experts able to provide specific numbers or is anything reported in found literature. Therefore, it is not exactly known what the hibernation percentage is, except for experts stating that a large part of the cables remains behind.

As it is still interesting to analyze how such a hibernation percentage would influence the hibernating stock and the potential of an urban mine, a first rough estimate would be that every year 25% of the EoL cables will be recovered, and the remaining 75% will be added to the hibernating stock. To analyze how this variable influences the results of the model, a sensitivity analysis will be performed. This sensitivity analysis will assume both a 65% and an 85% hibernation percentage and I will observe the effect of those on the material hibernating stock and the recovered material flow. I will also compare these results with the recovered material flow when there is no hibernating stock and all material will be recovered, so a hibernation percentage of 0%.

The reasons behind the fact that EoL cables are not recovered are discussed in the Results chapter.

2.2.2.3 Material share

An indication of the share of in-use cables with copper or aluminium cores has been provided by one of the MV and LV DSOs (Soepboer, 2019), and it has been assumed that these shares are representative for the entire MV and LV grids. For the MV and LV grid until the beginning of the 1970s, paper-insulated-lead-covered cables (PILC cables) have been used (Soepboer, 2019). At the beginning of the 1970s the use of PILC cables transitioned to using plastic cables. For the model, I assume that since 1971 only plastic cables were installed. Currently, by far the largest share of newly installed cables in the MV and LV grids have an aluminium core (P. Soepboer, personal communication, April 9, 2020; C. Bremer, personal communication, July 3, 2020). J. Smit (personal communication, June 4, 2020) has mentioned that the switch to mainly aluminium cores happened around 2010. So, in the model I assumed that since 2010 only aluminium cores are newly installed. The exact shares of copper and aluminium conductors that were *installed* in the past are unknown. But the shares of copper and aluminium cables which are still *in us*e today are known. To fill the data gap of shares of installed cables in the past, the assumption was made that in the past copper and aluminium PILC and plastic cables were installed with the same ratio as the ratio of the cables still in use today.

For the EHV and the HV grid, less detailed information is available. Aluminium cables first started to be used in the underground HV grid in the 1990s, and have been mainly used for around ten years (J. Smit, personal communication, June 4, 2020). As no specific data on the percentages of aluminium and copper cables before 2010 are available, and historic stocks are not the main aim of this research, it will be assumed for modeling purposes that until 2010 only copper is used for underground cables and from 2010 onwards only aluminium cables will be used. In the EHV, grid aluminium cables started to be used in 2016 (TenneT, 2016). As experts say that currently in the Netherlands by far the largest share of new cables contains aluminium cores (P. Soepboer, personal communication, April 9, 2020; J. Smit, personal communication, April 30, 2020), I assume that since 2016 only aluminium cables were used for the EHV underground grid.

For overhead EHV and HV cables, the assumption has been made that always only aluminium cables have been used. This might not be entirely the case, but the reason for this assumption is that there is no available data on if there was any copper used in overhead cables in the past, nor any information on the material content of potential overhead copper cables.

Offshore cables are modeled with only copper cores. J. Smit (personal communication, April 30, 2020) mentioned that in the EHV/HV grid, copper cables are still installed in some instances, but the main share of new cables contains aluminium cores. As I was unable to get any more data on

EHV overhead	Time period	1933-2050		
	Copper	0 %		
	Aluminium	100 %		
EHV underground	Time period	1933-2016	2017-2050	
	Copper	100 %	0 %	
	Aluminium	0 %	100 %	
HV overhead	Time period	1933-2050		
	Copper	0 %		
	Aluminium	100 %		
HV underground	Time period	1933-2009	2010-2050	
	Copper	100 %	0 %	
	Aluminium	0 %	100 %	
MV	Time period	1933-1970	1971-2009	2010-2050
	Copper	65,4 %	7,2 %	0 %
	Aluminium	34,6 %	92,8 %	100 %
LV	Time period	1933-1970	1971-2009	2010-2050
	Copper	96 %	28 %	0 %
	Aluminium	4 %	72 %	100 %
Offshore	Time period	1933-2050		
	Copper	100 %		
	Aluminium	0 %		

Table 4. The assumptions on the shares of installed copper and aluminium cables as used in the model.

the proportion of aluminium/copper cables still being installed, I have assumed that only the offshore cables which are still being installed are made of copper. Since they transport large amounts of energy at peak times of offshore wind production, this seems to fit the description of needing to have a high capacity.

The resulting shares of copper and aluminium cables are shown in Table 4.

2.2.2.4 Material content

The material intensities in the different voltage sections of the Dutch electricity grid have been previously researched by Van Oorschot et al. (2020), and these will largely be used here.

For the MV and LV grids, Van Oorschot et al. (2020) has averaged aluminium and copper intensities per km over the entire grid. As the cables in the grid contain only aluminium or copper cores, these material intensities have been translated to the aluminium and copper contents for respectively aluminium and copper cables, to add a level of detail.

The overhead cables of the EHV and HV grids consist of both steel and aluminium in all cables, thus for these sections the material intensities of Van Oorschot et al. (2020) are used.

The underground EHV and HV grids consist of both copper and aluminium cables, similar to the MV and LV grids (J. Smit, personal communication, June 4, 2020). The research of Van Oorschot et al. (2020) presents the copper intensity of the underground electricity grid which will be used. This copper intensity will also be used for offshore cables. For the aluminium underground cables, the aluminium intensity of the EHV and HV overhead grid is assumed to be a sufficiently close assumption.

The offshore cables consist of only cables with a copper core. When looking at their voltage levels offshore cables are part of the EHV grid, so the copper intensity of the EHV underground cables as found by Van Oorschot et al. (2020) will be assumed correct here.

Table 5 summarizes the resulting metal intensities for the different grid sections.

Ton/km	LV	MV	HV overhead	HV underground	EHV overhead	EHV underground	Offshore
Aluminium	1,37	1,83	0,79	0,79	0,79	0,79	-
Copper	1,20	1,08	-	6,05	-	6,05	6,05
Steel	-	-	0,55	-	0,55	-	-

Table 5. Metal intensities of the different grid sections in ton/km. Data by Van Oorschot et al. (2020)

A final summary of all discussed driving forces and the data sources used for them is given in Table 6.

Driving Force	Source
Lifetime distribution	- Li et al. (2020) - P. Soepboer (personal communication, April 9, 2020) - J. Smit (personal communication, April 30, 2020)
Hibernation percentage	- P. Soepboer (personal communication, April 9, 2020) - J. Smit (personal communication, April 30, 2020)
Material share	- Soepboer (2019) - J. Smit (personal communication, April 30, 2020)
Material content	- Van Oorschot et al. (2020)

Table 6. Overview of the driving forces and the data sources used for them. All driving forces are supplemented with assumptions.

2.3 Semi-structured interviews

Besides the MFA, semi-structured interviews have been conducted. Four experts on the electricity grid were interviewed. The interviews had two general purposes. Firstly, to gather specific data on the Dutch electricity grid, and secondly, to gather information on how cables are currently processed and how their outflows do or do not enter the circular economy as secondary material. Some of the data used for the MFA has been gathered from these interviews. Summaries of the interviews have been provided in Appendix A.

3 Scenarios and the expansion of the in-use stock

As mentioned in the previous chapter, the expansion of the in-use cable stock is defined by the overloading percentages of the in-use grid of 2019. These overloading percentages are calculated for four different scenarios for the energy transition. In this chapter, these four scenarios will first be discussed. Afterward, the assumptions and exact manner of calculating the future in-use stock from these overloading percentages will be explained.

3.1 Energy transition scenarios

The energy transition is placed highly on the Dutch political agenda. In 2019 the Dutch house of representatives accepted a climate law that declares by which amount the Netherlands should decrease its Greenhouse Gas emissions. The climate law states there should be an emission reduction of 49% by 2030, and 95% by 2050 compared to the emission levels of 1990 (Rijksoverheid, n.d.-b). The government has decided upon measures to be implemented to reach the 2030 goal, together with companies and other organizations, and these measures have been compiled into the Climate Agreement (Rijksoverheid, n.d.-a). One of the elements of decreasing the Dutch GHG emissions is transitioning to renewable energy instead of fossil fuel-based energy. The aim is to have at least 49 TWh (~11,5 GW) of offshore wind energy, and 35 TWh (~8,2 GW) of land-based renewable energy by 2030 (Ministry of Economic Affairs and Climate Policy, 2019). A larger ambition is expressed as well by aiming to produce a total of 120 TWh renewable energy (Ministry of Economic Affairs and Climate Policy, 2019).

Surely, when the electricity production system is changing, the electricity grid should change accordingly. As the exact pathway through the energy transition is not known, scenarios are developed which define possible future pathways. A study specifically focused on the energy system of the future has been performed by the research institute CE Delft, in collaboration with the Dutch DSOs (CE Delft, 2017b). They created four scenarios, which make assumptions on how the Netherlands will organize the energy transition and calculates what the capacity for the electricity grid should be to accommodate the resulting changes in the energy system (CE Delft, 2017c). The scenarios are meant to show 'the corners of the playing field' for an emission-free energy system (CE Delft, 2017c), and the actual path that the Dutch government will choose to follow will most likely be somewhere in the middle of these scenarios. The scenarios are developed on the government level which organizes the energy transition (CE Delft, 2017c).

This research uses these scenarios to calculate the expansion of the in-use cable stock, as expected to be needed for the energy transition.

I will shortly introduce the four scenarios. For a more elaborate explanation see the CE Delft report (CE Delft, 2017b) or Appendix B of this study.

Regional scenario

The first scenario assumes regional steering. In this scenario, the transition towards renewable energy is in the hands of local governments, such as the provinces and municipalities (CE Delft, 2017b). Electricity is generated locally. The main electricity production methods are solar (84 GW), wind at sea (26 GW), and wind on land (16 GW) (CE Delft, 2017c). As these production methods are fluctuating, there are still several renewable gas plants are storage facilities installed for times of low production (CE Delft, 2017c). The locally produced electricity is mainly transported over the MV and LV grids towards the users and storage facilities (CE Delft, 2017c). The electricity is thus transported from the MV and LV grids towards the EHV and HV grids, in contrast to the current situation where the electricity flows from the EHV and HV towards the MV and LV (CE Delft, 2017c). The demand increases greatly through the increased use of electric vehicles, all-electric heating installations, and industry based on recycling and hydrogen for which large amounts of electricity are needed (CE Delft, 2017c).

National scenario

In this second scenario, the national government has most power in hands to make decisions on the energy transition. This scenario assumes the government desires to be independent of other countries for electricity supply (CE Delft, 2017a). Because the national government is in charge, large projects can be organized easily, and thus large scale electricity production projects are set up quickly, among which offshore wind parks (CE Delft, 2017c). The production of electricity is 80% centralized production facilities and for 20% decentralized (CE Delft, 2017c). By far the largest share of production happens through offshore wind parks in the North Sea, which have an installed capacity of 53 GW (CE Delft, 2017c). Solar-PV and land-based wind follow with respectively 34 and 14 GW (CE Delft, 2017c). Similarly to the regional steering scenario, storage facilities and green gas facilities are installed to fill energy gaps in times of low renewable energy production (CE Delft, 2017c). There is slightly less increase in demand as in the regional scenario as a combination of different heating systems and energy carriers for cars is used (CE Delft, 2017c). The industry changes in the same manner as in the regional scenario: the petrochemical industry changes towards a recycling-, hydrogen- and methanol-based industry (CE Delft, 2017c). As the production still is mainly centralized, the expansions of the electricity are largely on the offshore and (E)HV grids, with medium increases on the MV grid and LV grid (CE Delft, 2017c).

International scenario

Instead of self-sufficiency, the focus in this international scenario is on the international energy market (CE Delft, 2017a). The Netherlands must bring her CO_2 emissions down, but the Dutch citizens do not accept the changes this will bring to the country (CE Delft, 2017c). Therefore large amounts of energy are imported in order to meet the demand (CE Delft, 2017c). The industry changes to a biomass-based industry combined with CCS (CE Delft, 2017c). Not only biomass is imported, but also hydrogen and hydrogen-derived products such as ammonia (CE Delft, 2017c). An increase in electricity demand is expected, but less than for the regional and national scenarios, since many other energy carriers are cheaper and will be used more (CE Delft, 2017c). Compared to the regional and national scenarios, the amount of electricity production is very little in the international scenario (CE Delft, 2017c). 16 GW solar-PV is installed, with 5 GW wind turbines on land and 6 GW wind turbines offshore as renewable energy (CE Delft, 2017c). The electricity grids barely change in this scenario (CE Delft, 2017c). The slightly increased capacity is mainly a result of the offshore wind turbines.

Generic scenario

In the generic scenario, there is no active governmental steering of the energy transition except for generic measures, such as an implemented CO2 tax (CE Delft, 2017a). While the emission taxes increase steadily until 2050, the changes towards renewable energy are slow (CE Delft, 2017c). The main reason for this is that projects which still do not seem profitable after CO_2 tax are not invested in by civilians or companies (CE Delft, 2017c). Similarly to the international scenario, the electricity production increases only slightly, as the import of other energy carriers is cheap (CE Delft, 2017c). 18 GW solar-PV is installed, for both wind-turbines on land and offshore wind turbines 5 GW has been installed with a total of 10 GW (CE Delft, 2017c). The electricity demand increases only slightly. The household demand still grows as more different types of heating and transport energy solutions are needed, but all-electric solutions take up only a part (CE Delft, 2017c). The existing petrochemical industry remains, combined with CCS, no specific changes towards hydrogen-based or recycling industries as in the previous scenarios are made, so no increase of demand results from this (CE Delft, 2017c). However, as it is unknown how exactly civilians and companies will act because of the emission tax, the electricity DSOs will have to take the possibilities into account that individuals will start locally producing electricity (CE Delft, 2017c). This will mean the electricity grid will need to be expanded on all voltage levels (CE Delft, 2017c).

3.2 Expansion of the in-use cable stock

As explained already in the methodology, the expansion of the stock in 2019-2050 is based on the overloading percentages of the current in-use electricity cables. These percentages were found in studies on the Dutch provinces of Noord-Holland, Groningen and Drenthe. This section explains how these overloading percentages have been used to calculate the development of the in-use stock until 2050.

Niet et al. (2019) and Leguijt et al. (2019) calculated the overloading percentages in 2050 for all cables of the high voltage grid (110-380 kV) in Noord-Holland, Groningen and Drenthe. I averaged the overloading percentages of all cables for the different grid sections, EHV and HV. As three out of twelve provinces of the Netherlands have been analyzed by Niet et al. (2019) and Leguijt et al. (2019) I assume that averaging these numbers gives a reasonable estimate for the overloading of *all* high voltage cables in the Netherlands. For both the EHV and the HV, two voltage levels exist, 110kV and 150kV for the HV, and 220kV and 380kV for the EHV. In order to make more accurate averages of the overloading, the total lengths of the cables of the different voltage levels have been used together with their respective overloading percentages.

The resulting calculated overloading percentages for the EHV and HV sections are shown in Table 7.

	Regional Scenario	**National Scenario**	**International Scenario**	**Generic Scenario**
Average overloading HV grid (110 & 150 kV)	124,22 %	63,11 %	64,21 %	61,96 %
Average overloading EHV grid (220 & 380 kV)	84,20 %	106,70 %	11,92 %	6,46 %

Table 7. Average overloading percentages for both the extra high voltage grid and the high voltage grid in 2050. The data results from calculations by the author of this study.

The calculation of the average overloading on the medium and low voltage grids is slightly more complex. For Groningen and Drenthe, a percentage of cables which will be overloaded in 2050 has been calculated. However, it is unknown to what *amount* these cables are overloaded. In this research I assumed that a cable which is overloaded needs to transport a load of 200% of its capacity, so that the bottlenecks are solved by additionally installing the same type of cable next to the existing one.

No specific data has been provided on the percentage of cables which will be overloaded in Noord-Holland, but Niet et al. (2019) and Leguijt et al. (2019) calculated the percentage of MV/LV stations which will be overloaded for all three provinces. Since MV/LV stations link the MV and LV grids, it is a reasonable assumption that the percentage of bottlenecks in the stations and the grids should influence each other, as the electricity runs through both.

So to make assumptions on the overloading percentages in Noord-Holland, the research on Groningen and Drenthe has been used. I plotted the percentages of the *cables* which will be overloaded against the percentages of the *stations* which will be overloaded for the different scenarios. This resulted in a largely linear trend for both cables, see Figure 9. This means the ratio between these two variables is remarkably similar for each scenario, for both the MV and LV grids. The average ratios resulting from this are 0.68 overloaded LV cable/overloaded station and 0.71 overloaded MV cable/overloaded station.

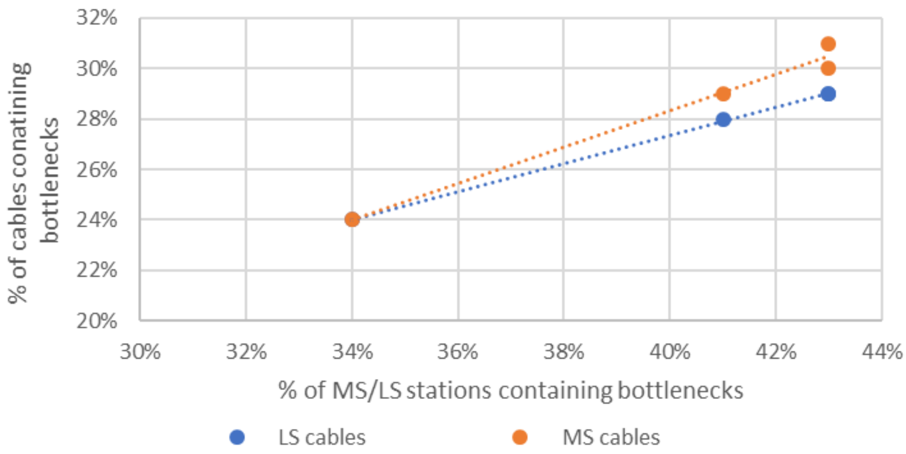

Figure 9. Trendline for deciding the ratio between the bottlenecks in MV/LV stations and MV and LV cables.

Using these ratios on the percentages of overloaded MV/LV stations in Noord-Holland results in the percentages of overloaded MV and LV cables in that province. The percentages for these three provinces have been averaged and this average has been assumed to be reasonably representable for the effects on the MV and LV grids in the entire Netherlands. The resulting overloading percentages of the MV and LV grids are shown in Table 8 and Table 9. This resulted in expected bottlenecks in 41-48% of the entire Dutch MV grid, and bottlenecks in 34-42% of the entire Dutch LV grid.

MV	**regional**	**national**	**international**	**generic**	***Data source***
Noord-Holland	65%	57%	57%	57%	*Calculations by author*
Groningen and Drenthe	31%	29%	24%	30%	*Niet et al. (2019)*
Average for the Netherlands	**48%**	**43%**	**41%**	**44%**	*Calculations by author*

Table 8. Percentage of MV cables in which bottlenecks arise. For the two studies and the average for the Netherlands. Origin of the data provided for clarity. The data which is used as input into the MFA is given in bold.

LV	**regional**	**national**	**international**	**generic**	***Data source***
Noord-Holland	55%	44%	44%	41%	*Calculations by author*
Groningen and Drenthe	29%	28%	24%	29%	*Niet et al. (2019)*
Average for the Netherlands	**42%**	**36%**	**34%**	**35%**	*Calculations by author*

Table 9. Percentage of LV cables in which bottlenecks arise. For the two studies and the average for the Netherlands. Origin of the data provided for clarity. The data which is used as input into the MFA is given in bold.

The future in-use stock of the EHV, HV, MV, and LV grid sections is based on the average overloading percentages for the entire Netherlands, the data of which is given in Table 7, Table 8, and Table 9. For example, every kilometer of overhead HV cable is in the regional scenario overloaded by 124%. Then for the HV grid to be able to provide enough transportation capacity by 2050, the grid should be expanded on average with 1,24 km of cable, for every kilometer of cable in the current grid.

The future in-use stock of the offshore grid has been calculated slightly differently. The production capacity of offshore wind for each of the four scenarios has been used, they are given in Table 10. Offshore wind is installed in separate parks that might not have the same distance to the shore as the current parks, and there are no specific plans until 2050 yet so an assumption needs to be made. I have made use of the plans which are made for the installation of wind-parks until 2030 (Dutch Enterprise Agency, 2020), and used the distance to the shore and the planned capacity of each wind-park, to calculate the length of needed cable per production capacity of the wind-park. For all planned wind-parks the needed km cable/MW are in the range 0.05-0.08, thus sufficiently similar that I have taken the average km/MW and used this to calculate the length (stock) of the offshore grid needed for transportation of the production capacity in 2050. The used average is 0.071 km of cable/MW.

Capacity [GW]	**Current**	**2050 Regional**	**2050 National**	**2050 International**	**2050 Generic**
Offshore wind	1	26	53	6	5

Table 10. The production capacity of offshore wind. Scenarios defined by (CE Delft, 2017b).

I assumed that the expansion of every grid section until 2050 will be linear, every year the same amount of materials will need to be added to expand the grid.

This section has only explained the method of calculating the expansion of the in-use stock until 2050. The resulting in-use stocks for all grid sections and scenarios are shown and discussed in the next chapter, the Results.

4 Results

In this chapter, the results of the study are discussed and shown. The first three sub-chapters will show and explain the stocks and flows resulting from the MFA model, and the last sub-chapter discusses the current processing method of EoL cables in the Netherlands.

4.1 In-use cable stocks

The developments of the in-use stocks of all sections of the Dutch electricity grid have been modeled with the help of the CE Delft scenarios (2017b), as elaborated upon in chapter 2. These resulting in-use stocks are shown in Figure 10.

Figure 10a-g. Comparison of in-use cable stocks per scenario, for all grid sections. The scale is different for each graph. The yellow line, of the national scenario, is not distinctly visible in all graphs. This is because in the HV overhead graph it falls behind the line of the international scenario, and in the MV graph it falls behind the line of the generic scenario.

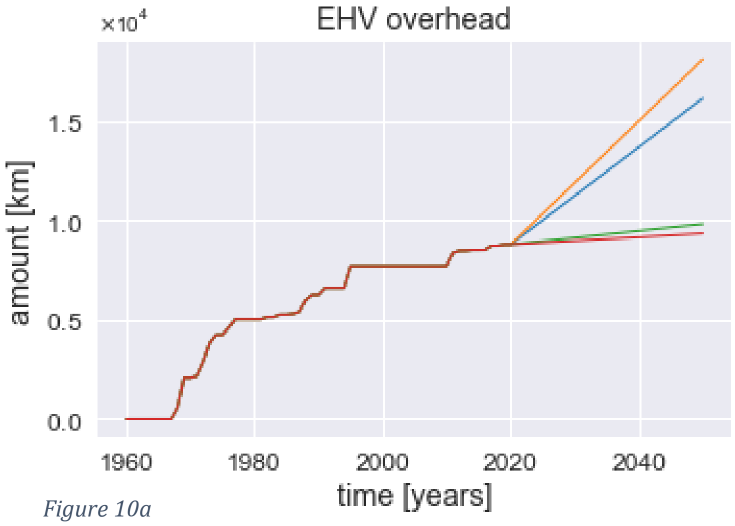

Figure 10a

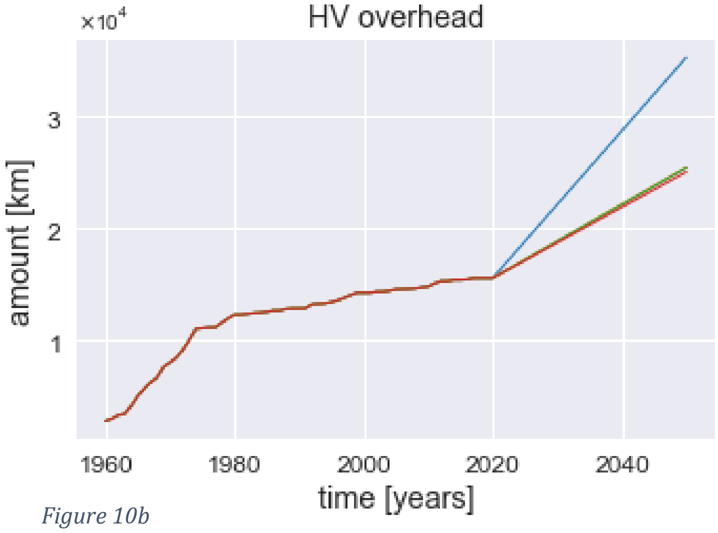

Figure 10b

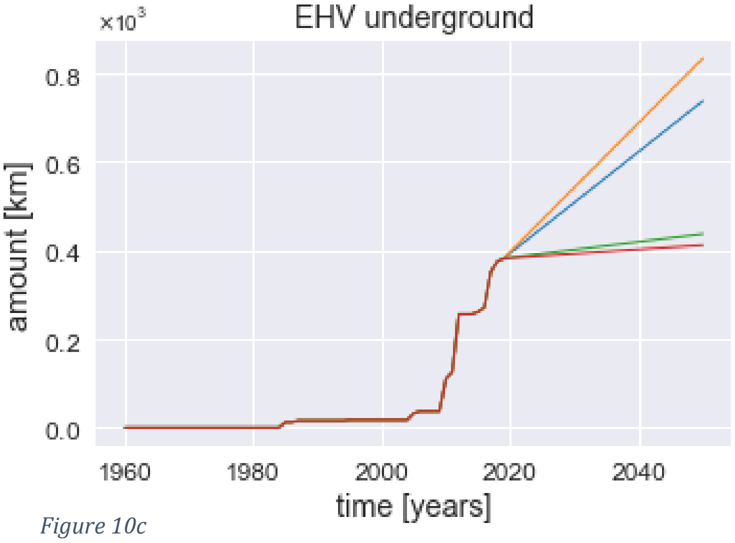

Figure 10c

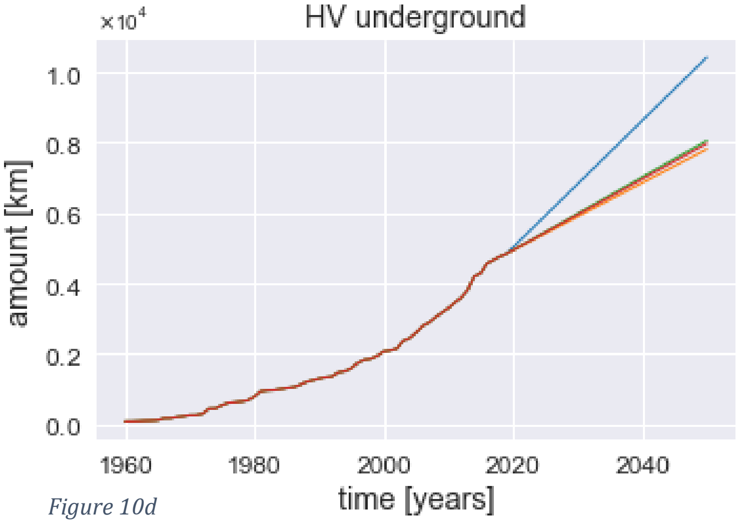

Figure 10d

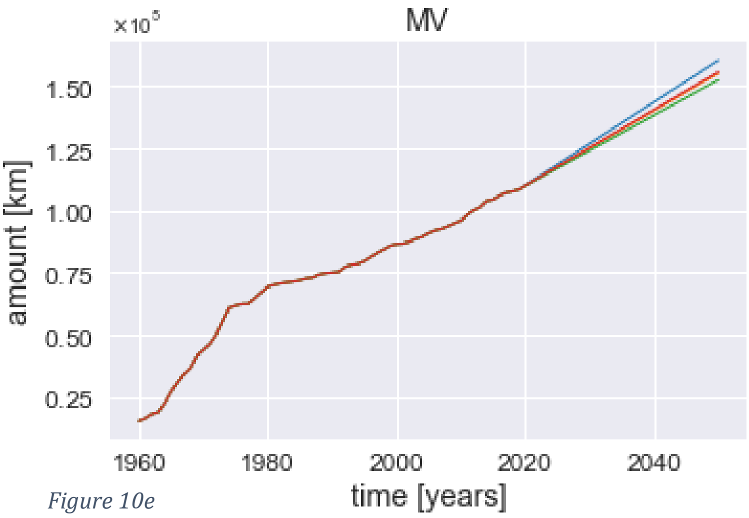

Figure 10e

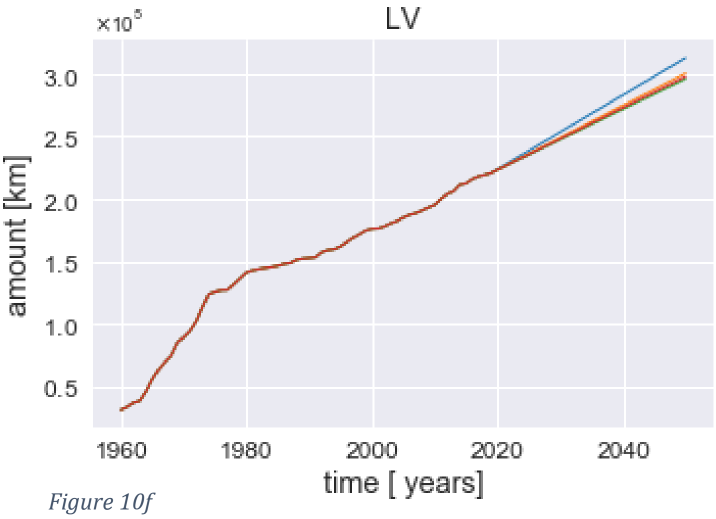

Figure 10f

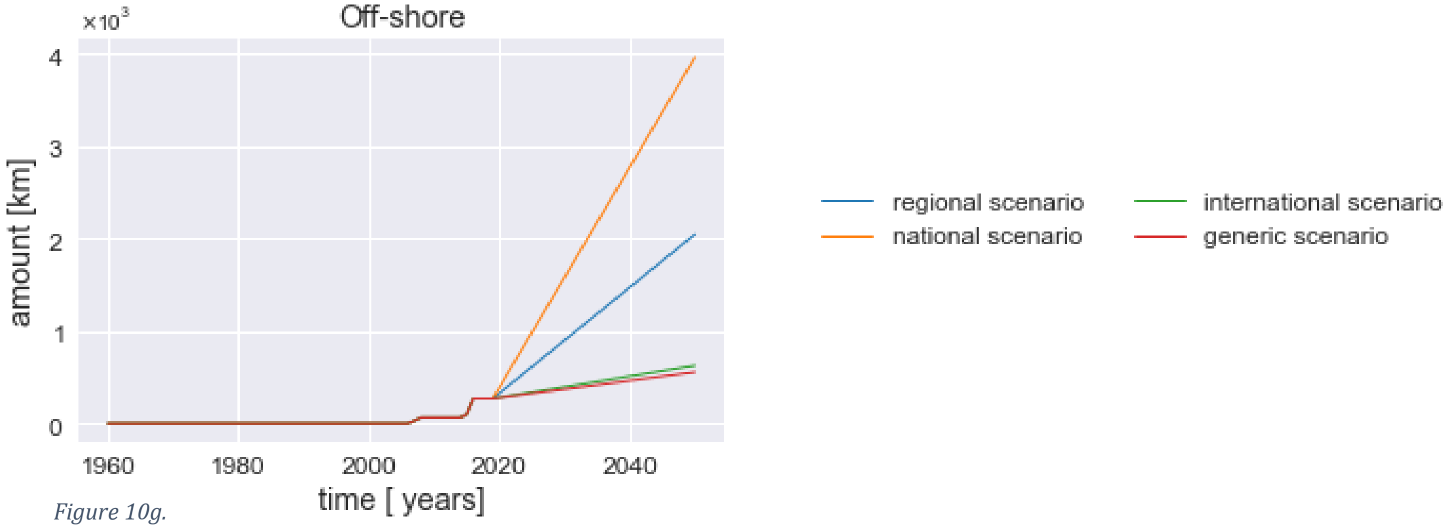

Figure 10g.

When looking at this figure, the first result that catches the eye is that every grid section expands for almost every scenario.

The in-use stocks resulting from the overloading percentages of the current grid show that the LV and MV grids will need to grow with the same growth rate as they currently do, to provide the needed transport capacity in 2050. As can be seen in Figure 10, the different scenarios do not seem to make much of a difference in the needed stocks. The reason for the small changes between the scenarios is that the bottlenecks in the MV and LV grids originate mainly from the increase in demand from households and other buildings in the winter (Leguijt et al., 2019; Niet et al., 2019). There is also an increase in electricity supply through rooftop solar panels in the summer, depending on the scenario, but the capacity needed for the demand in the winter transcends the capacity needed for the supply in summer (Leguijt et al., 2019; Niet et al., 2019). As each scenario assumes CO2 neutral energy supply, the increase in household electricity demand is largely similar. The small range between the scenarios results from differences in driven vehicles (electric vehicles, hydrogen fuel-cell, or powered by green gas) and the type of heating system for buildings. Although the changes are small, the regional scenario has the largest demand on both the LV and MV grids, as this scenario assumes 100% electric passenger vehicles and around 75% of all heating installations to be electric (CE Delft, 2017b). These numbers are lower in the other scenarios (CE Delft, 2017b).

The results also show that the EHV and the HV grids have a much greater range between the different scenarios (Figure 10). An interesting difference seen between these two grids is that in the HV grid the regional scenario greatly jumps out and the other three scenarios follow a lower growth pattern close to each other, while the EHV grid has the greatest growth in the national scenario, with the international and generic scenarios hardly showing any growth at all. This can be explained by several factors. First of all, the regional and national scenarios assume self-sufficiency in electricity, while the international and generic scenarios also contain imported electricity (or other energy carriers) (CE Delft, 2017b). For the EHV and HV grids, the main influencing factors are the greatly increased and fluctuating electricity production in the Netherlands (Leguijt et al., 2019; Niet et al., 2019).

On moments of peak production, the grid needs to be able to transport large amounts of electricity to different storage facilities (CE Delft, 2017c). The national scenario mainly influences the EHV grid, as this scenario assumes many large offshore wind facilities, several land-based wind parks, and several solar PV parks, which all have their connection EHV grid (CE Delft, 2017c). The EHV grid then transports it partly to storage facilities and partly to the HV grid for distribution. As the HV grid is then mainly used as a distribution grid, it explains why the HV grid does not have a major growth compared to the international and generic scenarios, where the increasing demand is the driving factor. In the regional scenario, electricity production happens largely on a regional scale, with smaller local land-based wind parks, solar PV parks, and solar PV on rooftops (CE Delft, 2017c). The PV on rooftops is connected to the MV or LV grid, but the land-based wind parks and PV parks are connected to the HV grids for further transport, as these are smaller than the ones in the national scenario (CE Delft, 2017c). This explains the large growth of the HV grid compared to the other scenarios. The regional scenario also assumes several offshore wind parks but there are fewer parks than in the national scenario, which explains why there is also a growth seen for the EHV grid, although it is a smaller growth than for the national scenario.

The growth between 2020 and 2050 needed in the toughest scenarios, resulting from this model, thus seems to be ~10,000 km for the EHV grid, ~25,000 km for the HV grid, ~50,000 km for the MV grid, ~90,000 km for the LV grid, and ~3,500 km for the offshore grid (see Figure 10). By far the largest challenge for the coming years will thus be for the MV and LV DSOs.

4.2 Material in- and outflows

To realize the growth of the electricity grid, materials are needed to produce the electricity cables. The materials discussed in this research are aluminium, copper, and steel. The needed inflows and resulting outflows for these materials have been modeled. The inflows and outflows

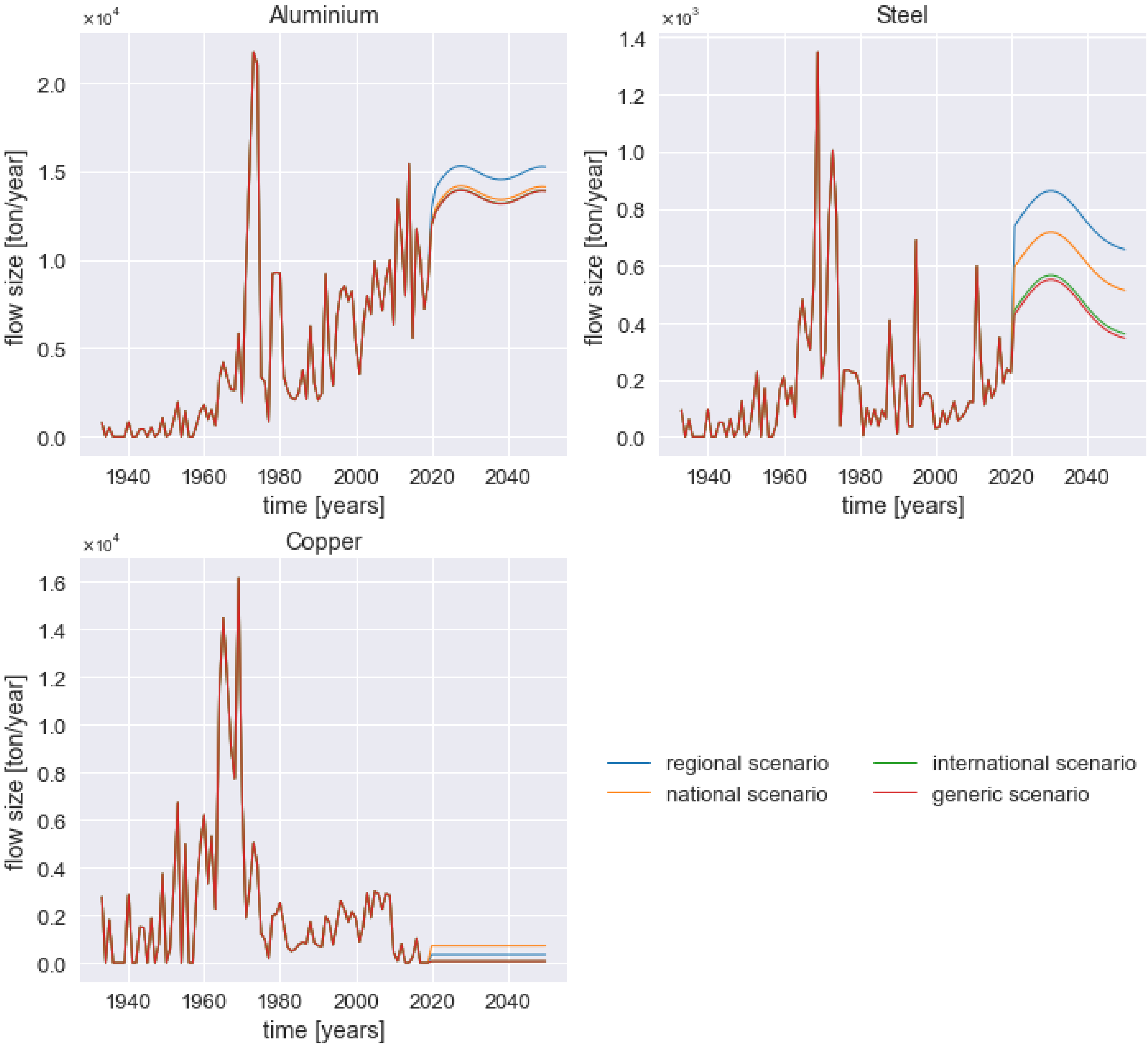

Figure 11. Material inflows per year, for both expansion of the electricity grid and replacement of EoL cables. The scale changes for each graph.

are shown in respectively Figure 11 and Figure 12. For visibility purposes, the graphs in both of these figures have different scales. The results seen in these graphs will now be discussed.

When analyzing the inflows, modeled in Figure 11, several conclusions can be drawn. First of all, the needed inflow of aluminium from 2020 onwards is quite high compared to the trend of the last 40 years. But when comparing the height of the inflow for 2020-2050 to the aluminium inflow in the last ten years (2010-2020), there have already been several years with an aluminium inflow of very similar amounts. There has also been an even greater inflow of aluminium around 1970, where the annual inflow even transcends the needed annual inflows for the period 2020-2050. The regional scenario has the highest aluminium demand, and the national, international, and generic scenarios lay close together at approximately 1000 tons/year demand, which is around 10% of the total annual demand.

A similar analysis can be made for steel. The needed annual inflow of steel in the future is a lot higher than the main trend has been since 1980. However, several peak years with similar amounts of steel inflow have already been accomplished, and again the peak around 1970 is much larger than the inflows needed for 2020-2050. For the steel inflows, a relatively much larger range is seen between the different scenarios. Once again, the regional scenario shows the highest demand, but for steel the national scenario also has a higher demand, while for the aluminium inflow the national scenario is quite low. Similar to aluminium, the international and generic scenarios are remarkably close together and have the lowest demand. Depending on the year, the inflows of the international and generic scenario are 25%-33% lower than the demand of the regional scenario. This means that for the steel demand, the scenario which the Netherlands will follow makes quite a large difference.

The copper inflows look vastly different compared to aluminium and steel. Instead of growing, the copper demand decreases. The range between the scenarios is large from a relative perspective. For copper, the national scenario shows the largest inflow, with approximately 1000 tons/year. the regional scenario is approximately half of that, and the international and generic scenarios are both insignificant compared to the other scenarios.

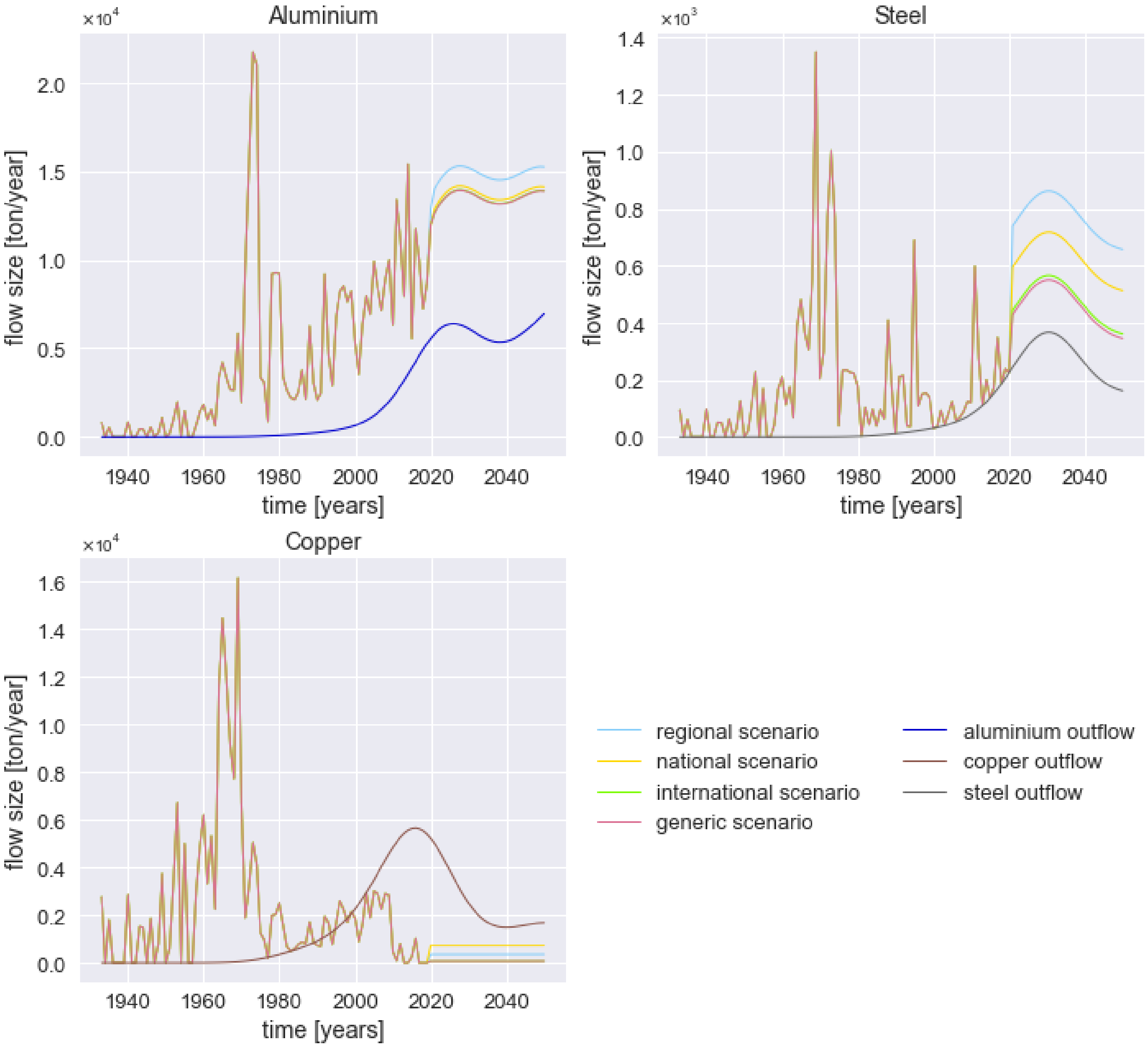

Figure 12. Material inflows for all scenarios and outflows of EoL cables. The graphs have a different order of magnitude.

In Figure 12 the outflow of each material has been shown compared to the inflows I just discussed. Looking at the aluminium flows, the aluminium outflow is around 33-50% of the aluminium demand in the coming thirty years. This is true for the steel flows as well. This means that for both aluminium and steel, the outflows will not be enough to create a fully circular supply chain by 2050 for any of the scenarios. For copper, the outflows exceed the copper demand for all scenarios, so theoretically a circular copper supply chain would be possible.

When comparing the three material streams among each other, another manner of showing the results is interesting, namely one where the scales of the axis are the same. This is shown in Figure 13**.**

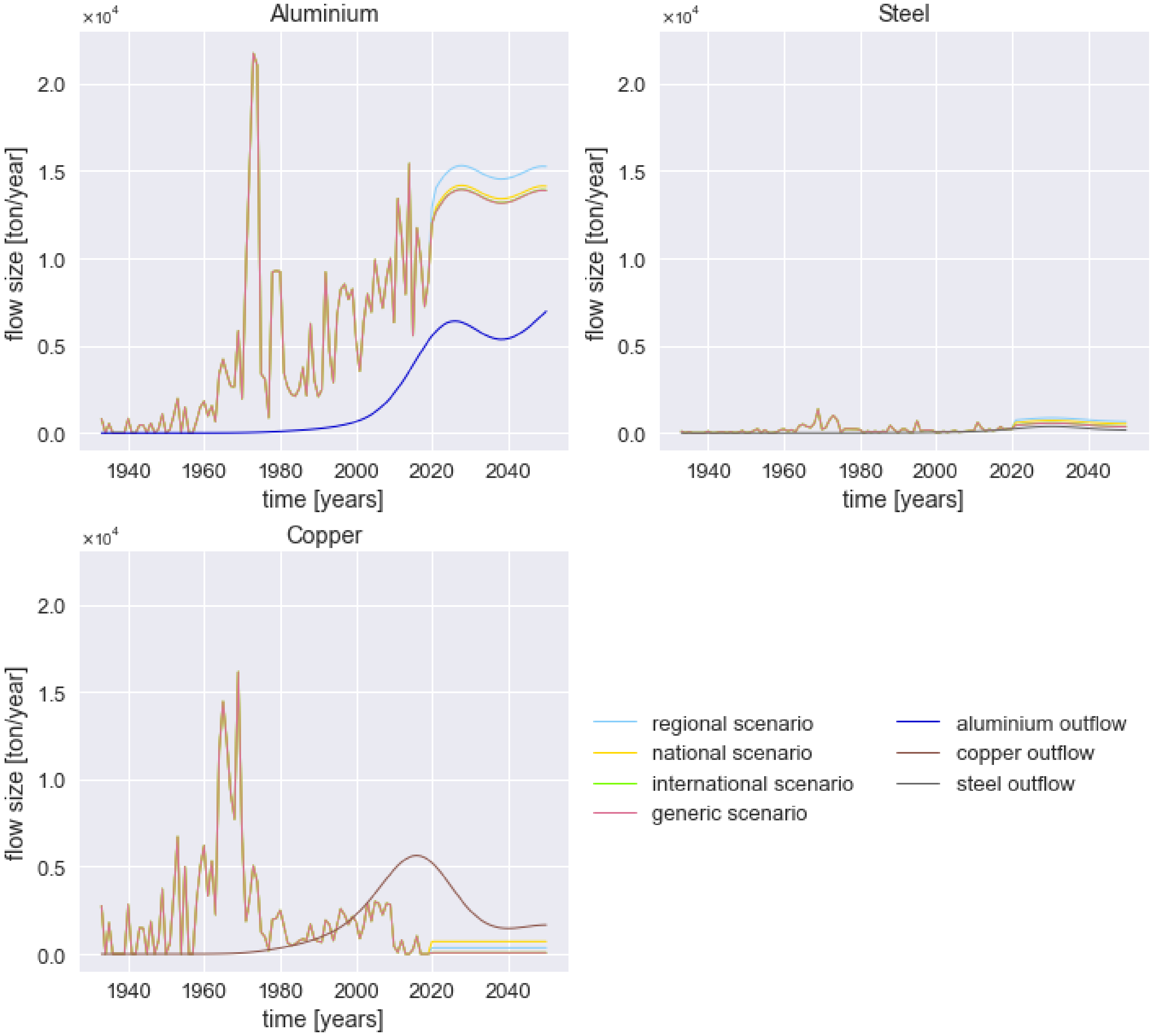

Figure 13. In- and outflows of the three metals compared at the same scale.

This figure immediately shows that the main material flows of cables are the aluminium flows. Especially the inflows of aluminium will become many times larger in the future than the inflows of both copper and steel.

Further issues and possibilities for circularity of the cable industry will be discussed in chapter 4.4. One issue which I have mode led and want to discuss in this chapter further is the recovery of the material outflows.

4.3 Recovery versus hibernation

The materials of cables are not always recovered, as explained in section 2.2.2.2. The outflow of EoL cables is divided into two: cables which are recovered, and cables which become part of the hibernating stock. As discussed in section 2.2.2.2 this research assumed 75% of EoL cables to remain underground and become part of the hibernating stock, and a sensitivity analysis is performed with 65% and 85% becoming hibernating stock. Overhead cables are always recovered, so steel is not part of the hibernating stock and only aluminium and copper will be discussed in this section. The resulting recovery flows of aluminium and copper for the different hibernation percentages are provided in Figure 14, and the resulting hibernating stock is shown in Figure 15. For comparison, the total outflows are also shown in Figure 14 to compare how much material could be recovered if there was no hibernating stock, i.e. as if the hibernation percentage were 0%.

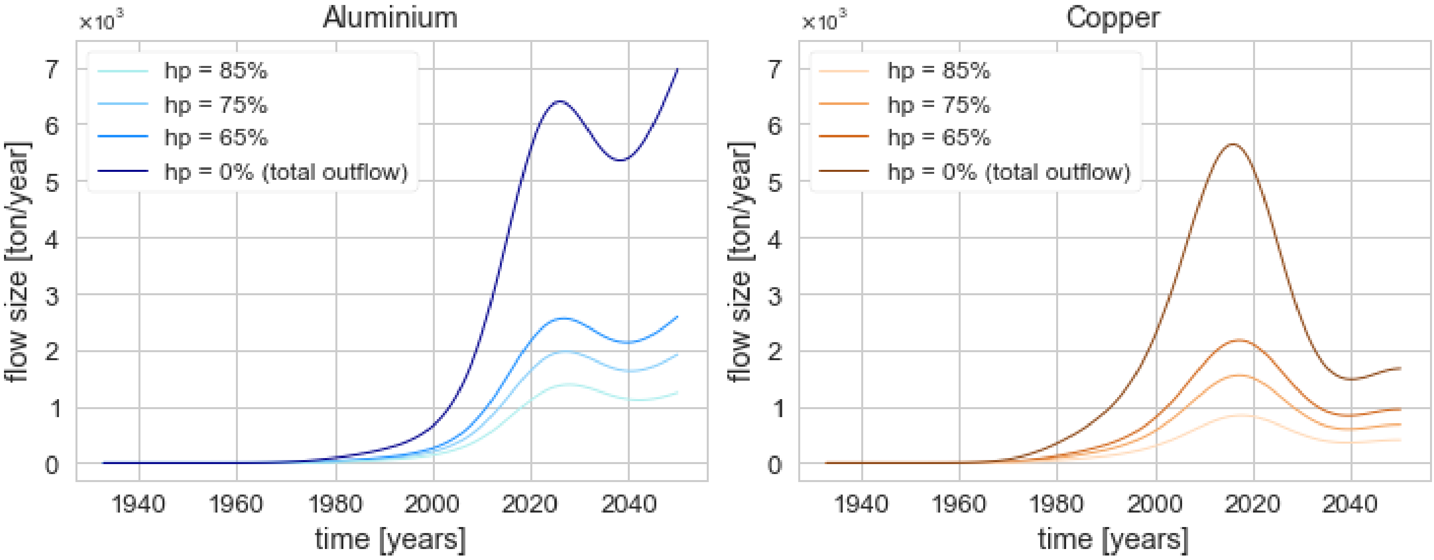

Figure 14. The recovered aluminium and copper flows, as they would be for different hibernation percentages (hp).

Figure 14 shows that quite a large amount of both aluminium and copper could in potential be recovered, but with the current situation of a large part of EoL cables being left behind, the recovered flow is significantly cut down. Especially for aluminium, by 2050 the difference is 2.500 ton/year for the lowest hibernation percentage of 65%. The difference that a 10% change in hibernation percentage makes is also quite significant by 2050, as a 10% lower hibernation percentage recovers around 500 ton/year more aluminium.

The story is slightly different for copper. The copper outflows are currently just coming out of a high peak, and the outflows will decrease from now until roughly 2040, after which the copper outflow becomes more stabilized. During this peak, during the next few years until 2040, the hibernation percentage makes an exceptionally large difference in the amount of copper which is recovered as secondary material. As currently copper is rarely used for new cables, the maximum available outflow is a lot smaller in 2050, and the difference between the hibernation percentages is not large either.

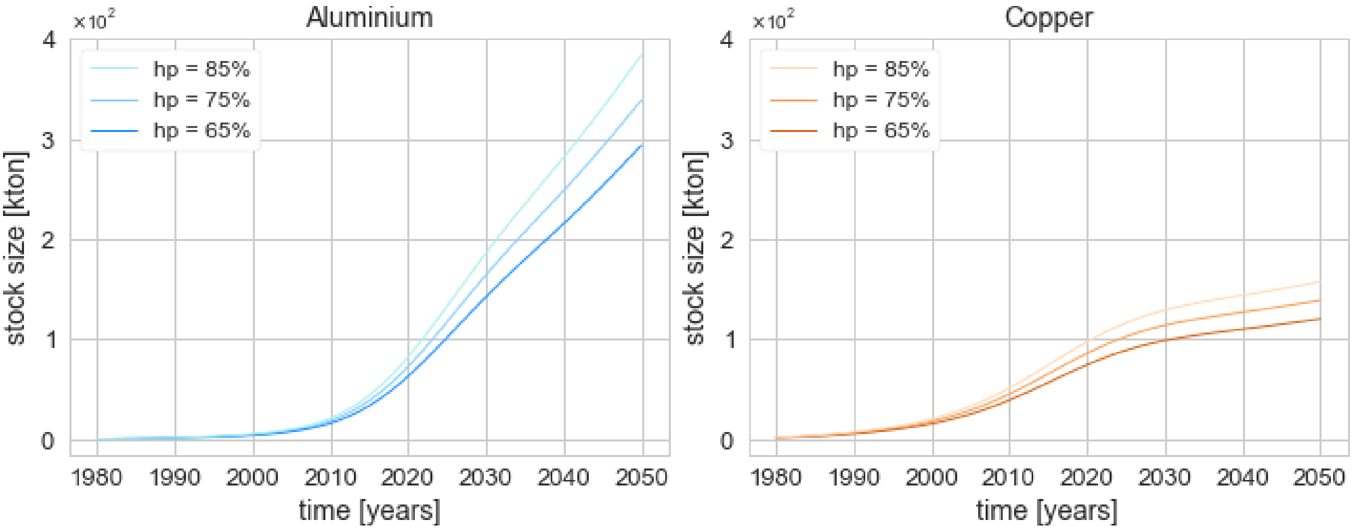

Figure 15. The size of the hibernating stock, as it would be for different hibernation percentages.

When looking at Figure 15, the hibernating stock of aluminium will grow significantly for all considered hibernation percentages, within a range of 180-250 kton. The hibernating stock of copper would be around half the size of the hibernating stock of aluminium, which is smaller, but with 90-140 kton it is still quite significant.

If I can assume that 'most cables remain underground' can indeed be interpreted as the range of hibernation percentage of 65-85%, then a large urban mine will form in the Dutch ground in the coming years.

4.4 Recycling to secondary material

In the previous sections of this results chapter, the material stocks and flows resulting from the MFA model have been discussed. The current section dives deeper into how EoL cables currently enter the economy as secondary material in the Netherlands. Through this discussion, issues are uncovered which the cable industry experiences with regards to the circular economy.

First of all, as already mentioned in section 2.2.2.2, EoL cables in the Netherlands are regularly left behind in the ground (P. Soepboer, personal communication, April 9, 2020; C. Bremer, personal communication, July 3, 2020). There are several reasons for this. When looking at the MV and LV grids, they are almost always placed underneath roads. This means that when a cable is replaced by a new one, the road needs to be opened up to install the new cable, which creates a lot of disturbance for the residents or companies along that street (P. Soepboer, personal communication, April 9, 2020; C. Bremer, personal communications, July 3, 2020). First, a new cable is placed underground, after which the street is closed again to minimize disturbance to surroundings. Then small areas of the street are opened up from the front door of the house towards the new cable, to connect the buildings to the new cable (P. Soepboer, personal communication, April 9, 2020). A DSO only wants to remove the old cable after fully installing the new cable, so that electricity is always available to the connected buildings. Therefore, in order to take out the old cable, the entire road needs to be opened up a second time (P. Soepboer, personal communication, April 9, 2020). This creates a longer period of disturbance to the surrounding residences or companies(P. Soepboer, personal communication, April 9, 2020; C. Bremer, personal communication, July 3, 2020), and greatly increases the costs of installing new cables (C. Bremer, personal communication, July 3, 2020). Municipalities usually have requirements for cable installation and excavation which can also hamper recovery of EoL cables. An example is that ambulances and the fire brigade should still be able to pass in case of emergencies, and to make this possible only the smallest possible part of the street is usually opened up for installing new cables (C. Bremer, personal communication, July 3, 2020). So to keep all involved stakeholders satisfied, often only the smallest part of the street possible is opened up, and for the shortest time possible. Besides these issues, often the ground underneath a street is rather crowded with other cables, such as internet cables, and water and gas pipes. This makes it difficult to extract a cable from the ground without breaking any of the other components there (C. Bremer, personal communication, July 3, 2020). All these reasons together seem to lead to the conclusion that recovery of MV and LV cables is often undesired by all stakeholders because of the high cost and high disturbance, and thus the decision is often taken to leave the old EoL cable behind in the ground. MV and LV cables could be excavated in a situation where for example a neighborhood is broken down, or when a cable is placed on private land and the landowner asks to remove it (P. Soepboer, personal communication, April 9, 2020). In some other cases, the license of a cable states that it needs to be removed (J. Smit, personal communication, April 30, 2020). A cable can also be removed when it becomes difficult to see which cable has which purpose because of overcrowding the ground underneath the street (C. Bremer, personal communication, July 3, 2020). When looking at the EHV and HV grid sections, the reasons for underground cables to remain behind are slightly different, as these don’t specifically run through residential areas. EHV and HV underground cables are difficult to recover as the long lifespan and long lengths of the cables create many opportunities for things to be built on top of them. For example, a new highway could be built over the cable (J. Smit, personal communication, April 30, 2020). Or the land through which a cable runs could have become a nature reserve (J. Smit, personal communication, April 30, 2020). As many EHV and HV cables as possible are excavated, but it is not always possible.

When a cable is recovered, there are two processing methods for EoL cables in the Netherlands, used for different cable types. Firstly, overhead cables and the newer underground PVC cables are recycled through the common recycling processes. This entails them being shredded into small pieces after which the materials are sorted. In this process, the metals can be easily taken out through Eddie-current sorting systems (M. Rijnsburger, personal communication, July 7, 2020). The second processing method is for the historically used PILC cables. They have to be recycled slightly differently because they contain paper drenched in oil used for insulation. When a PILC cable is directly thrown into the shredder everything will be covered in oil (M. Rijnsburger, personal communication, July 7, 2020). To prevent this, the cable is 'stripped'. This means the cable is cut in half over its entire length, and the different layers are peeled off by staff (M. Rijnsburger, personal communication, July 7, 2020). The paper-oil layer is then separated and incinerated. The remaining layers of the cable are thrown into the shredder to follow the same process as described above (M. Rijnsburger, personal communication, July 7, 2020).

The metals of EoL cables are always recycled. Metals are valuable and can be sold to other parties after recycling, which makes recycling EoL cables profitable (M. Rijnsburger, personal communication, July 7, 2020). However, the cable industry is still a long way from being circular. New cables are always made from virgin aluminium or copper, because very high purities of these materials are needed, for aluminium cables a purity of 99,99% aluminium is needed (P. Soepboer, personal communication, April 3, 2020; 2020, M. Rijnsburger, personal communication, July 7, 2020). Secondary aluminium and copper are not always, or only generally, sorted on alloy type, and many different types of alloys end up in the same smelter. Therefore, secondary aluminium and copper contain many pollutions and the purity of the secondary metals is never as high as needed (M. Rijnsburger, personal communication, July 7, 2020). Unfortunately, this means that for the production of cables only virgin aluminium can be used. This greatly hampers a circular economy since a circular economy wants to decrease, if not eradicate, not only its wastes but its virgin material inputs as well.

DSOs and waste management and treatment companies are very aware of the sustainability challenges regarding cables. Re-using a cable is much better than recycling on a material level. One of the DSOs, Enexis, has experimented with re-using a cable at the end of its use in another location (C. Bremer, personal communication, July 3, 2020). However, there are several issues connected to re-using. First of all, a retrieved cable needs to have enough length to fit the needs of the new location. Theoretically, shorter pieces can also be used and connected in series to make one long cable. However, this does not happen. Shorter pieces need to be connected through the use of sleeves. But sleeves have the disadvantage of being a lot more prone to failure which results in power-outages (C. Bremer, personal communication, July 3, 2020). As the main goal of a DSO is to deliver electricity and so-called security-of-supply, lower chances of failure are infinitely more desirable (C. Bremer, personal communication, July 3, 2020). Placing of sleeves is also labor-intensive work, which brings the topic back to the economic side of the coin, as man-hours are much more expensive than a new cable. The conclusion is that re-use never happens. If there would be an old cable with the correct length and transport capacity needed for a new project, the risk of the old cable having a flaw somewhere along its length is too big, because a cable is often only removed when the expected lifetime is expired (C. Bremer, personal communication, July 3, 2020). Therefore, although re-using cables could technically be possible, it never happens in practice.

5 Discussions

Two topics will be looked at in this discussion. First, the results will be discussed in light of the Dutch circular economy, and in the second section several modeling choices and their effect on the model used in this research will be discussed.

5.1 Discussion on results

The results as discussed in the previous chapter have shown that when the Netherlands wants to become CO_2 neutral and thus needs an energy transition, the electricity grid needs to be expanded in some order of magnitude for all analyzed scenarios. Since the scenarios have been created for the purpose of providing the Dutch government with an overview of the 'playing field' for the energy transition (CE Delft, 2017b), the actual pathway of the Dutch energy transition will likely be somewhere in between these scenarios. This means that the electricity grid indeed needs to be expanded before 2050. To accomplish this, many metals are needed, but there are also rather significant amounts of metals becoming available from outflows of the electricity grid in the form of EoL cables.

The focus of this research was to discover the stocks and flows for the Dutch circular economy. So when looking at the results that were found in light of the Dutch circular economy, there are large outflows of EoL copper, aluminium, and steel coming out of the electricity grid, which could become available as secondary resources in the coming years. As these metals and widely used resources and especially copper is very valuable, these could be useful secondary resources to use in the Dutch circular economy. And in reality, there are indeed secondary material streams from EoL cables, as the metals of excavated cables are recycled. However, a large part of these valuable secondary resource streams is not recycled and used as secondary material. This is the case because underground, EoL cables are currently often left behind in the ground. As has been discussed in section 4.3, this could greatly reduce the flow of usable recovered aluminium and copper and create a large unused hibernating stock. At the current time, the hibernating stock is not enormous yet, but as a part of the EoL cables join this stock every year, this is expected to grow to significant amounts. This is a large waste of valuable metals.

There are of course reasons to explain this. Two barriers to excavating a higher percentage of underground cables have been discussed in the last section of the results. The main barriers found were high costs and little stakeholder support for excavation. Several governmental instruments could be implemented to lower the barrier. One possible solution as mentioned by C. Bremer (personal communication, July 3, 2020) is to simply oblige DSOs to remove EoL cables from the ground. Licenses for placing cables contain many prerequisites, and adding the obligation of excavation in these prerequisites would force the DSOs to remove the EoL cables. However, this would only guarantee the excavation of cables that have yet to be installed as currently installed cables already obtained their license. Because of the long lifespan of cables, this would only show the desired results after 50 years, which exceeds both the time scope of this research and the time scope in which the Dutch government wants to become circular. Another possibility for stimulating the excavation of old cables is to use the Dutch 'precario'-tax ('precariobelasting') (C. Bremer, personal communication, July 3, 2020). The precario-tax can be placed on all things underneath, on top of, or above public municipal land (VNG, n.d.). This includes electricity cables underneath municipal streets. Municipalities can decide for themselves whether or not to demand precario-tax (VNG, n.d.). Demanding a precario-tax on hibernating cables will make the costs of leaving the cables behind a lot higher, which could result in an incentive to excavate them (C. Bremer, personal communication, July 3, 2020).

A second issue surrounding the electricity cables in light of the circular economy is the large amount of aluminium and the smaller amount of copper which will be needed as inflows into the electricity grid. The results section brought to light that the aluminium and copper of new cables need to have such high purities that currently recycled secondary aluminium and copper cannot be used for this purpose. This means that all new cables will need to be made of virgin aluminium and copper, and thus a large inflow of new materials will be added to the economy each year. Since one of the focus points of a circular economy is to decrease its extractions from the environment, the virgin aluminium and copper inflows should be decreased as much as possible. One option for doing this is re-using the aluminium and copper of EoL cables, already containing the specified high purity, for making new cables. Experts say that technologically and logistically speaking, it *could* be possible to re-use secondary aluminium and copper of EoL cables for new cables (M. Rijnsburger, personal communication, July 7, 2020). Logistically it could be possible because different waste types are sorted and piled up before being shredded. For each waste type, the shredding and sorting process is slightly adjusted depending on the valuable materials which the recycler aims to recover (M. Rijnsburger, personal communication, July 7, 2020). For example, at a certain moment, only aluminium cables are shredded. The pile of sorted aluminium at the end of the process thus results from only aluminium cables, and therefore the sorted aluminium has a very high purity. This aluminium could then theoretically be kept separate from all other aluminium alloys and processed separately for use in new cables. Technologically, reaching a very high purity could also be possible. There are quite advanced sorting methods which can sort different material types very well. However, the main issue on re-using aluminium and copper of old cables for new cables is an economic one. To get the purity of recycled aluminium or copper high enough, the material has to go through the separation process several times, as not all particles of other materials are removed in the first round (M. Rijnsburger, personal communication, July 7, 2020). This greatly increases the costs, while the worth of the material does not increase in the same rate. This poses a challenge, since a high purity, say 95%, can be achieved for relatively low costs, while the increase in purity of the last 4% to 99% exponentially increases the costs (M. Rijnsburger, personal communication, July 7, 2020). However, to end up with a valid business case for using recycled metals, the costs of recycled metal should be lower than the costs of virgin metals (M. Rijnsburger, personal communication, July 7, 2020). The government has instruments which could help to support such business cases, such as a tax on the use of virgin metals or a subsidy on the use of recycled metals. Putting a tax on the use of virgin metals might have the undesired effect of companies moving their business abroad, which makes implementing a subsidy seem to be the better alternative. These financial instruments might result in making used recycled metals more attractive compared to virgin metals and will stimulate a more circular supply chain.

After all, the aluminium and copper from old cables are the highest purity found outside of virgin material (M. Rijnsburger, personal communication, July 7, 2020). Not reusing this very pure material, but degrading it through smelting with other alloys would be a huge waste. At some point in time virgin metal will be too difficult or expensive to obtain from the earth and we will wonder why we did not make use of the pure sources we already had available to us.

However, although re-using metals of EoL cables would indeed decrease the input of virgin metals into the economy for new cables, the Results chapter showed that the outflows of secondary material from EoL cables do not nearly reach the amounts which the inflows do. This means that even when these secondary metals of EoL cables could be re-used in new cables, still a significant amount of virgin metals needs to be added to the inflows. It might thus be relevant for the circular economy to look at the front of the supply chain: would it not be possible to accept a lower purity for the conductor materials? Because if that would be possible, then it would be greatly easier to use secondary metals for new cables, possibly even secondary metals from other sources than EoL cables, and a more truly circular economy could be reached.

5.2 Discussion on modeling choices

A model never completely mirrors reality, and assumptions and modelling choices have to be made which try to portray reality as close as possible. However, different assumptions always depend on the author and the research, which is the case in this specific research as well. As data is sometimes missing in the field of the Dutch electricity grid, some (educated) assumptions had to be made. Since other assumptions may change the results which were found in this study slightly, it is important to discuss them and their effects on this model. So, to gain more insight in the direct and indirect effects that the assumptions caused they are discussed here.

First of all, because of a lack of data, for aluminium and copper only the materials used in the conductors have been taken into account in this research. However, all cables contain a thin wire shield as well which is often made out of copper. This means that the inflows of copper, in the future, might in reality be higher than the way they have been displayed in the results. Only one research has been found which has recorded the copper contents of such a wire shield in cables in Sweden (Krook et al., 2011). However, the copper contents that Krook et al. (2011) recorded for copper cables are very different from the copper contents that Van Oorschot (2020) found in the Netherlands. Because this made it uncertain how correct the recorded copper content of a wire shield by Krook et al. (2011) would be for the Netherlands, it was chosen to just focus on the materials of the conductors. But to give some more insight in the effect of the copper wire shields, a sensitivity analysis has been conducted. As a copper wires shield only has effects on the copper flows, the copper flows have been modelled with different copper contents for such a wire shield. It was chosen to analyze the effects of the copper wire shield on the flows of the national scenario, as this scenario had the highest copper inflows. It has been modelled what the

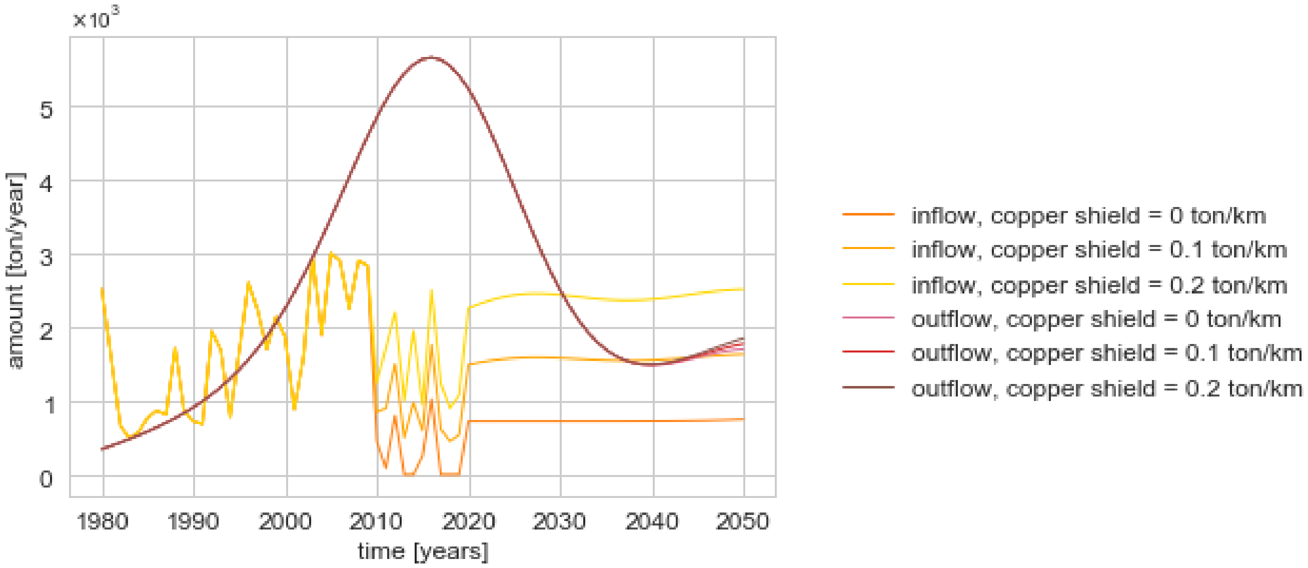

Figure 16. Sensitivity analysis on the effect of the copper wire shield.

effects on the copper flows would be if such a wire shield had an average of 0.1 ton/km and an average of 0.2 ton/km, because Krook et al. (2011) found similar orders of magnitude.

The results of the sensitivity analysis on the copper flows are shown in Figure 16. As can be seen it has little effect on the copper outflows, but it has quite a large effect on the copper inflows, which seem to double for 0.1 ton/km and triple for 0.2 ton/km copper shield. As this is a rather significant influence, it would be very useful to further research the actual copper contents of the wire shield for the different cable types.

The EHV and HV grids consist of both overhead and underground cables. For the model I have assumed that the overhead and underground grids expand with the same ratios. However, this might in reality not be the case. Sometimes overhead cables are replaced by underground cables, or the other way around. Perhaps in the future the Netherlands will only install underground cables. Because the mechanics for these choices are unclear, this has been left out of the research. If this had been implemented the effects would not be very large. The decision mainly influences the stock and inflows of steel, as the conductors for underground and overhead cables have been modelled with the same aluminium intensity. When the Netherlands would switch to only using underground cables, the inflow of steel would change to zero, as steel will then not be needed for new cables anymore. The outflows of steel would remain the same, as these result from cables that have already been placed fifty years ago.

The modelling of the hibernating stock in this study has been an educated guess. There is little to no data available on what share of EoL cables from a DSO enters the hibernating stock, except for the knowledge that ‘a large part of EoL underground cables is not excavated’. Often, this is sensitive information, and DSOs do not always have such data recorded. For this reason, I chose to perform a sensitivity analysis, to see how this variable would influence the model. The conclusion is drawn that even though the exact shares of cables being recovered or left in the ground, the hibernating stock is growing to become a very large stock by 2050. However, it would be useful to perform further research into the hibernating stocks of the Netherlands, as this will become a very useful source of material for the circular economy.

6 Conclusions and recommendations

In this chapter the conclusions of this research will be drawn, and recommendations will be given based on the conclusions.

6.1 Conclusions

This research has conducted a material flow analysis on stocks and flows of electricity cables in the Netherlands to gain more knowledge on the available urban mine for the Dutch circular economy.

The main research question as formulated at the beginning of this research is the following:

> *How will the metal stocks and flows of electricity cables in the Netherlands develop for different energy transition scenarios, and how can the outflows re-enter the circular economy?*

To answer this question, material flow analysis (MFA) has been used to study the main three materials in electricity cables: aluminium, copper, and steel.

Four different scenarios on the energy transition have been used to predict the possible development of the stocks and flows. These scenarios have been created to show all 'corners of the playing field' of the energy transition to the Dutch government, and the actual energy transition will likely find itself somewhere in the middle of these scenarios. For all four scenarios, it has become apparent that the electricity grid in its totality must be expanded considerably. There are rather large differences between the scenarios for the expansion of the high-voltage grid, but the medium and low-voltage networks must both expand considerably for all scenarios. The in-use stocks will thus increase rather significantly until 2050. For these expansions large metal inflows are needed. Although there is of course a difference between the inflows for the different scenarios, the needed inflows become quite high after 2020 for all scenarios, especially for aluminum, but also steel. However, although the needed inflows of aluminium and steel will be high, similar high amounts of inflows have also been achieved in the past, thus it is concluded the amount of inflows should be achievable. When looking at copper, the inflows decrease greatly instead of increase, as the use of copper in cables has been largely substituted by aluminium.

Not only the inflows change in the coming years, but the outflows also see interesting developments. The outflow of aluminum has seen an upward trend in recent years and will remain high until 2050, but when comparing the outflow with the inflow of aluminium, the outflow will remain significantly lower than the required inflow. The copper outflow is currently at a high peak, but will decrease again until 2040, after which the outflow will become fairly stable. The copper outflow has been found to always be higher than the required inflow of copper. The outflow of steel is heading towards a peak in 2030, but similar to the aluminum flows, the outflow of steel is always lower than the inflow. This means that for aluminium and steel, there is always more material inflow needed than the outflows could provide, so new material needs to be added into the system. However, I found that the aluminum and copper inflows in the electricity grid require a very high degree of purity to meet the current requirements for the conductors of cables. And even though the metals of EoL cables are recycled and enter the economy as secondary material, those high purity requirements make it impossible to use secondary material for new cables. This is because secondary material is smelted in a batch with multiple alloys which greatly decreases the purity of the material. Thus cables cannot be made of secondary aluminium or copper, and the entire inflow of aluminum and copper needs to be virgin material. Since a circular economy not only wants to reuse waste, but also wants to reduce its inputs, this is certainly not beneficial for the Dutch circular economy, as large amounts of virgin material will need to enter the economy. It would be greatly beneficial to encourage that the aluminum and copper from EoL cables can be reused in new cables, as this specific secondary aluminium and copper already has the necessary purity. The copper from EoL cables could even fully cover the demand for new copper, so that no new copper would need to be added to the circular economy. But when looking at aluminium, the demand until 2050 will remain higher than what the outflows could deliver. Therefore, to get a truly circular economy, the high purity requirements for new cables should perhaps be lowered, so that secondary material from all kinds of sectors instead of only from EoL cables can be used in new cables.

Unfortunately, not even all metal outflows of EoL cables can re-enter the economy as secondary material. This is because a large part of the underground cables is not excavated by Distribution System Operators (DSOs) but are left behind in the ground. The grid consists of both underground and overhead cables, but as the largest part consists of underground cables this has quite an impact on the actual recovered secondary material flow. The cables are often left behind because it is too expensive to get them out of the ground or there is not enough stakeholder support. These cables that remain in place then form a hibernating stock. Exact data on the percentage of cables which are recovered or, contrarily, enter the hibernating stock in the Netherlands, were not available. To show how the hibernating stock could develop until 2050, different hibernation rates have been analyzed. The model has shown that if indeed a large part of the cables remain underground, a huge hibernating stock will arise over the coming years, even though it is currently still relatively small. Since the Netherlands aims to create a circular economy, it is a huge waste of all possible secondary materials that are in EoL cables, and measures should be taken to stimulate the DSOs to remove the cables from the ground.

After all, the electricity grid contains large quantities of aluminum, copper, and steel, which could certainly be used for the circular economy, if only they are seen as a valuable material source and treated accordingly.

6.2 Recommendations

Based on this research I would like to make four recommendations.

First of all, there is a large data gap on what shares of underground cables are excavated or left behind, and I would recommend researching further what these shares would exactly be. The model used in this research has made an educated assumption on these shares and thus has gotten a general idea of what the hibernating stock could become. But gathering this data will provide much more specific knowledge on how large the hibernating stock will be in reality, and thus the exact amounts of material which can be taken from the hibernating stock for the circular economy. As this data is currently not available, I would also recommend recording the data on what exactly happens to EoL cables more thoroughly.

Secondly, to keep the hibernating stock as small as possible, and thus recover as much secondary material of EoL cables as possible, I recommend the government to implement instruments which entice DSOs to remove EoL cables from the ground. Two examples would be to simply oblige DSOs to excavate EoL cables, or to implement a precario-tax on cables which are out of use but left behind in the ground.

Thirdly, to keep the inputs of virgin aluminium and copper into the economy as low as possible I would recommend the government to implement financial instruments that incentivize cable producers to increase their use of secondary materials for new cables. Because it is currently much cheaper to get virgin metals at a high enough purity as is needed for cable conductors, using secondary metals for the conductors is not a valid business case. To change this for example a tax on the use of virgin materials could be implemented, or a subsidy for using secondary materials.

And lastly, I would greatly recommend the cable producers and DSOs to honestly look at the requirements made on aluminium and copper for new cables and whether they are truly necessary. If the requirements could be slightly lowered, it could be much easier to use secondary metals instead of virgin metals.

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Appendix A Interview summaries

A.1 Interview Piet Soepboer

Name: Piet Soepboer

Company: Enexis

Function: Asset Manager

Date: April 9, 2020

Summary

What would the average capacity of your current cables be?

I cannot say, it greatly differs per cable.

In the event of a large increase in electricity demand where the current cables do not have sufficient capacity, how would that be resolved? Will more cables be added on the same route or will cables be replaced by other cables with a larger capacity?

There will be more cables added, otherwise it would be throwing away materials which still hold value.

What I still find very difficult is that data on regional electricity demand will be available in the future, but I do not yet know how that total electricity demand affects the individual cables, because not every cable carries the total demand. Do you have any inspiration or advice on how I could approach something like this with estimates? For example, are there indicators for this?

Not really, this is the most difficult question currently. The grid operators themselves are still very busy thinking on how to approach the future.

Are your established expansion plans public? If so, where would I find it? Can you share other things about this? The 2020-2030 investment plans should be completed soon if it's all right? Do you know if they will be made public and if so when will they become available?

They are still only a concept, they are not yet public, but there will soon be a consultation round. They will eventually become public.

I heard from a contact person at Prysmian that in the Netherlands only cables with 100% aluminium conductors are used. Is that correct in your opinion?

Yes, by far the conductors of new cables are all 100% aluminium at the moment.

Do you know if there will be changes in the material composition of the cables in the future?

Pure aluminium is used. There is still a screen of copper around the cable for security. This screen cannot be aluminium because it will erode. Plastics are used as well, inside the cable is plastics and it has an outer sheath. The plastics used inside the cables cannot be recycled (on an equal level), while the outer sheath can be recycled. Part of the outer sheath is already made from production waste. However, recycling those materials is difficult, as currently the cables are recycled through shredding them and sorting the materials afterwards. But the two different types of plastics are not possible to be sorted anymore as they are not distinguishable anymore when shredded into pieces.

At the moment there are also old cables with copper conductors, paper insulation, lead screen/sheath, steel armour and a textile/bitumen outer sheath.

For how long are cables used? And for how long could they be used?

Basically 50-100 years. 100 years if the laying conditions are ideal, but if, for example, many cars drive over it, it will be around 50. The official lifespan is of cables 40+.

Are cables ever not used anymore while they could technically still be used?

That is almost never the case at the moment. Only in special circumstances such as the closure of an old wind farm, or other customer connection to the grid could the cables go out of use while their lifespan isn't reached yet.

Are all cables currently underground still in use?

No, part of the cables is out of use, a percentage of them is no longer used.

I heard that not all EOL cables are always taken out of the ground, is that correct? Why not, when would they be taken out of the ground?

In practise, they are not removed from the ground because the street then has to be opened up twice, which causes too much inconvenience. First for the installation of the new cable, then smaller manholes for installing the new connections with the houses, and then the entire street would have to be opened up again weeks later for the removal of the old cable. So they usually just remain in the ground. Situations when the old cables may be removed is when a neighbourhood is demolished and rebuilt. Then there is no longer a connection and construction is already going on so it does not cause any inconvenience. The layout of the area can also change and then the cables should be moved.

What does Enexis do with cables that are retrieved from the ground?

The cables are collected by Milgro, our waste manager, and then they are recycled. The biggest recycling problems are on plastics. Handing in old cables for recycling yields money per km.

What is a problem is that the cables must be made of 100% aluminium. This means that they cannot be made of recycled aluminium because many types of alloys are thrown in the same batch of recycled aluminium, so the purity will never be high enough.

A.2 Interview Charlotte Bremer

Name: Charlotte Bremer

Function: Waste Manager

Company: Enexis (middle- and low voltage grid operator)

Date: 3-7-2020

Summary

There is a cooperation of network operators: Groene Netten, a group of sustainability people from all network managers, telecom companies and possibly even pro-rail for the cables of the rail network, who talk about making the networks more sustainable. It is largely about replacement, and what do you replace it with / for, and how do you do that well. A subgroup of Groene Netten is concerned with the copper chain and the circularity of copper. Some people there think we have to get rid all copper for reasons such as that children in Africa have to get it out of the ground. Copper is still used in the wire shields. There is simply a lot of copper in the nets, it might be better to look at what we are going to do with them, and to ensure that it is used and processed properly or that it is not exported to China. People talk and think about it a lot.

Isn't only aluminium used in new cables in the Netherlands?

The conductors of new cable are always made of aluminium, but copper is still used in earth shields and the house connections, but not in the cores. A lot more copper comes out of the net but into the net, so you could probably recycle your old copper and that would probably be enough for new cables, but that is more of a gut feeling.

Why are or are not cables removed from the ground?

It is a complex thing, it can have several reasons.

It is mainly related to the price. If it is more complicated or more expensive to remove the cable, it will sometimes be left. If there is confusion about which cable is what, it will sometimes be removed. There are really a lot of cables underground, it is often very complicated to remove cables from the ground without accidentally breaking anything else. The surrounding neighbors also find it very annoying and disturbing if the street is open for too long or too big: for example in the city of Groningen, shop owners, shoppers will be very bothered, and the ambulance or fire brigade must still be able to go through the street. Often for a new cable, as little as possible of the street is opened so that multiple stakeholders are okay with this, and it must be safe. The municipality also has many requirements.

What % of the cables are taken from the ground?

No idea. A container is rented three days in advance, which is filled and afterwards there is a weighing receipt and then they know how much cable has been removed.

Grid operator companies have grown from mergers and acquisitions, etc. and all data from all those different companies still works on different systems and is not automatically all organized well.

What is needed to incentivize grid operators to retrieve more EOL cables?

A municipality owns the land. The municipality sets requirements on cables, they may prohibit things from being there or may oblige them to be removed. They can also levy taxes on dead cables. In the Netherlands this is the 'Precariobelasting' .

Municipalities might also misuse this tax. If a municipality is short of money, they will levy tax on cables in the ground, which the network operator then includes in the electricity price. It does not feel as if the tax has been increased, while that is actually the case, but it is paid through the electricity price. The electricity price is not allowed to just increase in one municipality, but must increase in at least the entire region, possibly even the entire country. When other municipality see this happening, they can pull the same trick and then all citizens will receive much higher electricity prices.

Does such a tax then still provide an incentive for grid operators to remove EOL cables?

Yes, this still gives an incentive to take out the old cables. A grid operator cannot simply increase their prices, as those are regulated. It also differs per location whether such a tax would work or not to take out a cable. For example, for a shopping street Groningen has to ask a considerable amount of money or simply make it obligatory for the cables to be removed. But the municipality will probably not do that, because it is not attractive to them. A municipality that mainly has pastures could say that much sooner.

If some of the cables are removed, can the copper from the old cables be used for, for example, a wire shield for a new cable?

Copper must also have a certain quality, the more it mixes, the worse it is. So a wire shield must also have good conductivity. You want the shield as thin as possible and if it does not work then it is of no use to you. So there are probably high demands on this.

There has been philosophized if we should want our aluminium and copper to be delivered directly back to the cable supplier. That turns out to be more complicated than we think and it never got off the ground. It is also unknown whether the cable suppliers are waiting for this.

People are also working on things like the material passport. I don't believe they put out to tender on a material passport. But it could be positive if the material passport says that it is recycled material instead of new material, from which you do not know where and by whom it was extracted. The transparency in that market is not yet good enough that you can make very strict demands on it. There are often so many technical requirements for those types of tenders that sustainability requirements are a bit snowed-under and not so important. What is the importance of a cable producer to apply that sustainability aspect. For example, Prysmian often presented their cables as circular, but what they mean is that it is recyclable at the end of its life. But in 60-80 years, at the end of its lifespan, we just don't yet know what can and cannot be recycled. They could make a circular supply chain if we remember in the future that a specific cable is a Prysmian cable, and not just forgot that was it and simply thought it on the pile with all the regular cables. You can have a recyclable plastic protective jacket, but if you cannot distinguish it, nothing will be done with it.

And how are EOL cables now processed?

We have two types of waste streams: waste streams released on a project, so an old cable that needs to be replaced, all this cable was installed at the same time so it is all the same type of cable in one container; and smaller pieces that are released during cable failures and the like. This is 30% of our waste, and these are all pieces that are thrown together in one container and contains different types of cables, with different thicknesses and different ages. Everything goes to a cable processor, who strips the cables. The cable processers do not show exactly how they process. But stripping means that it is peeled, the outer layer, earth screen, insulation material and core, and it goes on to traders and melting furnaces, etc in separate material streams.

The waste processing industry has traditionally consisted of cowboys or even criminals, so it is a market that currently has many different types of parties, from very transparent and reliable parties, and parties that need as much uncertainty as possible to get the highest price themselves, and get as few questions as possible about working conditions, the environment, safety, things like that. Sometimes it is quite difficult to get to a good party. We work with a good party which ensures that our materials end up with a good processor.

You are bound by tenders of course. You can't say, "hey, you feel good, I'll go for you guys"

No that's not possible. Your waste processor does business with party x, if you do not have stated in the contract that you are allowed come to see how they work, then that will not happen. My predecessor had visited a processer once, but everything was stoppen and everything was clean, there was no speck of material anywhere and all the workers had been sent home. He said "this is not a working visit, now I still don't know what you are all doing.". Then you get a strong feeling that something is not right. That is why it is extra important to pay close attention, but it is also extra difficult to really work in a circular way. It differs per party with whom you cooperate how much you can do. Ultimately, everyone is dependent on metal traders. That's world trade and they just ship the materials to china or turkey, they just go for the highest price and they are not about sustainability talks from semi-government organizations where people try to brainstorm 'how are we going to get the copper chains circular?' . The supply chain just goes past these traders and blast furnaces that have to melt things. And that is about such large quantities and large global flows, how I should influence that is not entirely clear to me.

Maybe there should be worldwide rules for that.

Yes, but well, the Chinese think: everything is for us, and they really will not think 'it would be nice to spare Europe a bit, or create less emissions, then we have we pay more, but then you have less CO2.‘ There are a lot of countries that don't think that way at all. Then we would sooner protect the European or the Benelux market a little better, or we will make bonds with cable suppliers who are located here. Then you have the European tendering rules… And then there are consultations about the copper chain and you can already see that there are three network operators within the Netherlands who are quite different and cannot always agree with each other, and then I already think 'oh oh, where is this going to go boys?'.

What is the quality of the materials of the cables coming out of the ground? For example, can you refurbish it and use it again?

There once has been a project in which a long piece of cable was taken out of the ground and used again.

The thing is: we are extremely hard on power outages, that is top priority, there should never be no power. Cables are expensive, but man hours are much, much more expensive. And making a sleeve, a connection between two pieces of cable, takes much longer and the chance of failure is much greater. An old cable could be damaged somewhere and that would increase the chance of malfunction. And there are many more sleeves needed when you are going to connect short pieces to each other, which are much more susceptible to malfunction. And making a sleeve just takes a lot of time, there's someone in a hole in the ground cutting one cable open, peeling it, cutting the other cable open and peeling it, putting it all together and stuffing it with resin, etc. and that's just a lot of hassle. So if you look at that it doesn't really happen.

It is only possible if you have more or exactly the same length of old cable as is necessary for the new piece.

But is the quality of the materials in old cables still fine?

Yes, in principle the quality of conductors doesn’t degrade. Rather it is the insulation material around the core that gets bad, but the conductivity of the core I have never heard of that is worse. But I am not a technician, so check that.

I still find it very frustrating that those cables are delivered on reel. There is a certain length of cable on such a reel, and if you do not need everything, there will be some left over. And if you, like Enexis, use a lot of cables, there are a lot of those last ends that are all thrown away. But because of the issue those sleeves, they are never used. Even if you all have short pieces of new cables, they are never used because it takes a lot more work and needs a lot more sleeves which increases the chance of malfunction. It is never known in advance exactly how long the piece of cable should be, because if there is for example a tree in the way you need a little more to go around it, so there is always a longer cable delivered just to be sure and there are always ends left.

A.3 Interview Merijn Rijnsburger

Name: Merijn Rijnsburger
Function: Waste Engineer
Company: Milgro
Date: July 7, 2020

Summary

Milgro provides sustainable waste management for companies. We look at the waste flows that are released at multiple locations for different customers, and then we look at how we can best process them. The first step is making the connection between what is released and who can process it in the most sustainable or cost-effective way. The second step is why the waste is produced, what type of production process causes it, or what is bought that causes waste at the end of the process. What is the origin of the waste and can you possibly prevent it. Ultimately, the goal is to go deeper into that entire chain. Your waste does not originate at a production location, but depends on everything you do in the steps before that, and on how you design a product as well.

We've been having Enexis as a customer for two years. We work with all kinds of flows. We ourselves do not process waste, but we are in between. We are actually a data company. We collect the data from waste streams and look at what can be done with it. Ultimately, the goal is to lift waste management to a higher level and to make a sustainability improvement. Increase the separation percentages, decrease residual waste, but also look at the prevention of waste or the different way of processing of what is released.

Is Enexis the only grid operator that you work with?

Yes, currently they are our only grid operator. We are in contact with other network operators as well, but as a customer we only have Enexis at this moment.

What happens to the cables that are retrieved from the ground? Do you have contracts with cable processors?

We don't actually work with contracts. There is the philosophy behind this that when you commit yourself to a contract, you are also bound to a quantity. We don't make our money from waste, but from performance, and if that is how we can reduce waste, we always want to do that. That is what distinguishes us from a regular waste company. Because a big waste company has incinerators, and they have contracts with energy suppliers to supply energy, so they have to fill those ovens. They must in any case have a certain percentage of residual waste, because then you can fill that oven. The moment you start separating your plastics they get into trouble, because then the mix that is put in the oven is no longer high-calorific enough to supply that energy. Everyone separates their plastic, but now so there is less residual waste, which is actually not so good if you have contracts for electricity from those ovens. We don't want to get into that situation, so we don't want a contract with parties to avoid creating waste if we can reduce it in some way. For example, cables, suppose you can use them again, then I prefer that over sending that cable to the recycling centre to retrieve the copper from it. It takes a lot more energy to make a new cable out of recycled copper than to reuse that cable immediately. So we don't have contracts, but we do work with partners. We now work with 500 parties. For each treatment company we look at what they are good at. We also do this for cables. There are quite a lot and they are quite valuable nowadays. Right now we've got a party in the middle of the country that receives those cables. They strip the cable from the sheath that surrounds it, and the precious metal that's in it goes through a big shredder and that is then sorted into the different materials. With Eddie current for the non-ferrous current and magnets for ferrous metals. There are different types of cables and each of those cables is a bit different. There are two main types. A cable with a PVC sheath around it, and there is a cable with a lead sheath around it. The latter often contains an oily substance for insulation. That lead sheath is not really used anymore in new cables, but there are still a lot of those cables in the ground. Those lead cables have to go through a separate machine, it makes a cut in the entire cable and then the lead sheath is peeled off. This is fairly labor intensive, someone has to stand there to peel of the sheath. The cable with a PVC sheath that goes in its entirety into the shredder, the plastic and the metals are sorted out, so it is slightly simpler.

I did hear that the peeling method exists, but I heard it is not been used that often. But is it actually used for lead cables then?

Yes. I cannot always see the process, so there may also be specific types of cables where they don’t use that method. But because it contains oil, you cannot throw it through a large shredder in one go, because then everything will be covered with oil. So you first want to remove that pollution, so that oil or fat part. In a paper-lead cable, there is paper soaked with oil in the cable, and you want to take that off first. The paper ends up in an incinerator, but the lead is recycled. The lead has a value, so it is worth it to separate that. Those paper lead cables are always peeled.

A cable can contain lead, aluminium and/or copper and you want to separate those. Mostly because aluminium and copper are not compatible if you throw them in the same melting process. So you really want those separated.

Milgro is very conscious about sustainability, do other treatment facilities process cables differently or is the process the same throughout the Netherlands?

Ultimately, a cable is always recycled because copper is simply of great value. I would assume that nobody throws that cable in a landfill. But it needs to be available. So that means you have to offer it to treatment facilities separately. The moment it ends up in the residual waste bin and it is thrown into the oven, you will not see it again. So the most important thing is that you deliver it separately. We provide that structure. When we start with a new customer, we are in between the process so that all orders and invoicing go through us in order to gather data, but first we keep the same treatment facility for the waste. We also did this with Enexis. There was another treatment party but it was not really clear what happened with those cables. They did not have to let that be known, but the largest part probably went to exports, to China or Turkey for example.

Are cables exported as a whole, or separated materials?

The cables in their entirety. They are first sorted. There is a lot of difference in not only the materials, but also how many cores they have, how thick those cables are, and you want to sort that out first. That's very easy as you can just see what they are. And then they are sold per type of cable, for a fixed price. Ultimately, you would assume that they will be recycled, but it doesn't happen in the Netherlands. Legislation differs quite a bit in countries, for example in China you have less legislation than in the Netherlands. If a cable is across the border, then you can no longer check where it goes. I assume that the copper is recycled, but I don't know what happens to the other material fractions. We currently work with a party that processes everything in the Netherlands. Everything goes to one point in the Netherlands, where it is dismantled, sorted and the aluminium, copper and lead are sold in separate fractions. Those do not always remain in the Netherlands, but we do have a large metal industry in Europe, so the majority of these materials will remain in Europe because there is a market for it. With our current party, we also get a breakdown of what types of cables there are.

What I understood is that for new cables very pure aluminium is needed. My current interpretation is that after processing, the metals end up on the big pile together with all possible alloys, and of this reason the recycled metals cannot be used in new cables, is that correct?

I can't say for 100% sure what happens after shredding and sorting. The party we work with does try to get the purity of copper as high as possible, making it the highest quality recycled copper. In my opinion, that copper could be used to make new cables. Whether that actually happens is another question. Although it is aimed for the quality to be as high as possible, the quality might be slightly lower than from a primary process. We have no agreements that new cables will be made from that copper or aluminium fraction. The processing party is free to do whatever they want with the material. We have no guarantee that it will re-enter the cable process, but it is recycled and used for copper products again. Whether that is also possible with aluminium I am not sure. I can imagine that because aluminium conducts less than copper, the purity of the material becomes more important than for copper.

Would it be possible to return the copper and aluminium of EoL cables directly to the cable manufacturer so that he can turn them into new cables?

Logistically speaking, absolutely. The shredders are adjusted to the material you treat. The materials resulting from each treatment come from a specific input. If you put all aluminium cables in at a certain moment, you will get the aluminium of all those cables. However, to get that aluminium pure enough you probably have to send the material not once in that process, but more like four times. There is a separation after shredding, for example with eddie-current, but also on things as colour. After one separation process, there are often small particles of other materials that you want to separate from the material fraction that you want. Then you would have to go through that cycle several times. That costs money. If the flow needs to be as pure as possible, the recycler will also have to invest a lot of costs. The question is if it is worth the costs, does the recycler actually get those costs back because the material is worth more.

So it's not just the question if it is technically possible, I suspect it is, but also how much it pays off versus how much cost you put in. That is the biggest challenge. You have to keep your costs low and still deliver the purest possible material. You could have 95% pure material with little cost and that already yields quite a bit, but if you want 99% purity you would have to add a lot of costs to get that last bit, and that might not weigh up against the extra yields.

Logistically, the cables are kept separate. So suppose the cable manufacturer says, I need these specifications, and that is technically possible to do, then it could be supplied.

I thought all the cables just went into the process at once.

No they already sort them out before shredding. You get large piles of cables with aluminium or copper conductors, and those piles are throw in the shredder one by one.

Do you know if there are any developments in processing methods or changes in the way of thinking about these processes?

Waste processing and metal recycling are fairly traditional processes. Metals have always been recycled and melted back into something new. And they have a value. So developments are more on all those material flows, if there are losses anywhere, or if it is not collected. Or that it goes abroad and disappears or is recycled in the wrong way. It is about how you get everything that is a waste stream as an input for recycling. And how to make recycling process more efficient. There is progress on how to get flows as pure as possible. For example, color sorting methods. They can even go so far that you can sort out alloys via that color sorting. The question is then again, do the costs outweigh the revenues. Does it pay to install such a machine. And the lower the cost of primary material is, the less attractive it will be to invest in recycling. Primary aluminium is currently very cheap. Copper is a different story, everyone expects that there will be a shortage of copper because of the energy transition. In the area of copper, precise sorting will be much sooner. But I also think companies should look at the front of the process, is it necessary that I make such extremely high demands on my products? Is it necessary that the cables are really 99.99% pure, or is 99% also possible? Because it often makes a world of difference to get it there. Until now, little thought has been given to this because it’s better to be on the safe side. It was not thought about whether it the high purity is really necessary on all fronts. It was simply so. There is now a change coming in that way of thinking, on the purchasing side of companies. What can they actually do to make sure the recycling chain can actually function. Perhaps impose a requirement that new cables must contain 30% recycled content. And maybe to lower the quality requirements a bit, to make it actually possible. There is much more thought about that lately. But our company enters at the waste side, while you would want to change things on the purchasing side. But those are two departments that often don't talk to each other at all.

If you are talking about developments, I think that in essence the recycling process remains the same, but hopefully the quality will get a bit higher. But it’s important to talk more and more about whether something must be recycled or if it can be reused. Because recycling is much better than using new material, but recycling still costs a lot of energy. While if you could take a cable out and clean it, and use it again somewhere, that is always preferable to throwing away and recycling. At least if you look at the footprint. Network companies are also thinking about this. In my view this has the biggest win. You want to collect what is still available separately, so that it can be reused as high-quality as possible.

Do you know what the quality of EoL cables is? For example, is only the sheath broken or is the entire cable no longer any good?

What I usually see from those cables, is that the core is still completely good. Especially copper. All copper recyclers are very happy when they get copper cables because that is the purest copper they are able to get. If you look at the material, the core is still good anyway, I don't know very well about the jacket.

In terms of the process, could it be done, for example, to remove the jacket from such a cable and just put a new one around it?

In terms of process, yes. But this is another cost issue. It is mainly a labour-intensive job and that is super expensive here in Europe. So I can imagine that you end up being more expensive then when making new cable. Another issue is that the lengths are not perfect. A primary alternative is often cheaper than a recycled alternative. The producers are focussed on making a new cable, and not on refurbishing or reusing old cables. It's not that it can't be done, but there is a large change needed.

Those cable producers are ultimately the parties with whom you should set up such a return chain. But that is difficult, because you have to completely change a conservative industry. It also has to do with legislation. If you no longer have to offer that great security of supply, you do not need such a very thick cable.

Another thing is the transformers. They convert a high voltage to a medium voltage. There are very large transformers, that are being written off early. Because in Groningen, where historically there is little energy demand, a lot of solar energy is now produced. So the grid over there is loaded much more heavily than what it was used for. So then those transformers are thrown out early to put down bigger ones, while the old ones could work for years to come. But they can also no longer be placed elsewhere because they no longer meet the necessary specifications. So that is a challenge, how can materials be used again that are no longer needed in other places.

Quite a lot is possible, but it is very complex. There are many different parties needed to get something done.

Another issue is that companies work with separate budgets, for example for purchasing and for waste management. The moment EoL cables are no longer thrown away, the waste management is short on money since they do no longer get money for those cables. While the purchasing department yields a much larger profit because it is much more expensive to buy new cables then to reuse old ones. But if those two departments don't talk to each other or share a budget, then you have someone who wins a lot, and someone who loses a lot. Even within companies there is still lot of friction on these topics.

Appendix B CE Delft energy scenarios

The scenarios used in this thesis have been introduced shortly in chapter 3. For the interested reader, more elaborate explanations of the scenarios can be found here.

B.1 Regional steering

The first scenario assumes regional steering. In this scenario the transition towards renewable energy is in the hands of local governments, such as the provinces and municipalities (CE Delft, 2017b). The regional governments are assertive in implementing the energy transition, and the focus is on decentral energy production (CE Delft, 2017c). Citizens are involved in the choices concerning energy production which causes more support on decentral energy production techniques, and thus a faster energy transition (CE Delft, 2017c). The petrochemical industry is replaced by recycling industry and hydrogen- and methanol-based chemical industry, because of an increase in awareness on the importance of recycling (CE Delft, 2017c).

On the demand side of electricity, increasing energy efficiency of machines is found, which would cause a decreased electricity demand (CE Delft, 2017c). However, this demand decrease is offset by increasing electricity demand from the changing industries. The new recycling and hydrogen-based industries run on electricity and hydrogen (CE Delft, 2017c). For the hydrogen production large scale electrolysis is needed, which in turn needs large amounts of electricity (CE Delft, 2017c). Another aspect influencing the demand is that all buildings are taken off the gas network. Other ways of heating will need to be used and around 75% of the heating installations will be electricity driven, 20% is fuelled by green gas, and the remaining 5% is fuelled by biomass (CE Delft, 2017c). The last influence on the demand is the energy demand for transport. The heavy transport will be 50% powered by green gas and the other 50% by hydrogen, and passenger transport will be 100% electrical (CE Delft, 2017c). The electricity driven passenger transport and the hydrogen driven heavy transport both require electricity.

Electricity is generated locally. The main electricity production methods are solar (84 GW), wind at sea (26 GW) and wind on land (16 GW) (CE Delft, 2017c). As these technologies are fluctuating, large storage technologies are implemented in the form of batteries, hydrogen and power to heat, which togeter can store 143 GW (CE Delft, 2017c). Batteries and power to heat are used for short-term storage, while hydrogen is used for long-term storage (CE Delft, 2017c). For more production security, there are still several plants running on renewable gas and a very small part on natural gas combined with CCS for a combined total of 30 GW (CE Delft, 2017c). The local produced electricity will be fed into the LV and MV grids for transmission to (local) storage and to the national grid (CE Delft, 2017c). The production of hydrogen is connected to all voltage levels (CE Delft, 2017c). A large increase in capacity for the LV and MV grids are thus expected from this scenario.

In this scenario, all available rooftop space has been used for solar PV together with several solar parks (CE Delft, 2017c). Many wind turbines are placed on land, and a few offshore wind parks have been developed (CE Delft, 2017c). The locally produced electricity is mainly transported over the MV and LV grids towards the users and storage facilities (CE Delft, 2017c). The electricity is thus transported from the MV and LV grids towards the EHV and HV grids, in contrast to the current situation where the electricity flows from the EHV and HV towards the MV and LV (CE Delft, 2017c).

B.2 National steering

In this second scenario the national government has most power in hands to make decisions on the energy transition. This scenario assumes the government desires to be independent of other countries for electricity supply (CE Delft, 2017a). Because the national government is in charge, large projects can be organised easily, and thus large scale electricity production projects are set up quickly, among which offshore wind parks (CE Delft, 2017c). Regional governments contribute as well with more local measures, such as creating energy neutrality in their area (CE Delft, 2017c). The industry changes in the same manner as in the regional scenario: the petrochemical industry changes towards a recycling-, hydrogen- and methanol-based industry (CE Delft, 2017c)

On the demand side, a decrease in electricity demand is expected because of increasing energy efficiency of machines (CE Delft, 2017c). As the industry changes are the same as in the regional scenario, this also means the same effect on the electricity demand: large amounts of electricity will be needed to power part of the industry, and even more will be needed for electrolysis to produce hydrogen for the hydrogen-based industry (CE Delft, 2017c). The heating systems for buildings will change from gas to more renewable options. Because of the wide availability of hydrogen, about 45% of the new systems will be a hybrid hydrogen heat pump (CE Delft, 2017c). Other hybrid pumps running on green gas are also used, and only around 15% are all-electric applications (CE Delft, 2017c). Passenger transport will be 75% electric-vehicles and 25% hydrogen-fuel-cell vehicles (CE Delft, 2017c). The heavy transport will be driven for 50% by green gas and 50% by hydrogen-fuel-cells.

The production of electricity is 80% centralised production facilities and for 20% decentralised (CE Delft, 2017c). By far the largest share of production happens through offshore wind parks in the North Sea, which have an installed capacity of 53 GW (CE Delft, 2017c). Solar-PV and land-based wind follow with respectively 34 and 14 GW (CE Delft, 2017c). For the solar energy this means that all available roofs are used for PV-cells (CE Delft, 2017c). The storage possibilities in this scenario also consist of batteries and power to heat for short-term storage, and hydrogen for long-term storage. Together they can store 118 GW (CE Delft, 2017c). Several plants for production security are running in this scenario as well, on renewable gas and a very small part on natural gas combined with CCS for a (smaller) combined total of 23 GW (CE Delft, 2017c). The production of hydrogen is mainly connected to the (E)HV and MV grids (CE Delft, 2017c).

As the production still is mainly centralised, the expansions of the electricity are largely on the offshore and (E)HV grids, with medium increase on the MV grid and a very slight increase on the LV grid (CE Delft, 2017c).

B.3 International steering

Instead of self-sufficiency, the focus in this international scenario is on the international energy market (CE Delft, 2017a). The Netherlands must bring her CO_2 emissions down, but the Dutch citizens do not accept the changes this will bring to the country (CE Delft, 2017c). Therefore large amounts of energy are imported in order to meet the demand (CE Delft, 2017c). The industry changes to a biomass-based industry combined with CCS (CE Delft, 2017c). Not only biomass is imported, but also hydrogen and hydrogen-derived products such as ammonia (CE Delft, 2017c)

On the demand side, a 25% decrease in energy demand is expected because of increasing efficiency in machines and more (CE Delft, 2017c). Heating is provided in this scenario mainly by green gas, biomass or hydrogen (CE Delft, 2017c). Less than 10% of heating systems are all-electric solutions, as the costs for these applications are much higher because of free trade biomass, green gas, etc. (CE Delft, 2017c). The entire industry has changed towards the use of biofuels combined with CCS (CE Delft, 2017c). For industrial heating hydrogen, bio-syngas and electrification are used (CE Delft, 2017c). This will have only a slight effect on the electricity grid, as the electricity demand only slightly increases (CE Delft, 2017c). Passenger transport changes towards 50% electric, 25% green gas and 25% hydrogen-fuel-cell powered (CE Delft, 2017c). Heavy transport is powered by 25% biofuels, 25% green gas and 50% hydrogen (CE Delft, 2017c).

Compared to the regional and national scenarios, the electricity production is very little in the international scenario (CE Delft, 2017c). 16 GW solar-PV is installed, with 5 GW wind turbines on land and 6 GW wind turbines offshore as renewable energy (CE Delft, 2017c). About 10 GW storage in the form of hydrogen, batteries and power to heat is available, and 22 GW of installed electricity production capacity of natural gas, green gas and biomass plants (CE Delft, 2017c).

The electricity grids barely change in this scenario (CE Delft, 2017c). The only increasing capacity is because of the offshore wind turbines.

B.4 Generic steering

In the generic scenario, there is not specific governmental steering of the energy production except for generic measures, such as an implemented CO2 tax (CE Delft, 2017a). This scenario thus describes a situation where the government does not actively steer the energy transition (CE Delft, 2017c). While the emission taxes increase steadily until 2050, the changes towards renewable energy are slow (CE Delft, 2017c). The main reason for this is that projects which still do not seem profitable after CO_2 tax are not invested in by civilians or companies (CE Delft, 2017c). The existing petrochemical industry remains, combined with CCS, no specific changes towards hydrogen-based or recycling industries as in the previous scenarios are made (CE Delft, 2017c).

Machines will use less electricity, as in all other scenarios, because of higher energy efficiency (CE Delft, 2017c). Because there is no governmental steering, collective solutions for heating of buildings aren't used, such as switching whole areas from natural gas to hydrogen (CE Delft, 2017c). As green gas and biomass are widely available and relatively cheap, 95% of the solutions run on green gas and the other 5% on biomass (CE Delft, 2017c). No use is made of hydrogen or all-electric solutions as these are more expensive (CE Delft, 2017c). The electricity demand of the industry barely changes over the years (CE Delft, 2017c). 20-30% increase in energy efficiency is expected, which decreases the electricity demand slightly, but as the industry remains largely the similar to what it is today, the sole changes in electricity demand will be from the changing energy efficiency (CE Delft, 2017c). Passenger transport is driven by 25% green gas, 25% hydrogen-fuel-cells and 50% electric engines. Heavy transport is powered by 25% biofuels, 25% green gas and 50% hydrogen (CE Delft, 2017c).

As in the international scenario, the production of electricity is very low compared to the regional and national scenarios. Solar-PV is the largest implemented renewable energy technology, 18 GW capacity is installed (CE Delft, 2017c). For both wind-turbines on land and offshore wind turbines, 5 GW has been installed with a total of 10 GW (CE Delft, 2017c). However, these renewable electricity sources will only fulfil 8% of the total electricity demand (CE Delft, 2017c). As there is still freedom to import natural gas alongside green gas and biomass, there are still several electricity plants running on these fuels, respectively 11 GW for natural gas, 6 GW for green gas and 7 GW for biomass (CE Delft, 2017c). In this scenario, only 5 GW storage capacity is installed (CE Delft, 2017c).

The total electricity demand in this scenario is exactly the same as the current electricity demand (CE Delft, 2017c). The reason for this is that the increased energy efficiency is about the same amount as the new demand from electrical transport and small changes in the industry (CE Delft, 2017c). As it is unknown how exactly civilians and companies will act because of the emission tax, the electricity grid operators will have to take the possibilities into account that individuals will start locally producing electricity (CE Delft, 2017c). This will mean the electricity grid will need to be expanded on all voltage levels (CE Delft, 2017c).