THE CITY IS MINE

Evaluating the Potential of Copper Urban Mining in Amsterdam for 2050

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Thesis report

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Executive Summary

Are cities mineable? How much can the old copper scraps be transformed into "nutrients" of the city and join the economy again? Can urban mining really take us towards a circular economy? Although there has been extensive discussions on the possibilities of urban mining in academic literatures and public media, the research on quantitatively evaluating the potential of urban mining is relatively little, especially when it comes to future material stocks. This study aims at examining the ambition of copper urban mining activities on the basis of quantifying the in-use stocks and demands, envisioning urban mining operation in action, assessing their sustainability implications, and identifying the knowledge gap to bring urban mining to practice in a circular economy. The study provides new ground in the domains of material flow analysis by generating necessary information to kick start the exploration of urban mining within the framework of circular economy.

In the face of the ever-growing challenges brought by unchecked human desire in the forms of climate change, environmental pollution, social inequality, and resource scarcity, etc., the City of Amsterdam envisions itself to tackle these problems with a progressive shift of energy landscape and transition towards a circular economy. To materialize these ambitions, copper has been given an indispensable role in decarbonizing Amsterdam.

Cities in The Netherlands are racing towards a circular economy with skyrocketing renewable energy goals and smart grids installations. As we champion the concept of circular economy, it is also critical to examine the emerging challenges that accompany the ambitions put forward by the society. First, a definition review of urban mining is carried out to compare the research in this field to sharpen the goals of the assessments in this study. The target of urban mining materials focuses on the waste generated annually and excludes the hibernating stocks such as landfills and obsolete products not handled by the waste treatment systems.

Although no one knows what the future has in store for us, and it would be impossible to try to predict an accurate scenario for 2050. However, it would be hard to have a discussion without graspable concept or data. To enable the discussion, this study quantifies the urban mine by applying the circular visions of the City of Amsterdam to construct a possible future scenario to reflect the transition towards circular economy. The estimation shows that the ever-increasing presence of copper in transport system and energy system is expected to make Amsterdam a copper urban mine 40% richer than its level today. The rich stock of copper urban ore will turn into waste at some point. Knowing the lifetime of the copper applications can provide valuable insights about when the copper resources become available and it allows planning for material recovery activities.

This study shows that the level of copper demand remains higher than the level of copper scrap generated all the way through 2050, but the gap also continues to narrow. In 2050, the copper waste is nearly reaching 90% of the copper demand. While closing the material loop on a local level is not the aim for a circular economy

for metals, the result could imply a continuous demand for primary raw material until the gap closes for Amsterdam.

Although the amount of copper waste is not expected to fluctuate dramatically towards 2050, the composition of the copper waste is going to be largely different than today. The current largest copper waste source comes from buildings, which is expected to be surpassed by the power distribution system in the infrastructure category in 2050. The power distribution system is chosen as the case study for an illustration of the institutional arrangement of the urban mining practices and the overview of the public and private policy environment for urban mining activities. It is found that urban mining end-of-life power cables is already a standard practice mandated by current regulations. The collected copper scrap is recovered in the smelters in The Netherlands, Germany, or Sweden. Finally, as law requires the removal of end-of-life cables, the leakage is not expected to take place in an urban anthropogenic cycle for copper.

Possible development directions of the power distribution system include DC grid and smart grid. While the DC grid has the potential of copper demand reduction by eliminating the DC/AC and AC/DC conversion, it is expected to take time to mature. On the other hand, smart grid technology could be more copper-intensive than the traditional grid, making the appetite for copper even larger. Synergies can be identified in the transition pathway adopted by Amsterdam. The low carbon economy implies a high copper era, but it phases out the non-reusable fossil fuel and calls for a material that is in theory infinitely recyclable. The material implications for low carbon society tests the ambition of a circular economy for copper, as the impacts goes beyond the city boundary under the current global trading scheme.

So can Amsterdam circle its economy for copper in 2050? It seems that the city is not going to be quite circular as it had wished for. Estimations in this study not only shows that Amsterdam cannot close the material loop for copper in 2050, the power cable case study also identifies knowledge gap to measure its circularity. The good news is, however, opportunities to facilitate the urban circularity also emerge during the process of characterizing the urban ore. Ultimately, if Amsterdam wants to systematically exploit its urban ore to work towards a circular city by 2050, a fair assessment on the ambitions announced by the Sustainability Agenda needs to be carried out with social, economic, and environmental considerations.

While Amsterdam is progressively seeking to upgrade its ambition in becoming a circular economy, social-technical changes also trigger a different spectrum of impacts that might not be immediately pronounced and therefore assessing such changes will inform Amsterdam inhabitants of its pathway. The assessment further calls for filling in the knowledge gap on life cycle information of urban copper ore to be proactively engaging all supply chain members from design to waste stage. Results in this study provide the essential information as the first step of prospecting the urban mine in urban ore characterization and address the issue of having a bigger appetite for copper than its scrap can satisfy. To live up to the ambition it signed up for, Amsterdam will not only have to bring innovative solutions to the table to shrink its appetite for copper, but also to shape an urban mining system to exploit the urban ore when the electric vehicles and solar panels are retiring. Furthermore, Amsterdam will need to address the environmental and social implications of the urban mining system to inform its inhabitants of the consequences life style.

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CHAPTER 1 / INTRODUCTION

1.1 Research context

Some studies have been raising concerns about possible depletion of global copper reserve before 2050 (Halada et al., 2008; Hertwich et al., 2014). Numerous resource scarcity and environmental challenges have prompted the policy makers to design legal instruments to facilitate transitions towards higher resource efficiencies. The circular economy package adopted by European Union in December 2015 provides a pathway to look beyond the dependence on primary materials and explore the potential utilization of secondary sources (European Commission, 2015). With the long-term carbon reduction goal of 80%-95% in EU, transition towards low carbon energy system is expected to create increasing demand of copper. According to International Copper Association, 2/3 of copper produced since 1900 is still in-use today, implying that the resources in-use could have great potential in providing future materials demands. It is therefore of interest to evaluate to what extent can the copper stock embodied in the economy be managed as resources.

Copper reserve

Copper is commonly used in energy related applications due to its high performance in heat and electricity conductivity and is therefore a critical element to sustain the modern lifestyle. As the demand continues to rise, securing the material supply becomes an increasingly significant issue. However, factors such as price volatility, political instability, recycling rates, and decreasing ore grades could all be endangering material security. According to Ellen MacArthur Foundation (2012), about half of the new copper mine development projects have high political risks. The political risks often lead to spikes in copper price and therefore create material scarcity, impacting development of fundamental infrastructure for the economies such as power grid, heat network, etc. Fig. 1 shows declining trend of ore grades under different consumption scenarios until 2100 (Northey et al., 2014). Declining ore grade implies extracting the same amount of resources at higher costs. Not only will the cost of extraction rise with lower ore grades, higher environmental impacts are also created during copper extraction activities (UNEP, 2011). Northey et al. (2014) argue that within this century, peak copper mining production will arrive and the major barrier in expanding the extraction activities would come from the resource and energy consumption.

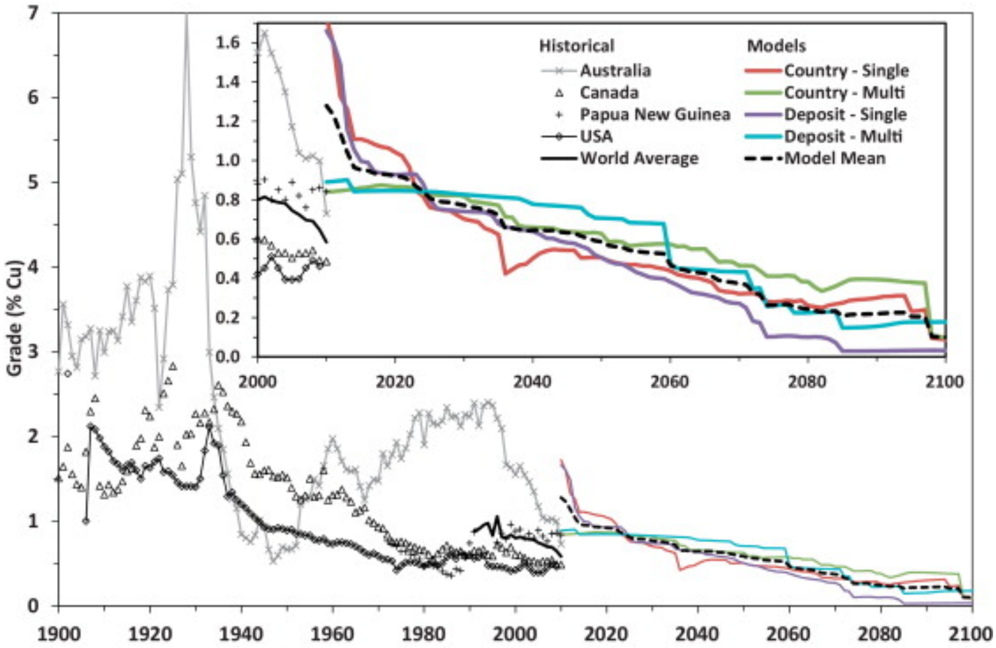

Fig. 1. Actual historical Cu ore grades for selected countries to 2010 (data from Mudd and Weng, 2012 and Mudd et al., 2013) and projected global ore grades 2010 onwards. (Northey et al. 2014)

Overview of circular economy

Circular economy has often called out as a solution to relieve resource scarcity and to reduce greenhouse gas emission while maintaining the economic prosperity. Circular economy has become an increasingly recognized idea to transform the current prominent linear economic model towards a circular model. A circular economy is an industrial system that restores and regenerates itself with a shift towards renewable energy systems and eliminates toxic chemical uses and wastes (EMF, 2012). The circular economy aims at closing the loop for materials and energy, creating enormous potentials to cut carbon emission. It seeks different uses for materials and products at the end of their lives, replacing the need of extracting primary materials from nature, and therefore, intentionally distinguishing itself from recycling to avoid labor and energy loss. Economies such as Japan, China, and EU have been introducing circular economy policies as an ambition to increase the material and energy efficiency, improve environmental performance, reduce carbon emissions, and revive the job market.

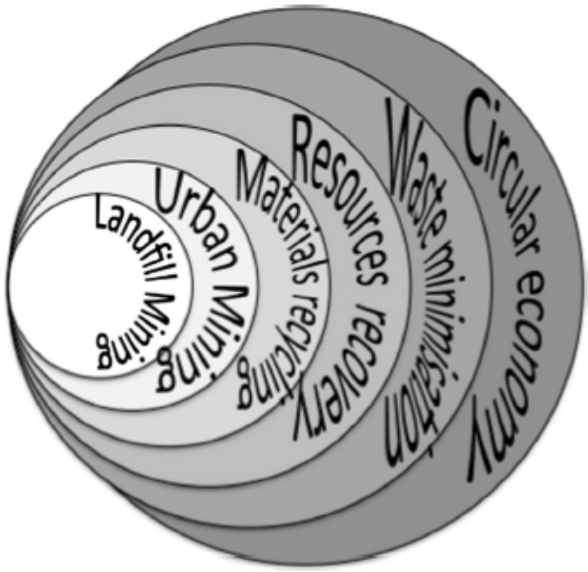

Fig. 2. Differences in the concept of recovery, recycling, and extraction of resources from waste. (Cossu and Williams, 2015)

Cities as a starting point to improve resource efficiency

Cities hold the key to a more sustainable society. The world has been going through rapid urbanization in the last century. For the first time in human history, more people live in cities than in rural area since 2008, setting a milestone of a new "urban millennium" (UN-Habitat, 2015). The unprecedented high urban population plays a vital role in the economy, generating 70% of global gross domestic product. Despite the relatively small area occupied by cities, the percentage of natural resources consumed by urban population is out of proportion due to the dense urban population. According to UNEP (2011), 3% of global surface area is occupied by cities and over half of the global population currently lives in cities. However, with such small land area, currently the urban population consumes about 75% of natural resources. Moreover, about 50-60% of the global greenhouse gas emission is generated by urban population (UNEP, 2013).

While the economic values created by cities are significant, the environmental impacts of the cities inevitably become a product of the intensive resource consumption pattern. For these reasons, urban environment that is heavily invested in resources could be seen as a repository for various resources. The built environment could be viewed as mines above the ground that the society can exploit to benefit the ongoing material flow of the society. Urban mining, a practical concept which is embedded within the framework of Circular Economy strategy has therefore arise as a way to systematically manage anthropogenic stocks that have been accumulating in the urban environment (Cossu and Williams, 2015; Bonifazi and Cossu, 2013).

1.2 Goal and scope

1.2.1 Research objectives

Goal: To evaluate how urban mining can contribute to fulfill copper demand in Amsterdam in 2050.

As the first step to understand the potential of urban mining as a source of future copper demand, it is important to find out where copper has been used, how much it has been used, and where the copper would end up after reaching the end of the service life. However, the goal of the thesis is to evaluate not only the quantity, but also the sustainability implications of urban mining for copper in the City of Amsterdam. Current policy measures will be reviewed to identify the institutional conditions for urban mining. Finally, recommendations will be made for different urban mining actors to achieve their resource efficiency improvement potentials and to limit the impacts of urban mining.

1.2.2 Project scope

a. Geographical scope

The geographical boundary of the study is defined by the boundary of city of Amsterdam, as shown in Fig. 3. The city of Amsterdam is divided into seven administrative districts (stadsdelen): West (10 km2), Nieuw-West (32 km2), Noord (64 km2), Oost (31 km2), Centrum (8 km2), Zuid (17km2), and Zuidoost (32 km2). The total inhabitant number is 811,185 (I amsterdam®, 2015).

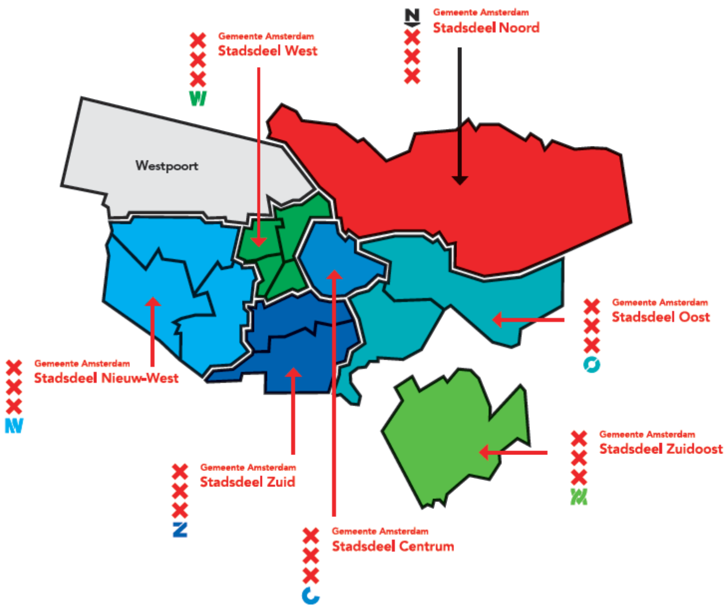

Fig. 3. Map of Amsterdam City Districts (I amsterdam®, 2010)

b. Time scope

The temporal scope of this study is 2016 - 2050.

c. Target material

This study will focus on copper as the target material.

1.3 Research questions

Part 1. Quantify copper resources

A1: What are the in-use stock and demand of copper in Amsterdam in 2050?

A2: How much copper can come from urban mining in 2050 in Amsterdam?

Part 2. Envision urban mining in action

B1: What would an urban mining system look like?

B2: What are the key activities for an urban mining system?

B3: What information is required in mining urban copper stocks?

B4: What is the knowledge gap of copper urban mining?

B5: What are some of the leakages for copper cycle in the urban system?

1.4 Methodology

1.4.1 Part 1: Quantifying copper resources

1.4.1.1 Quantifying the in-use stocks, demands, and discarded Cu

First of all, the target of the urban mining in this study is defined as the waste that is expected to be generated through 2050. Future waste comes from today's in-use stock, therefore, to understand the scale of the future waste, the anthropogenic in-use stock of copper that is expected to become available after it reaches the end-of-life is then estimated. Annual demand will be calculated with the lifetime parameter to compare the level of discarded copper and the demand for copper. The hibernating stock, including landfills, obsolete copper cables underground, and products not collected by waste handlers are not taken into account in this study due to the lack of data.

Top-down and bottom-up methods

Two methods are often used to quantify the material stock, "top-down" and "bottom-up" (Gerst and Graedel, 2008). To choose the appropriate method to adopt, it is realistic to look into what the two methods can offer. In this study it is intended to answer not only the question about how much copper is used but also what has the copper been used for. For the purpose of mining the copper material at the end of its life cycle, it is important to know: (1) When the copper application is expected to reach its end-of-life? (2) What products contain copper? (3) How much copper is in the product? Here the technicality of stripping the copper off its current application and the composition is set aside temporarily and it will be discussed in the barrier section.

The top-down method gathers the flow information on the material that enters and leaves the system and sums the annual balance (Zhang et al., 2014) as the stock in the society. In equation 1, T0 and` T mark the time step for the beginning and the end of the estimation. S0 is the initial stock and is usually small comparing with St and is therefore often neglected (Gerst and Graedel, 2008).

$$S_t = \sum_{T_0}^{T} (inflow_t - outflow_t) + S_0 \quad (1)$$

(Gerst and Graedel, 2008)

While this method is not highly data intensive, it does not provide the knowledge on the specific items that contain copper and their corresponding copper content for the purpose of urban mining exploration. It is therefore considered less suitable in this study.

Methodology choice for this study: bottom-up method

The bottom-up method, on the other hand, is able to provide the details required for identifying the size of stocks in different types of products and is therefore adopted in this study. The stock is calculated by gathering the inventory of copper-containing products within the system boundary, Amsterdam, in this case. By getting the information on the inventory of products that contain copper, the product quantity and products' copper content located within Amsterdam, the total amount of the copper embedded in the inventory of products can be obtained.

$$S_t = \sum_{i}^{A} N_{it} m_{it} \quad (2)$$

(Gerst and Graedel, 2008)

In equation 2, *Nit* is the number of copper-containing product *i* at the time *t*. m_{it} refers to the metal content of copper-containing product *i*. A represents the number of different copper-containing products.

Demand: statistics and calculation

In cases where the annual demand is not available from municipality's statistics database, calculations will be performed. To calculate the annual demand, equation 3 is used. The equation is derived from the research project in the Industrial Ecology Program of TU Delft and Leiden University for copper demand estimation in 2050 (Schipper et al., 2016). *Dt* stands for the total copper demand in year t. *Nt* refers to the number of products used in year *t*. *mt* is the copper content of the product in year *t*. *r* is the average lifespan of the product.

$$D_t = (N_t - N_{t-1}) \times m_t + \frac{N_{t-1}}{r} \times m_t \quad (3)$$

(Schipper et al., 2016)

1.4.1.2 Developing an inventory of copper-containing products

To determine the parameter A in equation 2, the list of different copper-containing products need to be inventoried to represent the applications of copper in the city of Amsterdam. Different categories were used in previous copper in-use stock studies. Wittmer and Lichtensteiger (2007) used five main categories (inorganic resources; mobiles; infrastructure, buildings, environmental compartments) and focused heavily on immovable applications. Zhang et al. (2014) defined the categories following the available data provided by the Bureau of Statistics in Shanghai (infrastructure, building, equipment, transportation). In this study, the categories by Joseph and Kundig (1999) and UNEP (2010) (see Table 1) are used as the preliminary list of products for data collection. The sub-categories have been adjusted according to the local conditions in Amsterdam. However, depending on the data availability, the categories might be adjusted accordingly.

Table 1. Category definition (Joseph and Kundig, 1999; UNEP, 2010)

Category	Sub-categories
Building construction	1) Residential buildings 2) Service buildings
Infrastructure	1) Power generation 2) Distribution & transmission 3) Traffic & street lights 4) Rail systems
Transportation	1) Cars 2) Rail cars: Trams and metro 3) Vessels 4) Trucks 5) Motorcycles
Consumer durables	1) TV 2) Refrigerator 3) Washing machine 4) PC 5) Electric heater 6) Microwave oven 7) Printer 8) Landline 9) Others
Corporate durables	1) Refrigerator 2) Washing machine 3) PC 4) Electric heater 5) Printer 6) Landline 7) Others
Industrial durables	1) Industrial machinery

1.4.1.3 Data collection

Main data sources are expected to rely on the statistics from municipality, trading records and local studies. Major data sources include: City of Amsterdam, CBS, port of Amsterdam, Amsterdam Smart City (big open data program), Amsterdam Economic Board, Metropoolregio Amsterdam (MRA), Cirkelstad, and European Environment Agency (EEA). This study will take advantage of the PUMA project's urban geological mapping initiatives and gather relevant copper content and in-use stock for the building sector information from the project. In cases that there are no available records for local data, proxy data is used with justification.

For the 2050 scenarios, the data from the sustainability agenda covers a list of goals for certain copper applications in various stages. For example, district-heating network, solar panels installation, smart grids installation, electric vehicle charging points, and share of electric vehicles, etc. The goals will be used to construct the scenarios until 2050.

1.4.2 Part 2: Envision urban mining in action

1.4.2.1 Envisioning an urban mining system in action

The quantification results from Part 1 will allow the identification of the copper-containing products that has the highest potential for urban mining as a case study. Information regarding how current practices handle the product after reaching its end-of-life is looked into through literature reviews and interviews, if possible. For the selected copper-containing product, the possible development of its in-use stock and flows coming in and out of the urban system towards 2050 is looked into with a more in-depth review. This possible trend provides the opportunity to discuss what might be the alternatives to lessen the material requirement and what are the possible trade-offs.

1.4.2.2 Policy overview and knowledge gap identification

A policy overview of the current institutional arrangement relevant with urban mining is conducted for both public and private sector. For the private sector, the urban mining relevant sustainability standards of the chosen copper-containing product's company is analyzed to address the ambition of the company. Furthermore, research on the voluntary initiatives that involve the public-private partnership is conducted to understand the institutional arrangement from different perspectives. Knowledge gap is identified to re-check the ambitions for a circular economy for copper.

1.4.3 Social and scientific relevance of the study

The study provides new ground in the domains of material flow analysis (MFA) by generating necessary information to kick start the exploration of urban mining within the framework of circular economy. The results map the possible urban stocks to be tapped into and gives clue on what to mine and when to mine.

The study also established a time dimension, enabling the results to provide insights to some of the synergies between energy and material taking place in the transition towards a circular city until 2050. Synergies take place during the shift from fossil fuel-based energy system to solar and wind based renewables, expanding the appetite on the demand for raw materials such as copper.

Although there has been extensive discussions on the possibilities of urban mining in academic literatures and public media, the quantitative research that evaluates the potential of urban mining is relatively little, especially when it comes to future urban stocks. In this study, MFA is first used to establish the quantitative scale of urban material configuration with copper as the target material in Amsterdam. The behavior of the incoming and outgoing flows of the copper can be seen based on the lifetime of the study objects are taken into consideration. Furthermore, the study looks beyond the current timeline and extends the temporal horizon to 2050.

The municipality's policy agenda is translated into the dynamics of copper stocks and flows until 2050. The research therefore has high social relevance because it is conducted based on the transition pathways addressed in the current policy. These transition pathways outline a possible future of Amsterdam inhabitants' way of living. On the societal level, the study examines what does reaching the ambitions of sociotechnical development means in terms of raw material demand.

As Amsterdam transitions towards a more circular city, capacities of relevant sectors needed to be fostered. The results of the study also gives directions to the technical capacity that is needed in order to handle the transition of energy landscape and the energy infrastructure needed to support the development along all stages of the material life cycle. This study informs possible future technical demand for recycling scheme as the desired renewable energy system and electric mobility system take shape. In order for urban mining to be achieving its goal of closing the material loop and minimizing the negative impacts of the material use, barriers and opportunities for urban mining are looked into.

To conduct MFA, the products are simplified and treated as materials that are independent of its function and the users' behavior. To make up for the lack of social dimension in the MFA due to the calculation requirement, I examined the social processes on the case study of copper-containing product. This provides insights of how the current practices are arranged in the energy distribution system and what knowledge is lacking for urban mining in a circular economy.

Overall, the results from this study invites Amsterdam to see itself as a living resource bank and makes future plans for its raw materials according to the urban metabolism. The results inform the policy makers on barriers and opportunities for urban mining in order to prioritize the streams with best potential. It also informs the industries on what recycling capacity is most needed in the market.

CHAPTER 2 / URBAN MINING

2.1 Literature review

Urban mining has become a trendy term across various sectors in recent years: public media promotes its benefits of turning trash into treasure; scrap handling facilities label their activities with the term to boost their businesses. The term urban mining has been so widely applied that the definition seems to touch upon almost anything things that has to do with material recycling (Cossu and Williams, 2015). Baccini and Brunner (2012) criticized that these days urban mining is used in a way that there is not much difference from waste management but "with a touch of label cheating". As a consequence, identifying the urban mine sometimes becomes a confusing process. Johansson and his team (2013) also argued that the term "urban mining" does not help us finding our way in the complex system of technosphere because of its lack of precision. For example, how is urban mining different from recycling? Does mining landfills count as urban mining? By conducting a literature review, it is found that various studies adopted different definitions to fit into their purposes. This section reviews the definitions of urban mining terminologies and past urban stock studies as a basis to delineate the goals of this study.

Taking a look at definition of urban mining

The definition of urban mining can be roughly categorized into four focus groups: waste (EU Commission, 2011; Wen et al., 2015; Oswald and Reller, 2011), holistic resource management (Brunner, 2011; Jacobs, 1969; Di Maria et al., 2013; Johansson et al., 2013; Cossu, 2013; Lichtensteiger & Baccini, 2008; Wittmer and Lichtensteiger, 2007), hibernating stock (Krook and Baas, 2013), and virgin mining (Dayani and Mohammad, 2010).

First of all, unlike most of the definitions that focus on the materials that ceased the service of their functions, Dayani and Mohammad (2010) focused on the extraction of primary material in urban area, making it a unique case when comparing with other studies.

Secondly, the definitions that focus on waste often draws the boundary based on the immediate economic feasibility, EU Commission (2011) defined urban mining as the process of extraction to obtain useful materials from the waste in urban area. In the study that evaluated urban mining's potential to relieve copper scarcity in China, Wen et al. (2015) also chose to focus on the waste generated by the society every year because of its relative higher economic viability to explore the copper. Although it might present a relatively more realistic picture of how much anthropogenic material can actually be mined when comparing with other definitions, this definition ignores the legacy stock in landfills, tailings, and other dissipative uses and therefore doesn't show the full potential of urban mining for long term planning.

Brunner (2011) proposed a broad interpretation of urban mining from a holistic resource management point of view. Besides the definition of using anthropogenic materials systematically in urban area, he proposed the establishment of life cycle information knowledge base and geographical information of recycling facilities for strategic urban metabolism design to enhance sustainability (Brunner, 2011).

Brunner further advocates the benefits of the localization of recycling activities to facilitate the energy efficiency. He argued that by sourcing and recycling within the cities, not only can the transportation energy requirement be lowered, the energy surplus from the recycling facilities can be incorporated to fuel the city (Brunner, 2011). While the life-cycle thinking and energy reuse sound like an attractive option, it is worth noting that growing cities and small size cities might not be able to generate enough waste to make local recycling an attractive option.

In their 400 page book titled "Metabolism of the Anthroposphere: Analysis, Evaluation, Design", Baccini and Brunner a wider interpretation of envisioning the fields urban mining. Baccini and Brunner (2012) defined urban mining as exploring and exploiting the urban anthropogenic material stocks and combining geology, design, engineering, and resource recovery."

This definition calls for wide extent of expertise to carry out the resource exploration in urban systems. Similarly, Lichtensteiger and Baccini (2008) emphasized the multi-disciplinary characteristics of urban mining which requires the knowledge from and urban geology with urban engineering. While Baccini, Lichtensteiger, and Brunner stressed the importance of knowledge capacity, the definition proposed in the economic model by Stenis and Hogland (2014) focused on capturing all the anthropogenic materials, including daily waste, constructions and substances that escaped from the material loops.

Two studies of dynamic material models provide a basis of methodology to assess urban mining on a national level for copper on both future and past time scopes (Wittmer and Lichtensteiger, 2007; Wen et al., 2015). Wen et al. (2015) established a dynamic model for the stocks and flows for Cu, Al, Pb, and Fe from 2010 -2050. It was found that urban mining provides a potential to increase the substitution rate in 2050 by 25.4% comparing with 2010 level (Wen et al., 2015). Also, Wen et al. (2015) concluded that short-term benefits of reducing the external dependence could be seen in the low consumption scenario while the strengthened recovery scenario provides more long-term benefits for material self-sufficiency.

Wittmer and Lichtensteiger (2007) defined urban mining as utilizing the secondary resources efficiently and with quality, with energy and building maintenance taken into consideration. They developed a dynamic material flow analysis model from 1900-2000 with 50 years as time step to identify the copper stocks and flows in Switzerland with detailed focus on buildings (Wittmer and Lichtensteiger, 2007). The results obtained by Wittmer and Lichtensteiger (2007) shows that the copper quantity of immovable applications in buildings and infrastructure are the most significant, and their long life times imply that the change of the stock overtime would be slow. However, the study results imply that the strong influence of structural changes in the industry and the regulations on development of buildings could be an opportunity for sustainability improvement (Wittmer and Lichtensteiger, 2007).

Krook and Baas (2013) reviewed a series of articles on urban mining and landfill mining for the special volume in Journal of Cleaner Production in 2013. They applied a stricter definition of urban mining that puts more attention on metal stocks in hibernation and turned away from the conventional waste management and in-use stock (Krook and Baas, 2013; Krook et al., 2011). Also focusing on hibernating stocks that already discontinued their functions, Krook et al. (2011) quantified the copper stock in hibernating power girds in Gothenburg and Linköping and assessed the economic feasibility of recovering the cables in urban area. According to Krook et al. (2011), the copper price would have to increase 7 - 25 times (5.4 €/ kg in 2010) in order to make the recovery of hibernating of copper cables economic justifiable. However, if the extraction of obsolete cables can be carried out at the same time that maintenance work takes place, benefits could outweigh the costs (Krook et al., 2011).

For hibernating material stocks, the critical limiting factor to carry out urban mining still lies in the availability of detailed spatial information (Krook and Baas, 2013). Moreover, given the lack of map-based information of infrastructure, to verify those information might even require physical digging work (Krook and Baas, 2013). However, Krook and Baas (2013) pointed out that the scale of hibernating metal stocks is simply too large to be ignored and immediate actions should be taken to fill in the knowledge gap for the learning process to kick-off.

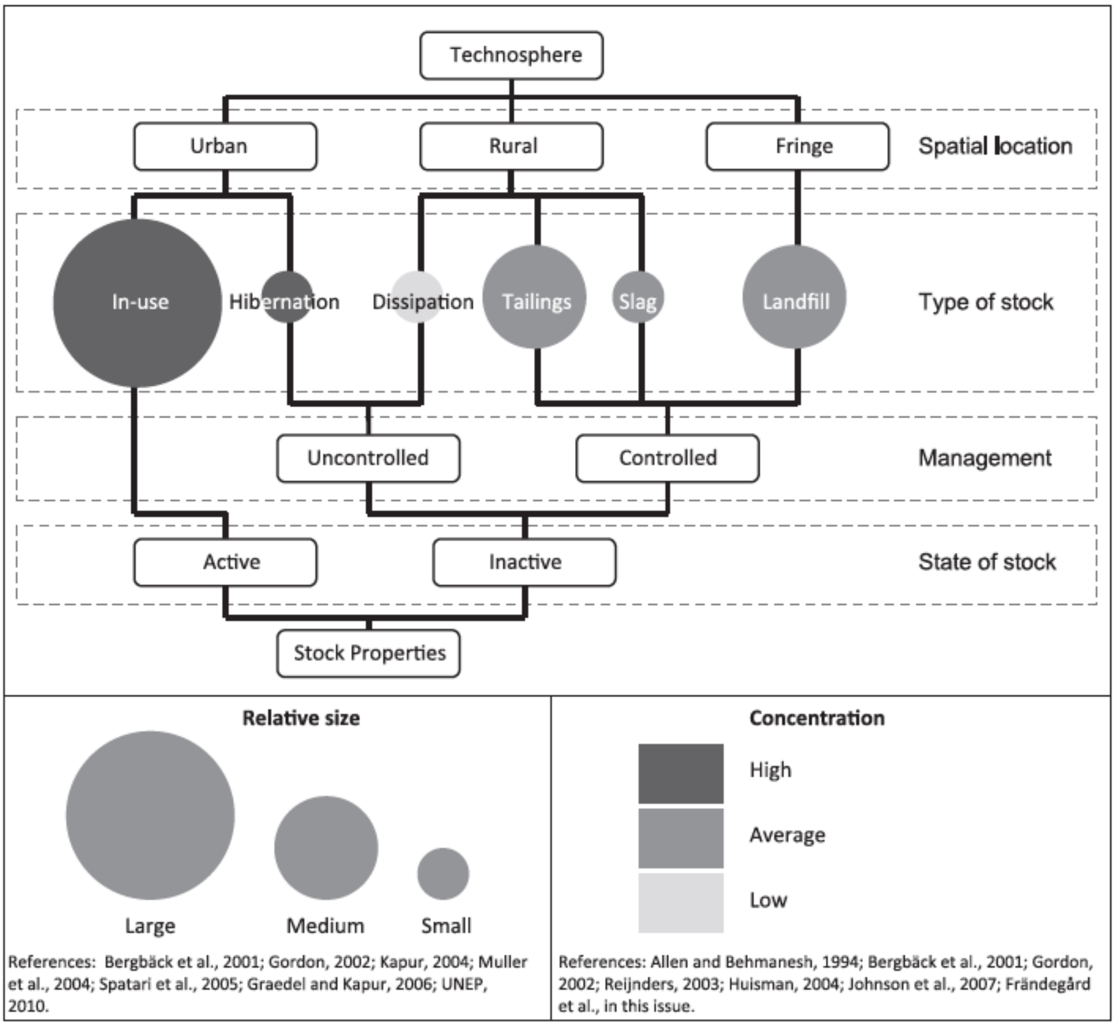

Fig. 4. Technospheric material stocks described by properties (applicable for iron and copper) graph from: Johansson et al., (2013)

Relevant Terminologies

Besides urban mining, there is also a series of terms that are relevant in recovering resources that's worth discussing (see Table 2). In order to further clarify the confusion of urban mining, Johansson et al. (2013) proposed a term to cover all the metal stocks. Johansson et al. (2013) divided metal stocks in the technosphere into two categories: active and inactive stocks (see Fig. 4). All metal goods with ownership and those that fulfill a function can be generally defined as active stock. (Spatari et al., 2005; van Beers and Graedel, 2007; Drakonakis et al., 2007; UNEP, 2010). Inactive stocks are metals that do not fulfill a function, therefore, they are generally considered undesirable and they are categorized into controlled and uncontrolled stocks by how they are contained (Johansson et al., 2013). The difference between controlled and uncontrolled in active metal stocks is whether they are handled by waste management activities or not (Johansson et al., 2013). Under this definition, the metal stock in urban area is either active stock that are in-use or uncontrolled inactive stock in hibernation. This characterization helps locating where the material stock is in its life cycle and bringing focusing on the material stock in urban systems.

Table 2. List of terms that are relevant with urban mining

Terminology	Concept explanation
Technospheric mining	Extracting the technospheric mineral stocks that have not joined the material flows in the anthropogenic cycle (Johansson et al., 2013)
Mining above ground	Recycling the materials that are shifted from lithospheric to anthropospheric stock. Activities could include urban mining, recovering technospheric resources. (Kapur and Graedel, 2006; UNEP, 2010)
Waste mining	Completely recover resources from waste is in line with the second law of thermodynamics. Primary material mining and environmental damages can be reduced with increasing recycling and recovering of metals. (Ayres, 1999; Ayres et al., 2001)
Secondary mining	Recovering resources from historic tailing ponds by reprocessing. (Pirrone and Mahaffey, 2005)
	Recovering metals from ash generated from incinerators with engineering recycling technologies. (Tateda et al., 1997)
	Also called pillar recovery operation. The recovery of pillars that were left in the coal mine for the purpose of preventing the mine roof from collapsing (Ghasemi et al., 2010)
Landfill mining	Recovering valuable resources such as metals materials from landfills (Johanson, 2013).

Differences between recycling and urban mining

Coming back to the point of clarifying the confusion about the difference between recycling and urban mining, it is important to take the whole life cycle into account. As Baccini and Brunner (2012) pointed out, the "label cheating" of recycling into urban mining often lies in the lack of consideration in the stock dynamics. Since the copper in-use today turns into waste at some point in the future (Brunner, 2007), the availability of the material depends largely on the lifetime of the stock (Baccini and Brunner, 2012; Wittmer and Lichtensteiger, 2007).

In Fig. 5, the dynamic material model for copper developed from data of Bader et al. (2010) and Wittmer and Lichtensteiger (2007) for the copper cycle in Switzerland in 2000 shows that the largest copper stock is in infrastructure (105 kg/cap), followed by buildings (80 kg/cap), and mobiles (35 kg/cap). Having the stock size information gives an idea of which sector is the copper located. With the information on stock development, composition, and spatial information, the basis of urban geology can be formed. However, recycling in urban area only focuses on receiving and processing the scraps that the resource management perspective is not taken into account and stock development is not covered.

Secondly, most urban mining literatures found in this study largely focus on recycling (Brunner, 2011; Wen et al., 2015) and rarely shines lights on activities such as refurbish and reuse that extends the lifetime. An example can be found in Fig. 1 developed by Cossu and Williams (2015), where urban mining nests under the material recycling. The fact that the product needs to be dismantled, sorted, smelted, and then remanufactured for second use does not fully utilize the potential of circular economy. Considering that the current market environment encourages consumers to go for a newer product with better functions even before the product breaks down. These short-lived products are tossed while they can still serve functions and are now forced into a faster life cycle than they were originally designed for. In that sense, equating urban mining with recycling might rule out some possibilities for urban mining.

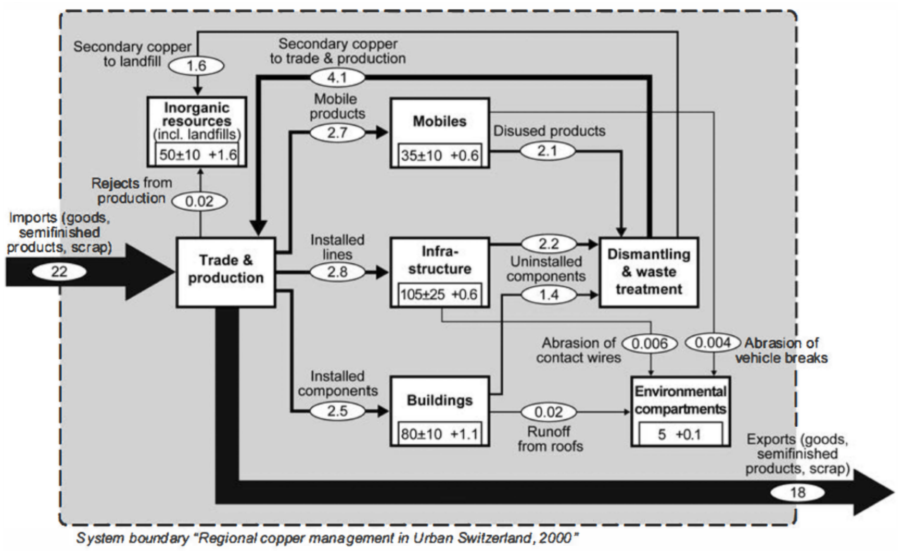

Fig. 5. The copper material system in urban Switzerland in 2000. Data of the stock and flow values are based on study of Bader et al., (2010). Units: stocks (kg/c); flows (kg/c); stock increase: + signs in boxes. (Wittmer & Lichtensteiger; 2007; Baccini and Brunner, 2012)

Defining urban mining for this study

Urban mining in this study is to reuse or recycle the urban waste generated from anthropogenic activities. The goal of this study is to evaluate the potential of urban mining for copper and determine to what extent can urban mining fulfill the demand for the city of Amsterdam in 2050. To compose a definition of urban mining that can evaluate how much copper could come from urban mining, it is important to identify the target stocks. The stocks that will be evaluated in this study are the in-use stocks that are actively serving their functions in the economy. At the end of the product life, the copper-containing products will be released into the waste stream for reuse or recycle. The hibernating stocks of copper that are not entering the waste-handling sector are excluded. Landfills, underground obsolete copper cables, and the stocks that are dissipated into the environment are not part of the focus in this study. It should be noted that while it is true that the accumulated quantity of hibernating stock might be too significant to be ignored (Krook and Baas, 2013), the characteristics of the hibernating stocks and in-use stocks are drastically different. It would require a different set of research questions and resources to explore the potentials to mine landfills and hibernating stock and are therefore excluded. In this study, the dynamics of the in-use stock would serve as a critical piece of information to estimate how much copper is leaving the economy for material recovery.

2.2 Overview of circular economy initiatives in Amsterdam

In March 2015, the Municipal Council of Amsterdam adopted the Sustainable Agenda in order to draw the picture of the future pathway for the city to tackle existing environmental challenges and to enhance the role of sustainability as a driver of the economy. These five pathways include: Renewable energy, clean air, circular economy, a climate-resilient city and sustainability of the municipality's operational management (City of Amsterdam, 2015). Under the circular economy pathway, implementation plans that focus on the economy transition and the recovery of resources are established for 2015 -2018. Initiatives related to urban mining mainly include the following (under implementation programme):

- Develop plans for circular use of construction and building materials
- Identifying overall opportunities to strengthen the recycling and repair sectors
- Provide visions on sharing economy (e.g., car-sharing, buildings, goods)
- Enhanced waste management with household waste recycling goals

To identify the opportunities and challenges of reaching a circular economy, the city of Amsterdam commissioned Circle Economy, TNO, and the Fabric to conduct a study to delineate the current resources use on a city level in October 2015. A quick "circle scan" was conducted in the report " *CIRCULAR AMSTERDAM. A vision and action agenda for the city and metropolitan area* ". The report investigated various sectors on the incoming and outgoing flows of natural resources. The report also evaluated the opportunities and economic potential for businesses, research organizations and government activities (Gemeente Amsterdam, 2015). The results gave direction for the municipality to develop a roadmap and agenda for action towards the realization of a circular city (Gemeente Amsterdam, 2015). The construction sector and the chain of organic waste streams (for value added uses such as protein for animal feed, biogas, bioplastics production ingredient, etc.) are identified as highly promising in circularity in the quick scan evaluation.

Various projects are being carried out to gain insights on the resource flows and stocks dynamics in Amsterdam have been carried out. Urban Pulse is a project funded by Amsterdam Institute for Advanced Metropolitan Solutions (AMS), Waternet and Amsterdam Energy Company that aims at investigating the flows of food, organic/inorganic materials, water, and energy using material flow analysis (MFA) (Wageningen University, 2014).

Another project that aims at investigating the material stocks in the built environment is Prospecting the Urban Mines of Amsterdam (PUMA). Commissioned by AMS and implemented by TU Delft, Waag Society, CML Leiden University, and Metabolic, the project will map the urban geology for four materials, Cu, Fe, Pb, and Al. Moreover, a step-wise plan to carry out urban mining will be proposed for the exploration of the urban metal resources.

Some EU-wide initiatives have been started to investigate the urban mine properties to enhance EU's raw material supply knowledge base. While the geographical scope is not under Amsterdam, the EU Horizon 2020 project "Prospecting Secondary raw materials in the Urban mine and Mining wastes" (ProSUM) provides aims at building a database platform that hosts information on stocks, flows, and treatment of mining wastes, batteries, electrical and electronic wastes and end-of-life vehicles at EU level.

2.3 Living in Amsterdam in 2050: Policy-based scenario description

The quantification of the copper in-use stock from 2016 to 2050 is based on a possible future scenario that is constructed in line with the visions drawn up in the city's current sustainable policy. The following policies and action plans adopted by the City of Amsterdam is used as the basis of the 2050 scenario in this section. These policies and action plans include:

- Structural Vision: Amsterdam 2040 (City of Amsterdam, 2011)
- Sustainable Agenda (City of Amsterdam, 2015)
- Amsterdam Electric (City of Amsterdam, 2009)
- Amsterdam Definitely Sustainable - Sustainable Program 2011/2014 (City of Amsterdam, 2011)

Fig. 6. The policies of the City of Amsterdam towards 2040 as the basis of the scenario.

The scenario tells a story of what it's like to live in Amsterdam in 2050, including the human environment such as population density and the physical economy movement such as mobility, energy source, and infrastructure. This scenario not only paints a possible future that forms the basis of the copper stock estimation, it also tests the coherence of the assumptions and the baseline characteristics of the city envisioned in policies such as how the transport system influences local lifestyle and living quality via cutting down air pollution.

The City of Amsterdam has aimed at being the frontrunner of circular economy. Sustainability policies and goals have been introduced to build a circular economy. This translates to pragmatic actions that involve various public and private sectors to tackle the challenges that business as usual has brought upon the society. For example, waste, resource scarcity, pollution, climate change, etc.

Taking a snapshot in the future, in 2050, the city of Amsterdam becomes more densely populated (8% growth compared with 2016). Rather than growing into a sprawling urban area, the urban infrastructure policy has been steered to accommodate densification. Although the city population continues to increase, it is growing at a slower rate, making the population profile coming towards stabilization. The population growth rate had come down from 1.37% in 2014 to 0.05% in 2050. In addition, less and less members now live under one roof. The number of household members decreases from 1.97 to 1.92.

In 2050, there are about 80,000 more residential units. Much development has been happening for service buildings. The municipality has actively seeking investments and businesses that would be interested in coming to areas such as Amsterdam Zuid, Buiksloterham, and Overhoek. The housing development has shifted towards mix use of buildings where there is no clear distinction between business and residential area. All the tasks and functions that a citizen needs are within reach of 30 minutes traveling. This relieves the demand of long distance travel.

Inside people's homes, not much has changed to the ownership home appliances comparing with 2016. An exception is desktop personal computers are slowly being phased out while the share of laptop is increasing to replace the bulky computers.

Decarbonizing Amsterdam: greening the power

Climate change has been one of the key driving forces that urges the city take a transformative pathway. In line with the IPCC recommendation of 80-90% of CO2 reduction by 2050 by developed countries, City of Amsterdam adopted a series of measures to cut carbon emission by 40% and 75% by 2025 and 2040, respectively (City of Amsterdam, 2015). As shown in Fig. 7, these ambitions are realized through cutting back the dependency on fossil fuels in energy system and transport system.

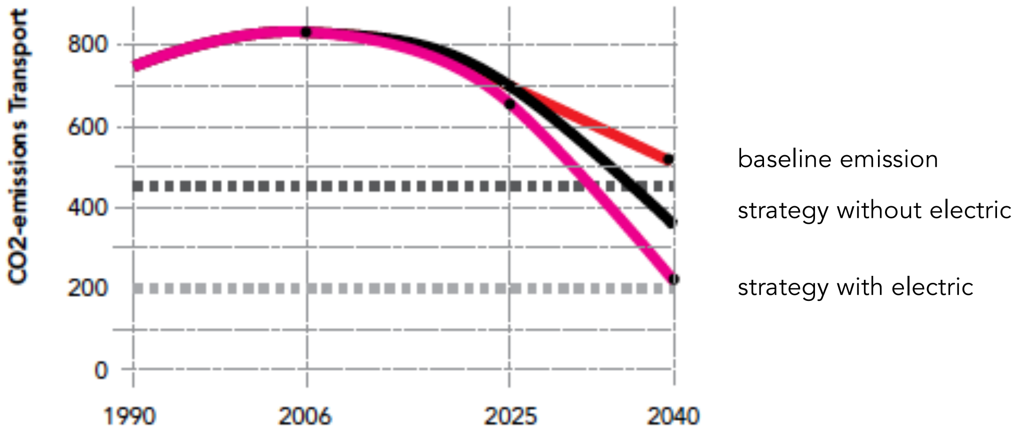

Fig. 7. Projected carbon emission until 2040 in Amsterdam with various carbon strategies (City of Amsterdam, 2015)

In 2050, nearly all the electricity in city of Amsterdam is powered by renewable electricity, with a small contribution from the waste-to-energy facility. By 2040, over half of the electricity was already generated within the city's boundary. The expanded district-heating network facilitates the sharing of the energy demands and lessens the consumption of electricity. On a per capita basis, Amsterdammers are consuming much less energy comparing to the level in 2016.

The development of renewable energy is not just chasing the wind, the electricity generated by wind power is 6.5 times larger than 2016's level. Solar panels now cover tens of thousands of roofs in Amsterdam. With more than 450,000 houses having their solar panels installed, the capacity grew 63 times comparing with 2016. On the other hand, the coal-fired power plant Hemweg 8 is shut down in 2034, after providing service for 40 years. The waste-to-energy facility continues to deliver electricity to the city of Amsterdam at the same level of 2016.

Moving around Amsterdam: Land and water

Decarbonizing measures have been implemented to eliminate emissions from vehicles in Amsterdam. The mobility system is largely electrified, with at least 60-90% of the traveling mileage powered by renewable energies. All public buses, light duty vehicles and cargo vans (<12 tonnes) are fully electric in 2050 to reach a zero emission transportation system. The light duty car ownership growth has hit the ceiling since 2016, which means less than a quarter of the Amsterdam population are car owners. The concept of sharing economy and business models inspired by sharing economy have slowly matured and are gaining momentum in the market. With online platforms speeding up the connection between the private car owners and people in need of car service, the idea of owning a car becomes ever more optional.

In order to power the electric vehicles, EV charging stations can be seen in every corner of the city. The number of charging stations grew eight times comparing with 2016 level (from 2,500 in 2016 to 22,760 in 2050), with every charging station serving 11 vehicles in average.

The city doesn't go to sleep in 2050. With the booming nighttime economy, the metro and tram system are kept busy around the clock. The metro system has also been expanded to better connect the greater metropolitan area.

Biking has been a strong tradition for Amsterdam citizens to move around the city. The introduction of e-bikes provides an extra push for the Amsterdammers to live the tradition. With more and more E-bikes on the market, people can now on longer trips without renting a car or relying on public transport. Motorcycles and scooters have also been gaining popularity in the city because of their convenience and affordability. To meet the zero-emission goal for transport system, all the motorcycles and scooters are powered by electricity by 2040.

Another strong tradition of Amsterdam's lifestyle is traveling on water. The canal cruises that show the tourists around the city continues to be busy in 2050. Half of the leisure boats run on electricity, while the other half are manually propelled.

In terms of living standard, Amsterdammers in 2050 live in an urban environment that is designed to leave minimal carbon footprint while building an economy that is driven by upgrading the performance of sustainability. Living standards such as air quality is significantly improved by transformative technologies in transport system and the corresponding infrastructure.

As most of the policy goals are designed until the timeline of 2040, extrapolations and assumptions were made for 2050. The detailed assumptions for the 2050 scenario can be found in the appendix, as listed in the right column of Table 3.

Table 3. Summary of the 2050 scenario in Amsterdam

Category	2050 Goal	Source	Appendix
Population	8% more than 2016	Based on CBS prediction until 2040 and declining annual growth rate	-
Household size	1.97 (2016); 1.92 (2050)	CBS population projection	-
Residential buildings	80,000+ more units than 2016	Amsterdam housing plan	1.1
Offices	13% more floor area	Zoning plan	1.2
CO_2 emission	80-90% reduction	IPCC	-
Solar energy	450,000+ houses install sola panels, city generates 1600 MW solar power (63 times of 2016 level)	Sustainable Agenda	2.1.1
Wind energy	500 MW (6.5 times of 2016 level)	Sustainable Agenda	2.1.2
Coal-fired power plant	0 MW	Hemweg 8	2.1.4
Gas power plant	0 MW	Hemweg 9	2.1.5
Electricity distribution	70% capacity growth	Based on power generation in Sustainable Agenda	2.2
Charging station	23,000 charging stations (9.2 times of 2016 level)	Based on electric cars policy goals in Sustainable Agenda	2.7
Household appliances	Same level ownership	Assumption	4
Cars	100% electric 250,000 electric vehicles (175 times of 2016 level)	Sustainable Agenda	3.1
E-bikes	Ownership doubles	Market research CBS	3.4.2
Trucks	All vans (<12 t) electric	Assumptions derived from Sustainable Agenda	3.6
Bus	100% electric	GVB	3.5
Motorcycle	100% electric	Sustainable Agenda	3.4
Railcars	All day operation from nighttime economy	Metronieuws	3.2

How likely is the future scenario going to come true?

The scenario depicted here is largely based on policy of municipality that describes a possible future for the city for the upcoming three decades. It does not guarantee that the future described here will definitely happen, but we can assume that the city is going to more or less trying to follow this path, with some course adjustment along the way.

The sustainability agenda policy is used as the blueprint to set the course for the city's economic and sociotechnical development, various degrees of uncertainties can be described within the categories of the copper urban mine. In Table 4, the uncertainties of different categories are ranked from high-low. For developments driven by carbon reduction policies, the adoption of Paris Agreement in 2015 can be expected to stimulate stricter carbon policies on a national and municipality level. This development may further speed up the progress to phase out fossil fuel and encourage the penetration of renewable energy systems and electromobility system, giving more certainty to the transportation system and energy-related infrastructure items.

On the other hand, the power grid needs to adapt to the development of energy system. If the goals for renewable energy capacity are indeed achieved, not only does the grid's distribution capacity need to be upgraded to handle the power load, the power grid might also face the possibilities of going towards a smart grid system or even dc grid system for newly developed neighborhoods. In terms of urban copper stock, it is expected that the grid system would face more uncertainties because of technologies in this area is fast changing.

For consumer durables, it is difficult to foresee how the ownership of the products will be influenced by the circular economy concept. As the ownership is strongly driven by individual behavior and influenced by social factors, it is unclear how much product service businesses could shave off the ownership. Here a modest assumption of no-growth ownership is made. From existing data is can be said that people are already living relatively well off comparing with non-western countries and therefore household appliances can be considered to be quite close to level of saturation. It is also assumed that it is likely that people will be going towards a path of luxury lifestyle. Corporate and industrial durables have much higher uncertainties due to the limitation on data availability and lack of clarity for future development in the policy. However, these two categories are less relevant to Amsterdam's urban mining because the municipality has limited influence to interfere with the handling of the retiring corporate assets.

Table 4. Level of uncertainties of the future scenarios in Amsterdam

Category	Level of uncertainty	Descriptions
Building	Near-term: low Mid-term: Medium	Housing plan for near-term is available. Long-term plan could change.
Infrastructure	Medium	Renewable energy system has lower uncertainties from carbon policy. The grid system faces more uncertainties due to technological changes.
Transportation	Low- Medium	Carbon policy driven measures are expected to have strong support for implementation
Consumer durable	Low- Medium	Uncertainties in how sharing economy influences ownership of household appliances. Large change not expected for citizens' lifestyle.
Corporate & industrial durables	High	Limited data availability. Low relevance for urban mining.

PART 1: Quantify the copper urban mine in Amsterdam

CHAPTER 3 / HOW BIG IS THE URBAN MINE?

3.1 Developing products categories

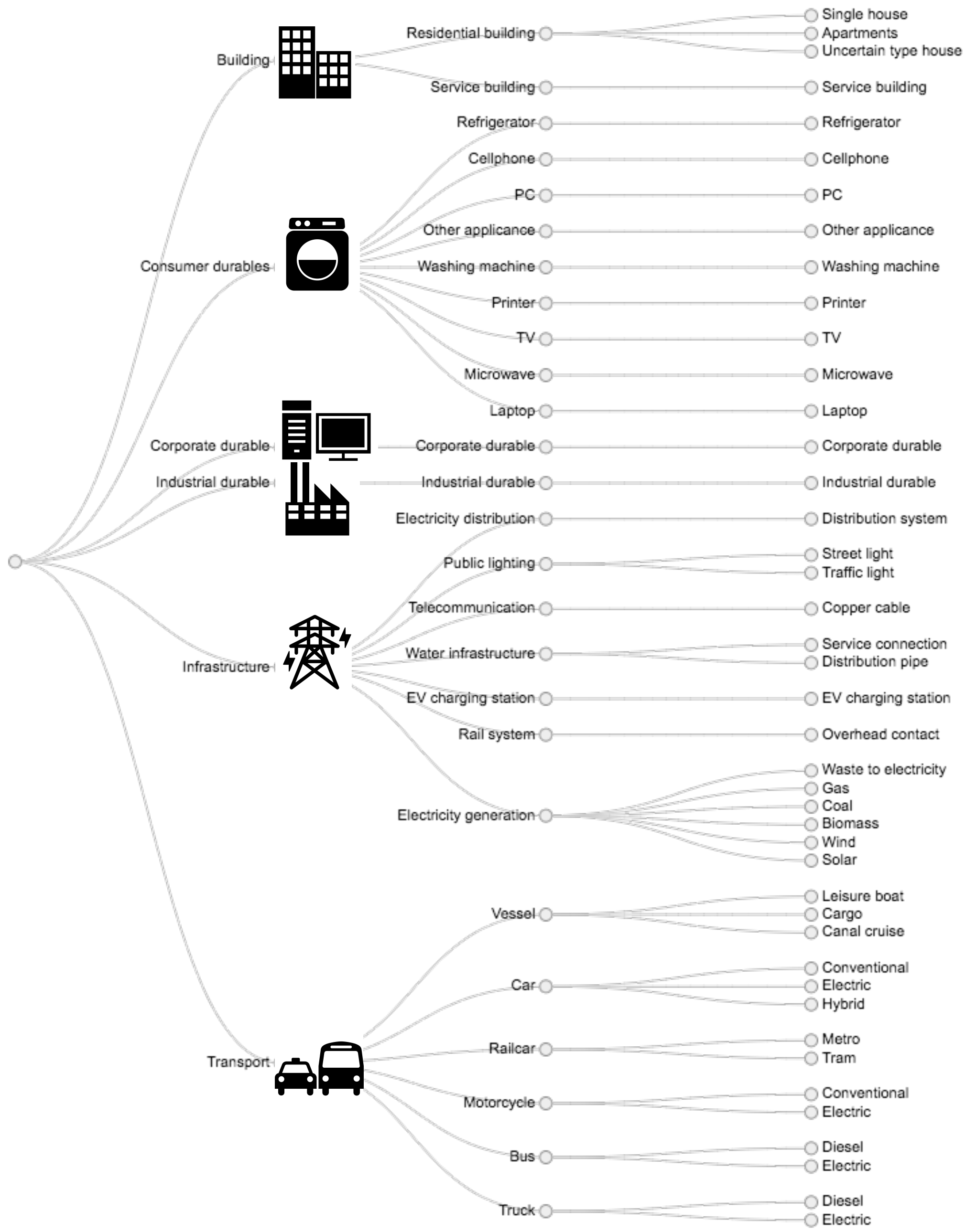

Fig. 8. The categories of copper-containing products in this study. Six main categories, 25 sub-categories, and 43 copper-containing products.

The product categories are structured as in Fig. 8. The six main categories are listed one the left side of the graph. The lines branching towards the right are connected to the sub-categories. To the far right of the graph are the copper-containing products included in the estimation. The list of copper-containing products is chosen to best represent the copper-containing products in Amsterdam from now to 2050 to account for the transition towards the ambition enshrined in the city's policy agenda. The list of the sub-categories and the products are adjusted along the way of data collection. This is because the copper-containing products in past studies have different geographical focus, therefore, categories in literature don't always best represent the in-use copper stock in Amsterdam. Besides the geographical scope, the temporal scope also plays an important role in determining the product list. For example, the development of policies on low carbon transportation system is the driving force of introducing electric vehicles.

Copper is a material that is appears everywhere in products using electricity. It is impossible to account for all products in this study. To ensure that the study captures the most important stocks and to avoid overinvesting time in relatively insignificant stocks, some initial approximation is done with accessible data to evaluate the necessity of further data collection. For example, motorcycles were initially assumed to have low contribution to the in-use copper stock. However, the preliminary estimation proved the copper in motorcycles and scooters to be substantial among all categories. In this case, more detailed data collection was conducted to refine the initial approximation.

On the other hand, some categories that were originally assumed to be important were taken off the list due to the relative little contribution to the overall copper in-use stock. The copper content in overhead contact system of the tramline and the metro line are assumed to be negligible according to Eckelman et al. (2007).

Due to the restriction of data availability, the gas pipelines and the heating network were not taken into consideration. It was originally assumed that the increase of district heating network would drive up the demand of copper. However, the contractor of the district heating pipelines mainly uses pipes made of steel, rather than copper as originally presumed. The district heating network is therefore not included in the stock estimation.

3.2 Assumptions

This section presents general assumptions that were made for the estimation of copper stock in Amsterdam. The assumptions described here are used as a general rule of thumb to make decisions in the stock estimation. For the assumptions and data for each copper-containing product, the information can be found in detail in Appendix 1.

It is important to emphasize that this study is conducted with no intention to accurately predict the future. The quantification is performed to explore the possibilities of how the stock might develop based on the city's policy. It is true that the scenarios comprised of the assumptions may give some level of indications on the future development of the copper quantity in Amsterdam. However, knowing the unpredictable nature of the future socio-economic development, the results should be viewed with the consideration of the underlined assumptions in this study.

The assumptions made in the parameters that contribute to the estimation are explained as following. In addition, how the assumptions influence the stock estimation is also explained.

Deciding the level of detail in stock estimation: policy as a starting point

Some of the product categories are categorized in more detail than other categories. For example, under transportation category, vehicles are further categorized into electric vehicle, conventional vehicle, and hybrid vehicles. The decision is based on its relevance of urban mining, which is determined by (1) past MFA studies and (2) stock size (3) future scenario in current Amsterdam policy. First, for products that presents a significant copper stock in past MFA studies and those that have significant stock in Amsterdam, more time is invested to investigate the detailed composition of the product types (fuel type, sizes, product varieties, etc.).

Furthermore, based on the existing sustainability agenda of Amsterdam, the products that are expected to have less influence on the urban mine (such as washing machines) are kept at a more simple level. On the other hand, for categories such as energy systems that are expected to go through dramatic transition, the structure of energy system is investigated and detailed types of energy sources are calculated. This enables the estimation to capture the influence of the introduction of renewable energy sources on the urban mine and is therefore highly relevant to urban mining activities.

Copper content

For each individual product (such as electric vehicles, television, leisure boat), copper content is assumed to be constant. The percentage of copper content or the Cu weight/unit does not change with time. If the expected change of copper content is going to impact the result of stock estimation, the product is further divided into different subcategories to capture the change (for example, electric vehicles have 3 times more copper than conventional vehicles, phasing out conventional vehicles means a more copper-intensive transportation system. Therefore it is needed to make the distinction between electric and conventional vehicles in the stock estimation in order to reflect the change of urban copper stock.)

Product lifetime

In this study, the life span of each product is also assumed to be constant for the convenience of calculation, a fixed length of life span is assumed. However, in reality products on the market might be more durable in the future because of technological improvement and the enhanced circulation of second hand products. This means that both the outflow of copper estimated by this study is entering and leaving the in-use-stock at a faster rate. The inflow is also therefore faster than because of the need for replacement of stock, making the urban mine renewing at a faster rate. If indeed the lifetime of products are in general lengthened in the future due to better technology and stronger second hand markets, the level of mineable EOL products would be lower than what is estimated by this study.

Stock estimation

When the total stock of copper-containing product for Amsterdam can be found, they are used in the calculation. For example, the current stock of residential buildings, buses, cars, and motorcycles are available through the transportation company or the municipality. When the local data is not available, national data is used and scaled down to represent the conditions in Amsterdam. However, it is possible that such proxy data fails to capture the urban characteristics of Amsterdam. For example, the stock of e-bikes is built up by the accumulation of annual sale of e-bikes in the Netherlands and scaled down to Amsterdam by population. But Amsterdam might have lower e-bikes market comparing with the rest of the Netherlands because of its relatively young population profile. This could lead to a slight overestimation of the e-bike stock in this study for e-bikes.

3.3 Results

This section explains the results from Part 1 quantification, which illustrates how anthropogenic copper flows and stock behave in the urban system. By analyzing the development of the copper stock and flows in the physical environment, it is possible to characterize how the copper material in the built environment behaves in the system through time. This enables us to understand the distribution of material resources in the physical economy. For example, we can now identify the largest copper reservoir in the society during the study period and learn how it changes through time. In addition, by analyzing the copper demand, we can identify which product category requires the most copper to provide goods and services. Furthermore, the estimated outflow of copper allows us to see how much copper is expected to reach its end of life and becomes available again as a material resource for value recovery.

The second part of this section presents the development of copper stock and flows of the selected subcategory to highlight the copper-containing products that influence the geology of the urban mine the most. The results from infrastructure, building, and transport categories are that gives the resolution of how the demands and discarded copper in different applications change through time.

Combining this analysis in stocks and flows, a possible reality is constructed to show the societal development in terms of raw materials, which provides us with necessary information to evaluate the challenges that our desired future scenario might bring about. Finally, detailed graphs that present all the estimation results for the full list of products are included in Appendix 2.

3.3.1 Copper in-use stock 2016-2050

The in-use stock estimation in this study provides an overview of the amount of the anthropogenic copper embedded in the physical economy. This section discusses the development of the quantity and growth of the in-use copper stock in Amsterdam. Table 5 summarizes the total demand, outflow, and in-use stock by quantity in metric tons. The detailed comparison is presented in 3.3.1.1-3.3.1.3.

Table 5. The copper demand, outflow, and in-use stock between 2016 and 2050.

Category tonnes/year	Demand		Growth rate (%)	Outflow		Growth rate (%)	In-use stock		Growth rate (%)
	2016	2050		2016	2050		2016	2050	
Buildings	3,198	759	-76%	2,509	792	-68%	76,299	86,805	14%
Infrastructure	2,947	3,627	23%	1,633	3,018	85%	65,178	117,153	80%
Transport	2,344	3,125	33%	1,858	2,788	50%	48,378	63,147	31%
Consumer durables	539	562	4%	464	559	20%	4,505	5,369	19%
Industrial durables	761	797	5%	726	794	9%	5,843	6,358	9%
Corporate Durables	53	55	4%	50	55	10%	405	441	9%
Total	9,842	8,926	-9%	7,240	8,006	11%	200,608	279,273	39%

3.3.1.1 In-use stock: quantity

Copper reservoir

The side-by-side comparison of all six major categories of in-use copper stock between 2016 and 2050 is shown in Fig. 9. The in-use stock in all the categories is estimated to increase between 2016 and 2050, with infrastructure having the highest growth.

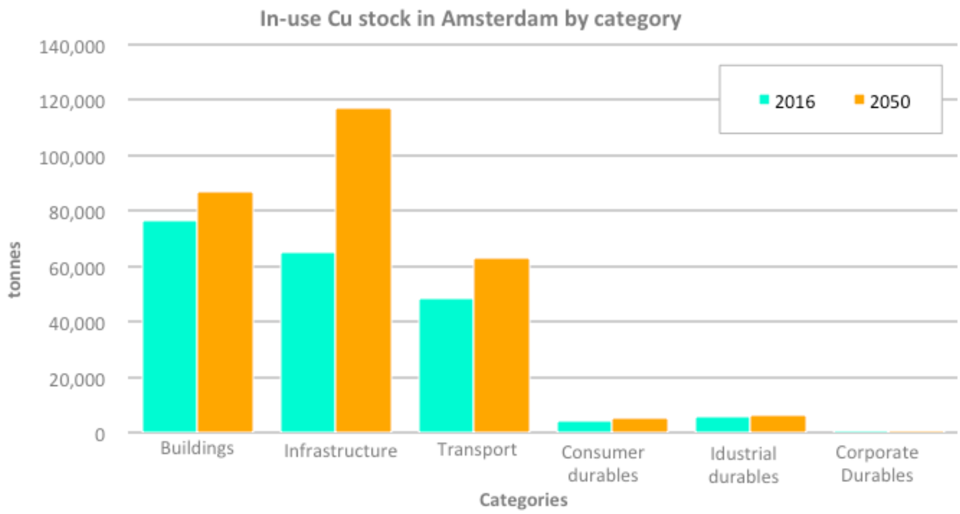

Fig. 9. Comparison of 2016 and 2050 in-use stock of copper in Amsterdam (unit: tonne)

The in-use stock of copper in 2016 and 2050 are compared in Fig 10. and Fig 11. In 2016, the building category acts as the largest urban reservoir for copper in Amsterdam, followed by infrastructure and transport. In 2050, copper in-use stock in infrastructure surpassed building and became the largest copper reservoir, making building and transport the second and third biggest copper reservoir in 2050. To look in further details of the copper in-use stock, electricity distribution and residential buildings have similar levels in 2016. In 2050, electricity distribution became much larger than any other sub-categories (see Fig. 2 and Fig. 3).

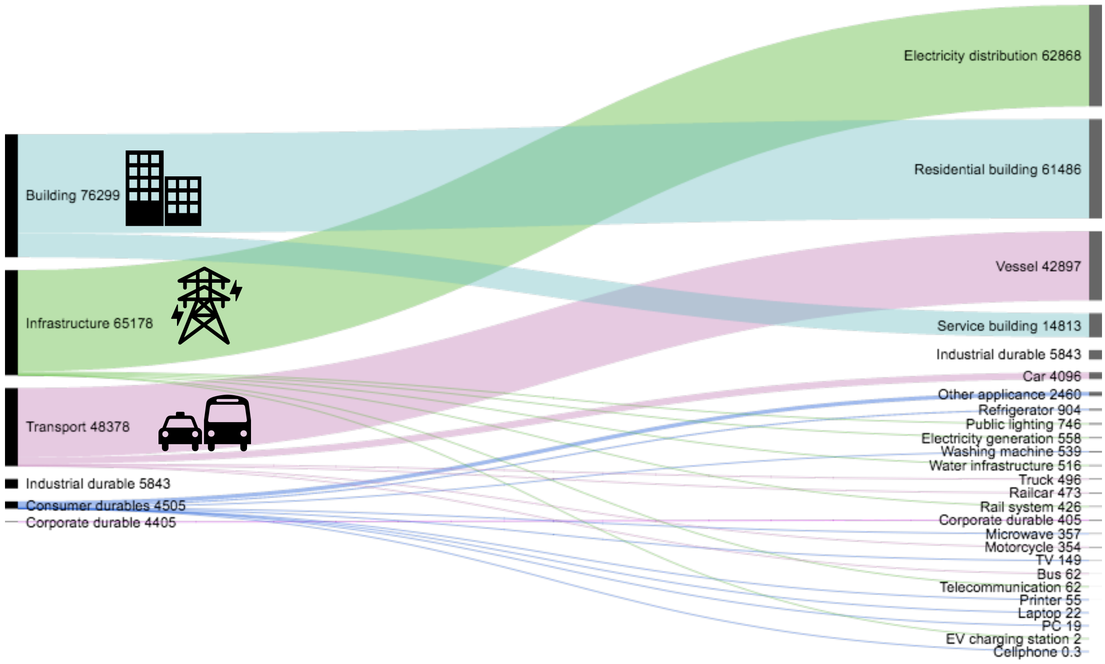

Fig. 10. In-use stock in 2016 by applications. Left side of the graph is the category. Right side of the graph shows the products under certain categories. The thickness of the belts reflects the quantities. The order of the categories is also ranked from top to down by quantity. (unit: tonne; or metric ton)

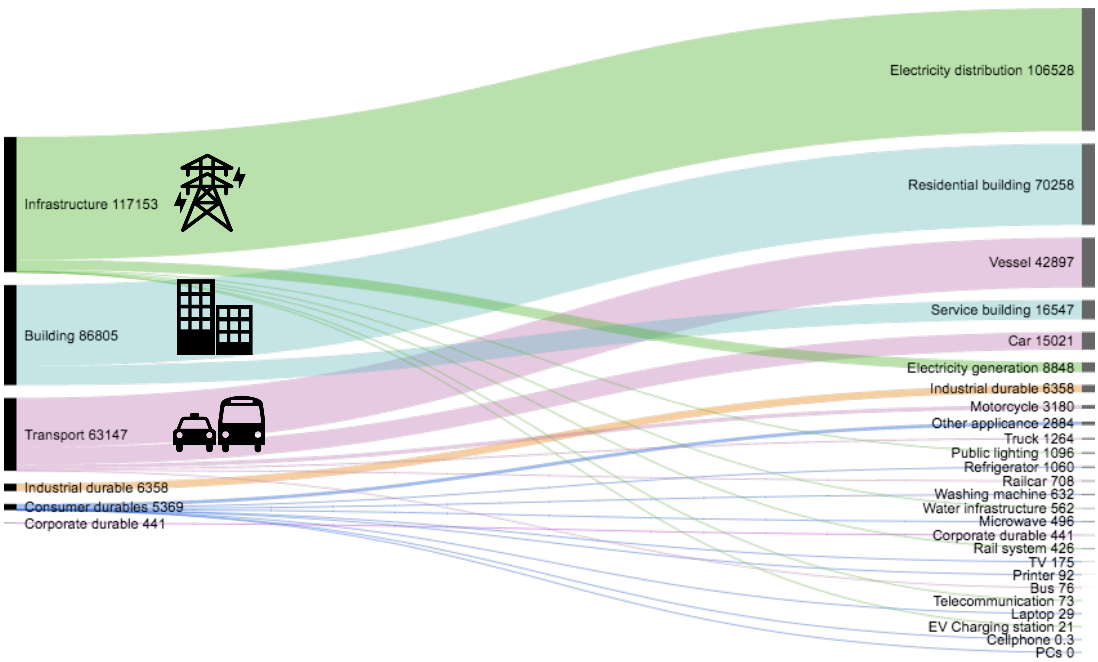

Fig. 11. Copper in-use stock in 2050. Left side of the graph is the category. Right side of the graph shows the products under certain categories. (unit: tonne)

To make it easier to compare with other cities and to see how the copper mine changes, per capita copper demand (inflow), outflow, and in-use stock by category between 2016 and 2050 is calculated, as shown in Table 6. The growth rate (%) are listed immediately to the right. The development between 2016 and 2050 shows a decrease of copper per capita net flow (from 3 to 1 kg/capita-year), meaning that the stock is growing, but at a much slower rate in 2050 comparing with the current speed.

Among all categories, the negative growth of both inflow and outflow of copper in buildings shows the biggest change. This is because the housing development plans before 2038 plans for a large amount of new houses to be built. As further plans are available from 2039-2050, an assumption is made. (see 3.3.3.1 Results: Building). Even if the copper demand already takes into account the copper required for renovation, demand remains low because of the total housing stock is assumed to be based on the projected household numbers. As the household numbers is calculated by the stabilizing population profile, demand for copper to build new house is also low.

Table 6. The per capita copper demand, outflow, and in-use stock and the growth rate between 2016 and 2050.

	Demand (kg/capita-yr)		Growth rate (%)	Outflow (kg/capita-yr)		Growth rate (%)	Stock (kg/capita-yr)		Growth rate (%)
year/category	2016	2050		2016	2050		2016	2050	
Buildings	3.90	0.91	-77%	3.01	0.87	-71%	91.41	95.57	5%
Infrastructure	3.53	3.99	13%	1.96	3.32	70%	78.08	128.98	65%
Transport	2.81	3.44	23%	2.23	3.07	38%	57.96	69.52	20%
Consumer Durables	0.65	0.62	-4%	0.56	0.62	11%	5.40	5.91	10%
Industrial Durables	0.91	0.88	-4%	0.87	0.87	1%	7.00	7.00	0.0%
Corporate Durables	0.06	0.06	-4%	0.06	0.06	1%	0.49	0.49	0.0%
Total	11.86	9.90	-17%	8.67	8.81	2%	240.33	307.48	28%

3.3.1.2 In-use stock growth

As Fig. 9 shows, all the categories show an increase of in-use stock between 2016 and 2050. To make the growth results more graspable, it is presented on per capita basis in this section. The size of the total in-use stock per capita increased by a quarter and grows from 240 kg/capita to 307 kg/capita. Among all the categories, the per capita copper in-use stock in infrastructure has the strongest growth of 65% (from 78 to 129 kg/capita), followed by transport that grows 20% (from 58 to 70 kg/capita), as shown in Fig. 12. It's worth mentioning that quantity-wise, the building represents one-third of the total in-use stock. But the growth rate shows it does not change with time significantly.

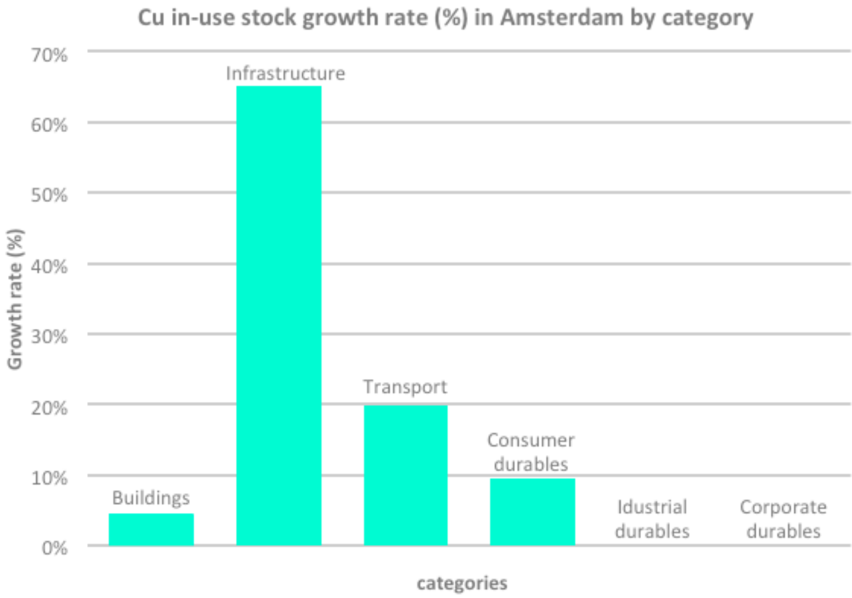

Fig. 12. The growth of in-use stock for copper in Amsterdam by category between 2016 and 2050.

3.3.1.3 Demand growth

Fig. 13 shows that transport has the strongest growth in copper demand (23%), followed by infrastructure (13%). This can be largely attributed to the ambitious policy goals to reduce carbon emission. In the current policy, City of Amsterdam is set to have zero emission vehicles and larger share of renewable energies by 2040. In order to realize the vision, more copper-intensive technology will be introduced into the transportation sector in order to electrify various types of vehicles (e.g., motorcycles, cars, trucks, etc.). The strongest growth in infrastructure comes from the electricity generation, which is expected to be eight times larger in 2050 than the current demand. For the transport category, the demand for motorcycles is expected to be 2.4 times larger than the current level due to the electrification of the motorcycles.

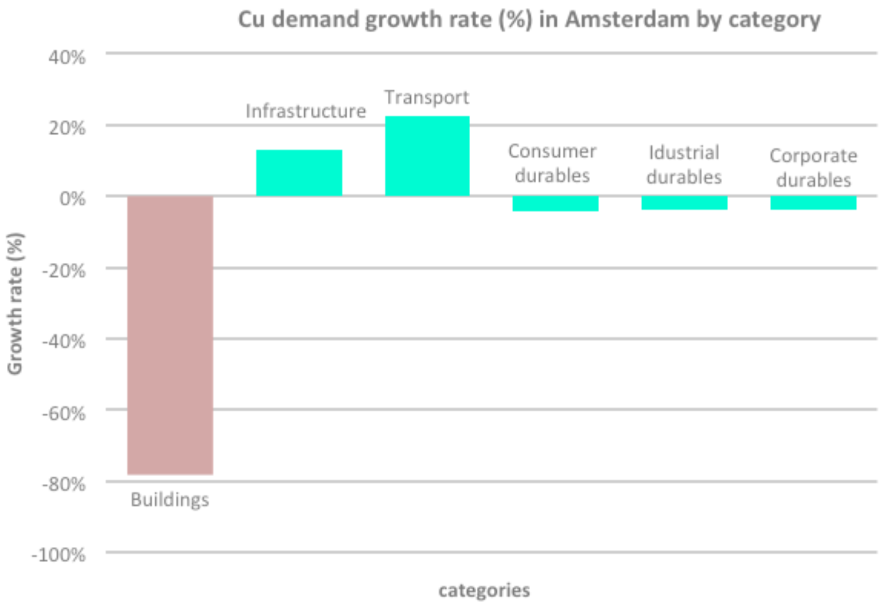

Fig. 13. The growth rates of demand for copper in Amsterdam by category between 2016 and 2050.

Building demand: growth declined, but still adding to the stock

On the other hand, not all the categories have a rising demand. The demand for building decreases significantly and drops by 77% in 2050, as shown on the pink bar on the left side of Fig. 13. This is due to the saturation of the housing and service building development. However, this does not mean that the building sector have zero demand. An annual net inflow is still being fed into the buildings and added to the in-use copper stock but at a much slower rate.

3.3.1.4 Outflow growth

Fig. 14 shows that the discarded copper for infrastructure and transport have the strongest growth. The discarded copper from infrastructure grows 70% (from 2 to 3.3 kg/capita-year) while the transport grows 38% (from 2.2 to 3 kg/capita-year). The copper released from the building sector, on the other hand, is much smaller in 2050 comparing with 2016. It decreases by 71% (from 3 to 0.9 kg/capita-year), as shown in the left side of Fig. 14 in pink bar.

Fast growth rates of discarded copper mean that the category is releasing copper out of the urban system at a faster rate. This largely has to do with the lifetime of the product and how quickly it can be relieved from the current function. For the purpose of evaluating the potential as urban mining source, this information could be useful when evaluated together with the flow and stock quantity.

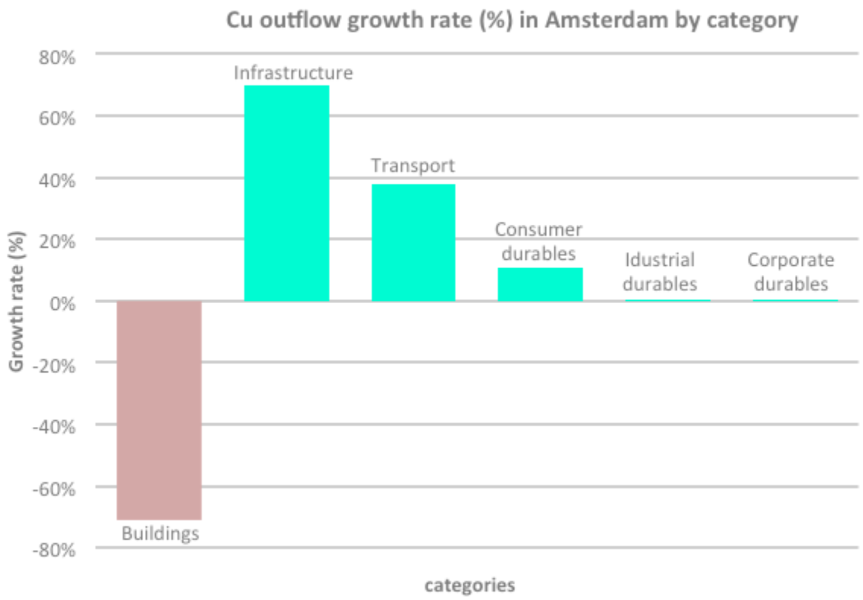

Fig. 14. The growth rates of outflow for copper in Amsterdam by category between 2016 and 2050.

3.3.2 Comparing in-use stocks, inflow, and outflow by category

Table 7. The percentages of copper demand, outflow, and in-use stock by category between 2016 and 2050.

Category	Demand		Outflow		Stock	
	2016	2050	2016	2050	2016	2050
Buildings	33%	9%	35%	10%	38%	31%
Infrastructure	30%	40%	23%	38%	32%	42%
Transport	24%	35%	26%	35%	24%	23%
Consumer durables	5%	6%	6%	7%	2%	2%
Industrial durables	8%	9%	10%	10%	3%	2%
Corporate Durables	1%	1%	1%	1%	0%	0%

Which category has the biggest share of in-use copper stock?

The current largest stock identified is in buildings (38%), followed by infrastructure (32%). In 2050, infrastructure (42%) surpasses buildings (31%) and tops all in-use stocks, followed by buildings (31%) and transport (23%), as shown in Fig. 15.

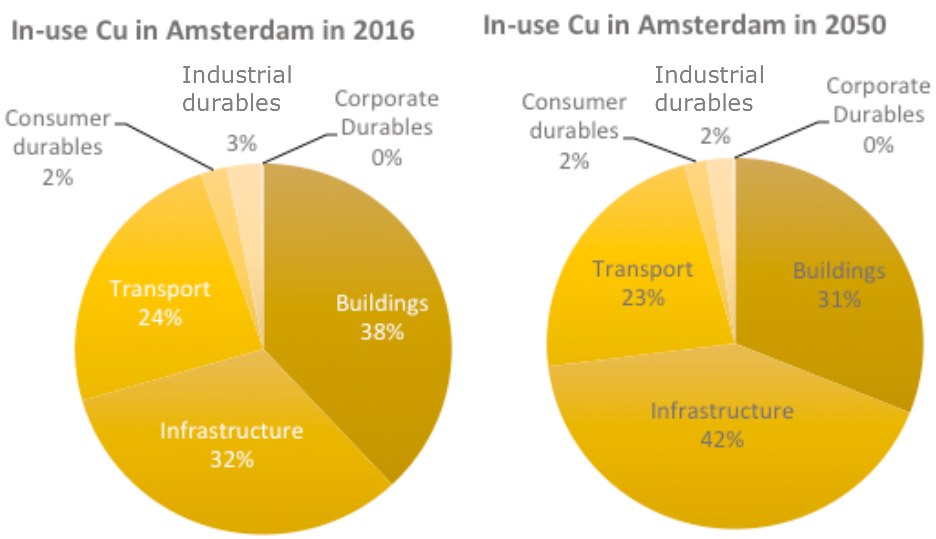

Fig. 15. Comparison of the share of in-use Cu stock by category in Amsterdam in 2016 (left) and 2050 (right).

Which product category needs the most copper?

Currently buildings (33%) consume the most copper, followed by infrastructure (30%) and transport (24%). However, in 2050, most copper demand is represented by infrastructure (40%), followed by transport (35%) (see Fig. 16.)

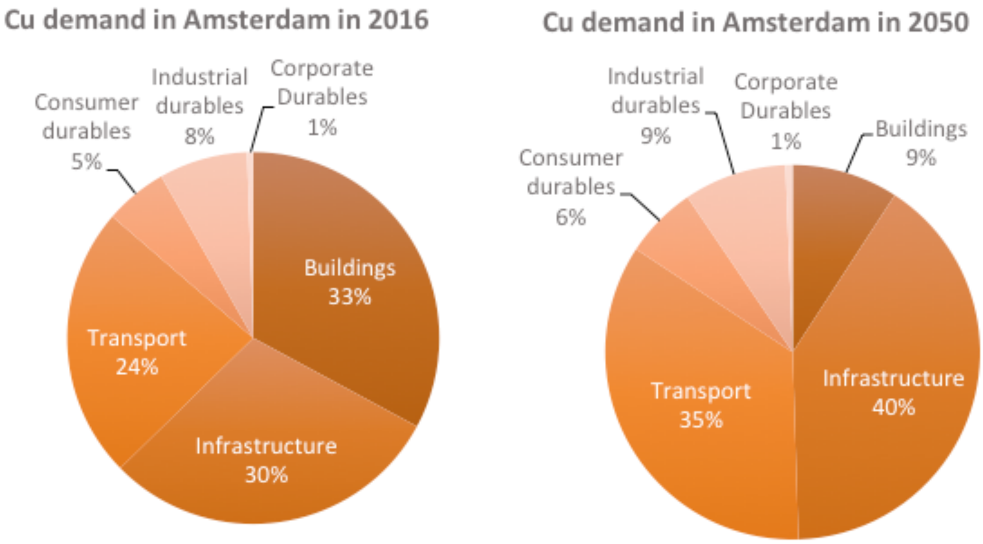

Fig. 16. Comparison of the share of in-use Cu demand by category in Amsterdam in 2016 (left) and 2050 (right).

Which category generates the most copper waste?

Currently buildings (35%) generate the most copper waste, followed by transport (26%). In 2050, infrastructure (38%) generates the most copper waste, followed by transport (35%). Building represents 10% of copper waste in 2050 (see Fig. 17).

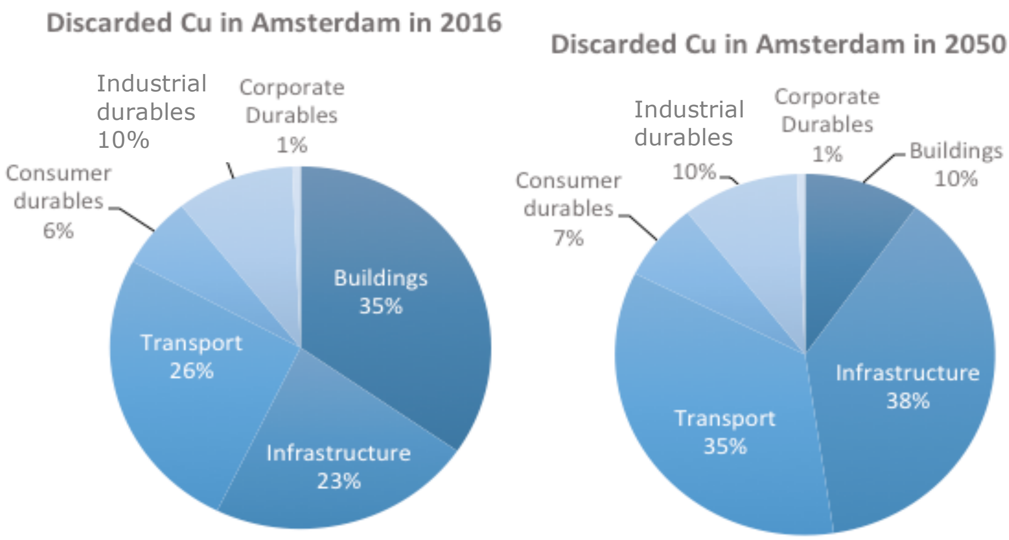

Fig. 17. Comparison of the share of discarded Cu by category in Amsterdam in 2016 and 2050.

3.3.3 Stock development 2016-2050

This section discusses the development of stock, inflow, and outflow between 2016-2050. It provides explanation to why the stock rises, falls, or stabilizes by piecing together the estimation results with the underlying assumptions. Three categories that are considered to best represent the copper stock in Amsterdam are presented in the following sections: 3.3.3.1 Building; 3.3.3.2 Infrastructure; 3.3.3.3 Transport. These three categories are considered more representative than the rest mainly for three reasons, data quality, data availability, and stock size.

First, the data in these three categories are in general closer to the local situation in terms of accuracy because the source (mostly from the municipality database). The second reason is that data in these three categories is more available comparing with other categories. For consumer durables, corporate durables and industrial durables, there are no graspable policy goals in place to be translated into the needed parameters such as household appliances ownership. For industrial durables, the data availability for the past is rarely available because of business confidentiality. Finally, the estimation shows that the size of the in-use stock in consumer durables, corporate durables and industrial durables are far less significant in terms of overall quantity (see Fig. 18). It is therefore decided that the following discussion will be focused on the more impactful categories.

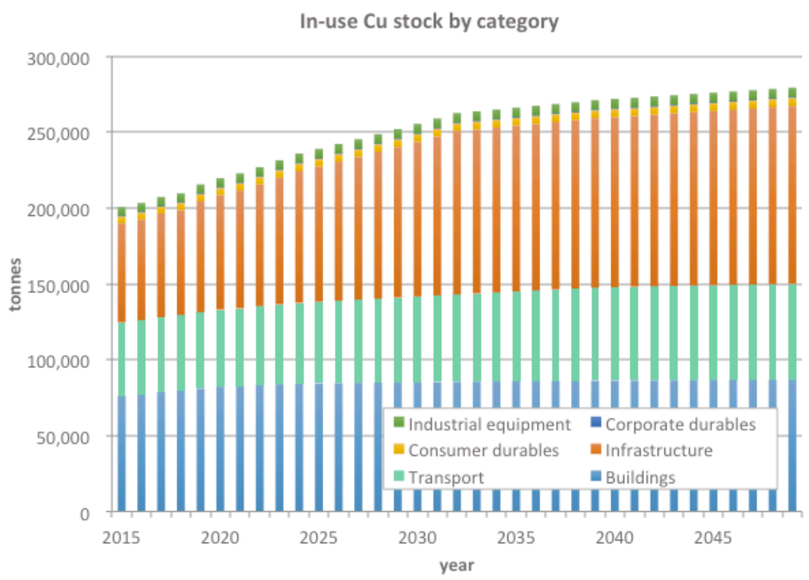

Fig. 18. In-use stock of copper by category in Amsterdam from 2016 to 2050.

3.3.3.1 Results: Building

Booming housing development until 2036

Detail assumptions and data for buildings can be found in Appendix 1. The in-use stock for copper initially shows strong growth before 2023. After 2023, the stock growth slowed down until around 2036, and plateaued afterwards. This can be explained by the residential housing development in the coming decade according to the municipality database. The construction of 61,830 housing units is set to be completed during the period of 2016 to 2024. This development is expected to consume large quantities of copper, as shown in Figure 12. The spikes highlights the larger development in 2017 (10,995 units), 2019 (8,947 units), and 2020 (9,237 units) (see Appendix 2, Table A2).

2040's: Slow down period from population stabilization

The data for housing development plan is only available until 2038 in municipality database. For 2039-2050, it is assumed that the annual demolition unit number is the same as the average of 2014-2038, which comes to 431 houses per year. As for newly built houses, the newly added stock is calculated based on the projected population profile and household size. The 2039-2050 stock residential buildings is assumed to be the same as the household number. I assumed the population growth rate to gradually decline from 0.1% per year in 2040 to 0.046% (about half of 2040) in 2050. As the population growth slows down, household number also stabilizes, making the demand for copper to build new houses much less than previous years.

Table 8. Population and population growth rate used for house units estimation.

Year	Population	Population growth rate (%)
2040	902100	0.10%
2041	902919	0.091%
2042	903693	0.086%
2043	904422	0.081%
2044	905107	0.076%
2045	905748	0.071%
2046	906343	0.066%
2047	906894	0.061%
2048	907399	0.056%
2049	907859	0.051%
2050	908275	0.046%

As for the service buildings, the development growth is evenly spread out in between the timelines (2015-2020, after 2020) set by the municipality. From the Fig 18 and 19, it can be seen that buildings act as a significant reservoir for copper until, and possibly beyond 2050. However, according to the urban housing development plan, building demolitions are not often carried out as generally assumed. Around 1,000 housing units are demolished annually before 2023, making the lifetime of buildings far longer than the 50 years lifetime that is often assumed by previous studies. The amount of copper waste that is generated annually is therefore not as high as normally assumed. As a result, although large amount of copper is embedded in buildings, the end-of-life copper is released at such slow rates that its overall share becomes relatively insignificant towards 2050 (from 35% in 2016 to 10% in 2050).

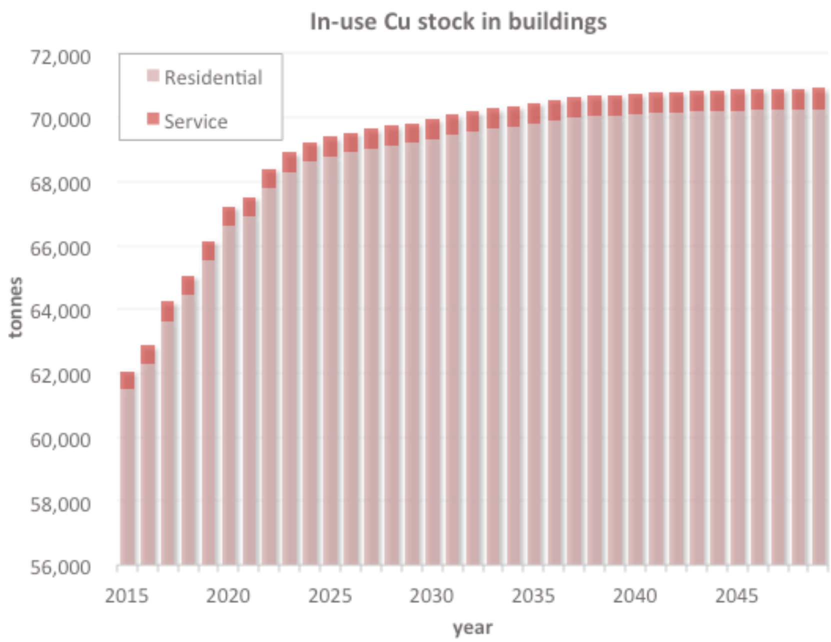

Fig. 19. In-use stock of copper for the building category in Amsterdam from 2016 to 2050.

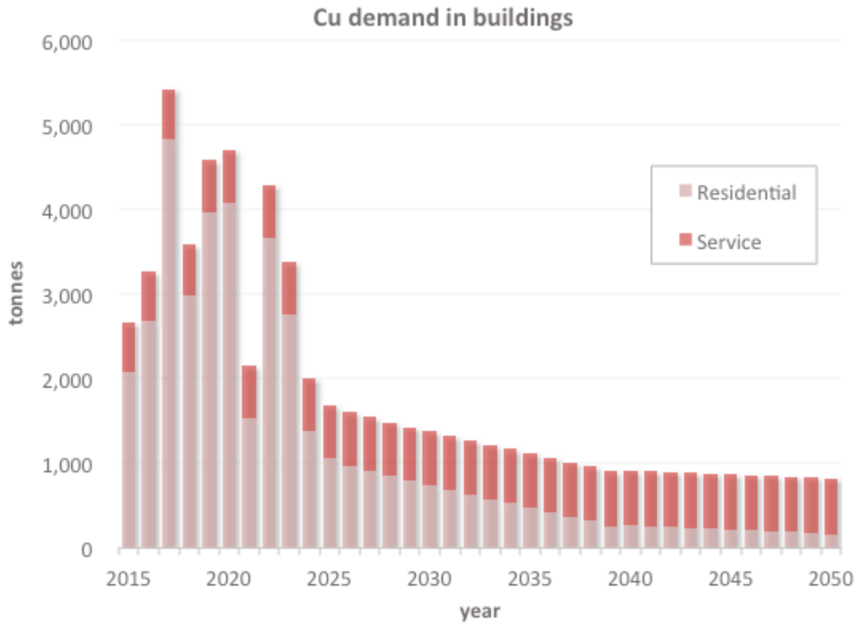

Fig. 20. Cu demand for the building category in Amsterdam from 2016 to 2050.

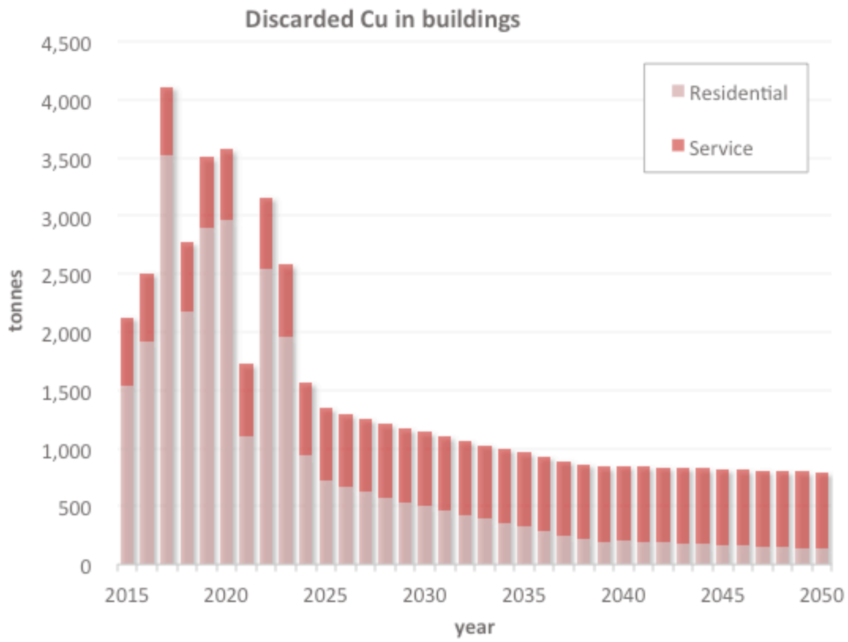

Fig. 21. Discarded Cu for the building category in Amsterdam from 2016 to 2050.

3.3.3.2 Infrastructure

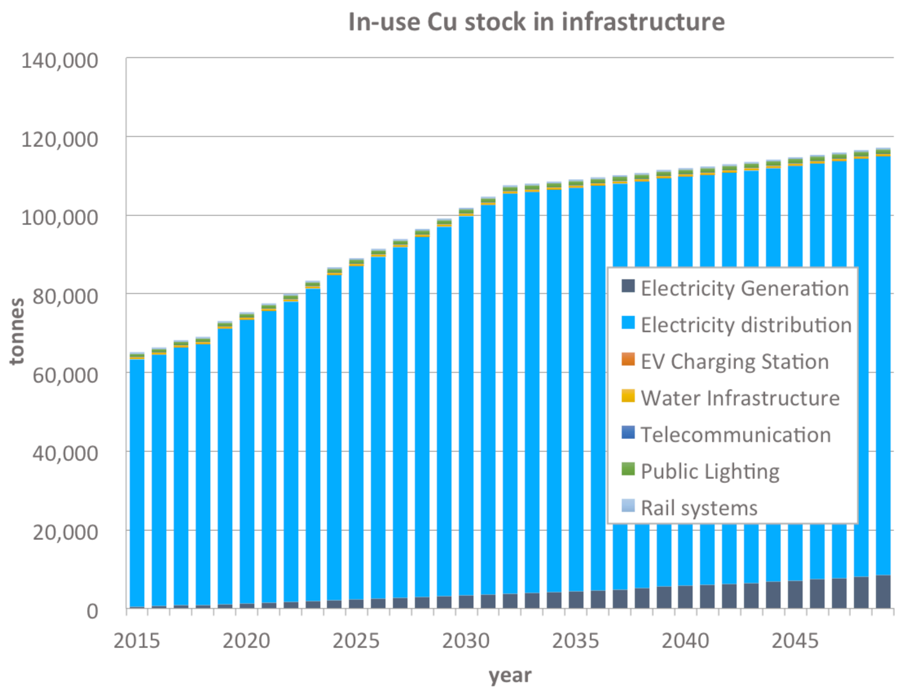

Fig. 22. In-use copper stock for the infrastructure category in Amsterdam from 2016 to 2050

The infrastructure category is expected to grow into the largest reservoir for copper in 2050. The fast-changing energy landscape stimulates the growth of copper embedded in this category, specifically in the electricity distribution network and the electricity generation systems.

The electricity generation systems include: solar, wind, coal-fired, gas, biomass, and waste to energy. Currently coal and gas are the largest source of electricity, owned by Vattenfall Group. It is important to point out that the ownership of the power plants belongs to Vattenfall Group, and so is the copper stock. The copper stock in the power plants is estimated and presented with the purpose to show the relative scale of quantity among all categories since the municipality does not have control of the raw material after the plants are shut down.

The in-use stock of copper in infrastructure is estimated by the copper-intensity per unit of distribution capacity multiplied by the total distribution capacity, which is assumed to be the same as the total power generation capacity. The rise of copper demand takes place especially before 2033. This is mainly because of the strong ambition in renewable energy growth and upcoming retirement of the 650 MW coal-fire power plants in 2034.

While the skyrocketing capacity of renewable energy generation may seem relatively insignificant to the overall in-use stock, the growing capacity that's added on to the load of Amsterdam's distribution grids is the key role of the ever-rising urban copper mine. With the ambition of growing the solar energy 63 times and wind energy 6.5 times comparing with 2016's level, the distribution network requires more capacity than ever to handle the distribution load. This requires large amount of copper to build up the handling capacity, making the demand and in-use stock both highest among all categories in 2050. In addition, the amount of copper waste generated by the distribution network also tops all categories in 2050. It is therefore probably the copper-containing product with the highest potential for urban mining.

Another copper-containing product that is also expected to experience significant growth is electric vehicle charging station. Comparing with today's level, the number of EV charging station in Amsterdam is 8 times higher in 2050 comparing with today's level. The growing coverage of EV charging stations are set up to power the electric vehicles that are expected to replace conventional vehicles. However, the amount of copper in EV charging station is relatively small comparing with electricity generation and distribution network.

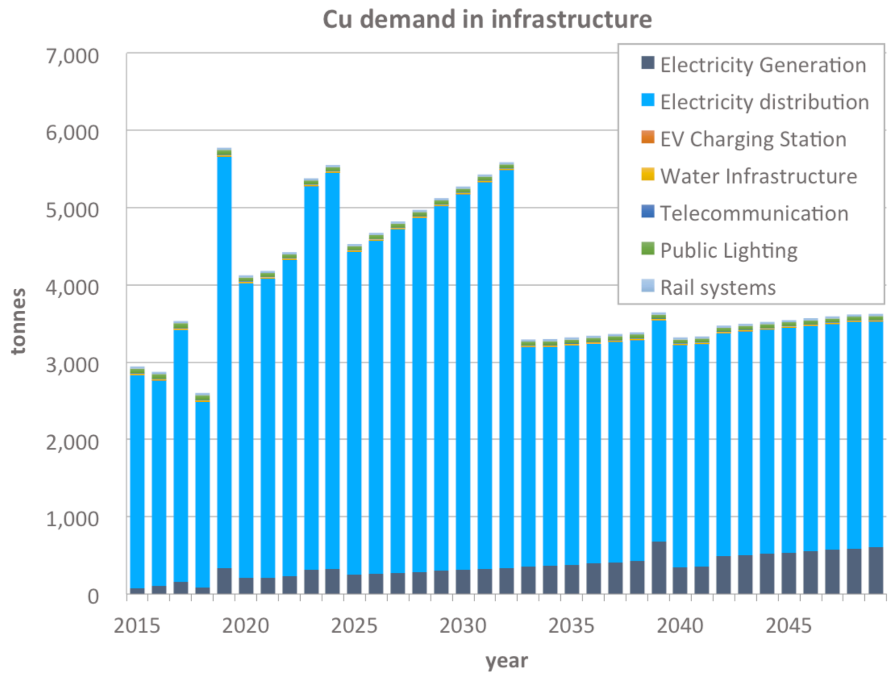

Fig. 23. In-use copper stock for infrastructure in Amsterdam from 2016 to 2050

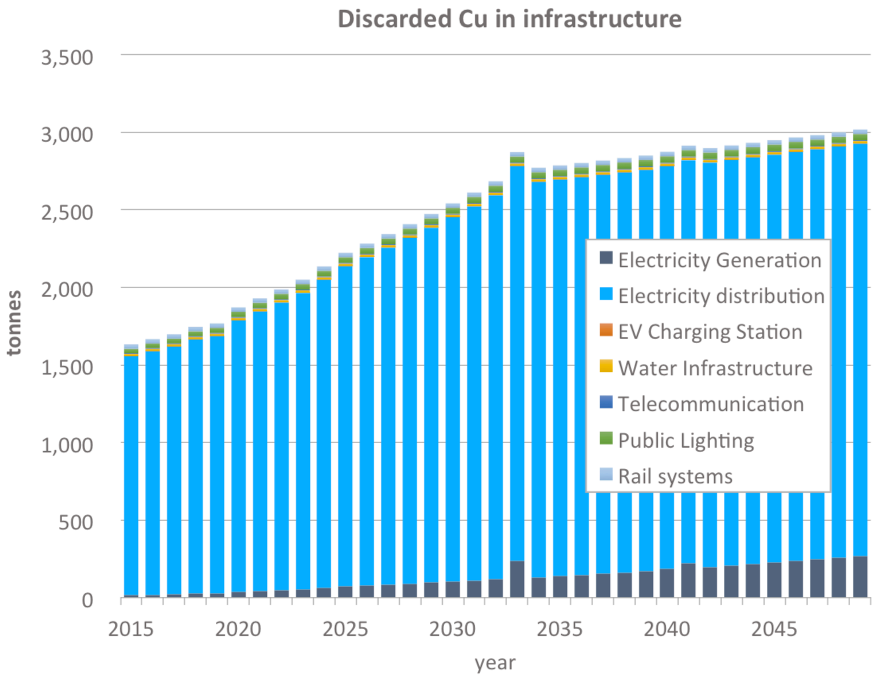

Fig. 24. Discarded copper in infrastructure in Amsterdam from 2016 to 2050

3.3.3.3 Transport

Among the copper-containing products in the transport categories, vessels are the most significant copper reservoir, followed by cars and motorcycles. All the products in transport category are expected to grow in copper content except for vessel, which is overwhelmingly dominated by cargo ship. The vessels are not taken into further considerations because the material recovery decisions are entirely up to the vessel companies, making it less relevant with the urban mining potentials by the City of Amsterdam.

The in-use copper stock for vessels are calculated by the estimated number of cargo ship owned by companies in Amsterdam. Sizes of cargo ship could vary greatly and therefore the degree of uncertainty in this study is quite high (Ranging from 5,000-500,000 tonnes, according to Papanikolaou (2014). However, considering the relative sizes between cargo ship and vehicles, buses, or railcars, this estimation gives an idea of the scale of in-use copper that could be embedded in cargo ship.

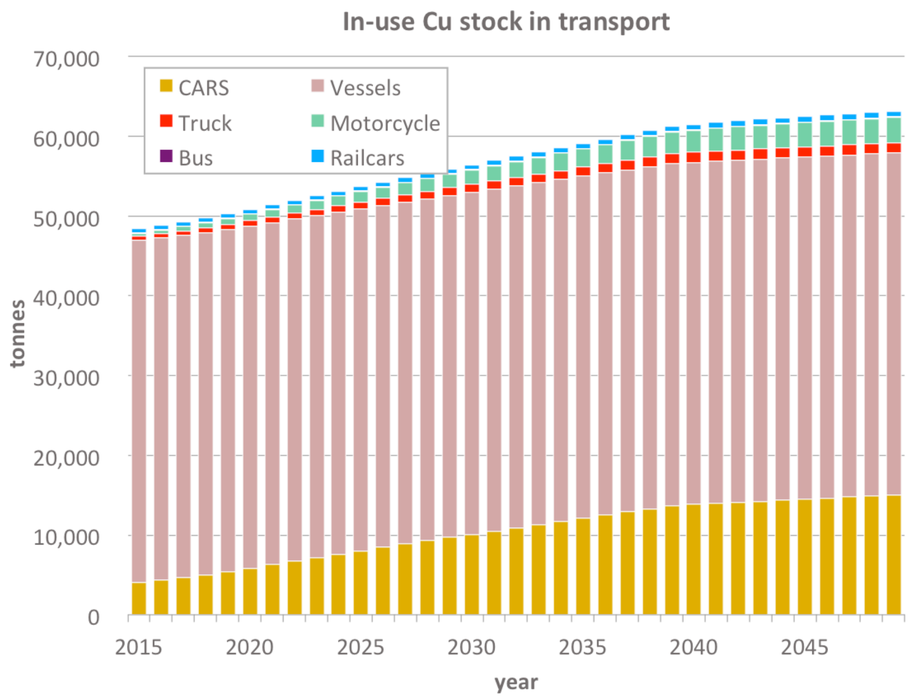

Fig. 25. In-use stock for copper in the transport in Amsterdam from 2016 to 2050

Cars, buses, trucks, and motorcycles all go through a transformation to meet the city's policy. Especially for cars, the zero emission policy goal by 2040 serves as a driving force to shift the light duty vehicles from fossil fuel based to electrical. By 2050, the in-use stock vehicles are fully electric. This transformation is enabled by copper-intensive technology since electric vehicles are 4 times copper intensive than conventional vehicles. Electric vehicles and hybrid vehicles are expected to grow from less than 1,500 units today to 200,000 units before 2040, causing the copper demand in cars to more than double. On the other hand, the level of discarded copper from cars is also expected to rise strongly. By 2050, the copper waste from vehicles is expected to quadruple when comparing with today's annual copper waste flow.

Motorcycles and trucks go through similar development to decarbonize the vehicles. For public buses, the transformation is even more progressive. All the bus fleet is expected to go electric by 2025. Each electric bus has about twice the copper content compared with a diesel bus. However, the electrification of bus stock takes place quickly and the total number of buses is assumed to have a limited growth (2 buses/year). The copper coming in and out of the urban system in buses therefore does not have a strong influence on the overall copper resources in Amsterdam.

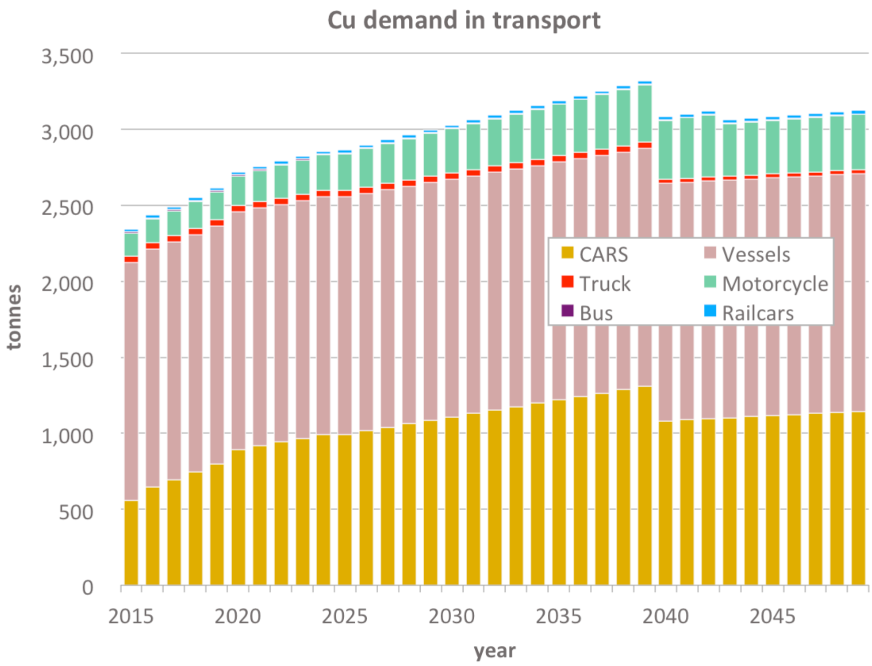

Fig. 26. Copper demand in transport category in Amsterdam from 2016 to 2050

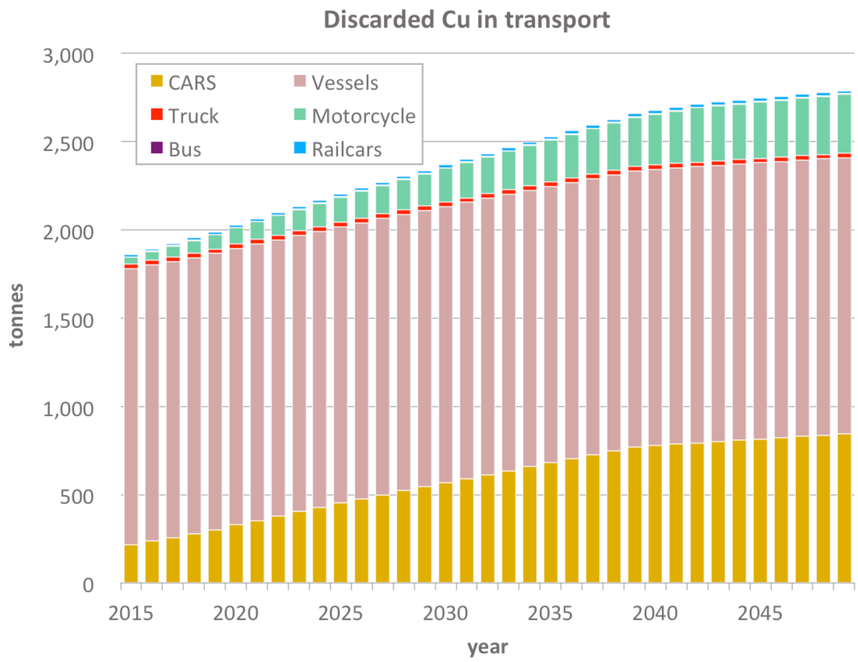

Fig. 27. Discarded Cu in transport category in Amsterdam from 2016 to 2050

CHAPTER 4 / PRELIMINARY CONCLUSION

4.1 Result summary

To answer the research questions raised in Part 1 (Quantify copper resources) of this study, this chapter summarizes the result comparison while highlighting the main findings to continue with Part 2 (Envision and assess urban mining in action). As a memory refresher, let's bring back the Part 1 research questions:

A1: What are the in-use stock and demand of copper in Amsterdam in 2050?

A2: How much copper can come from urban mining in 2050 in Amsterdam?

The in-use stock of copper in Amsterdam in 2050 is estimated to reach 0.28 million tonnes, which can also be expressed as 307 kg/capita. Comparing to 2016 level (240 kg/capita), the copper in-use stock experiences 28% growth per capita.

The demand of copper in Amsterdam in 2050 is 9,000 tonnes. This equals to 10 kg/capita. The per capita demand dropped by 16% from 2016 to 2050, meaning that the city consumes less copper than the current level.

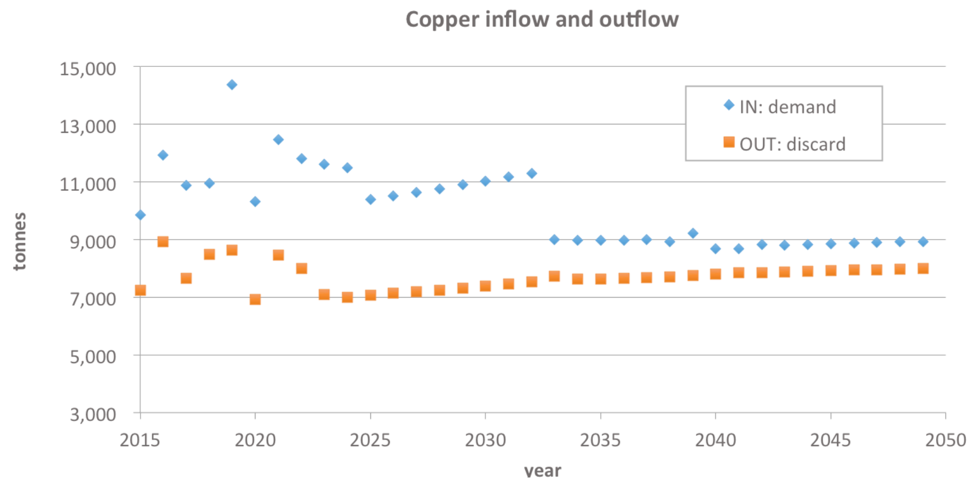

Fig. 28. Comparing copper demand (blue) and discarded copper (orange) in Amsterdam from 2016 to 2050

If all the end-of-life copper-containing products are fully collected for reuse or recycle, maximum 8,000 tonnes of copper could come from urban mining in 2050. This equals to 9 kg/capita. The quantity of copper extracted from urban mining remains more or less at the same level in the upcoming three decades, as shown in Fig. 28. The discarded copper only increased less than 2% on a per capita basis.

Copper urban mine in the making

The amount of copper entering Amsterdam is still higher than the amount of copper leaving the urban system, leading to a growing copper urban mine in Amsterdam. However, a narrowing gap can be seen when comparing the inflow (demand) and outflow (discarded copper) from 2016 to 2050. In 2050, Amsterdam consumes 8,006 tonnes of copper and generates 8,926 tonnes of copper waste. This could imply that the in-use stock of copper is on its path to stabilization.

What product has the biggest potential for urban mining?

In order to pinpoint the institutional arrangement around urban mining activities, a copper-containing product should be selected to set the basis for the second part of the study from Chapter 5 to 7. Although buildings represent the largest in-use stock and the waste flow of copper in 2016, the share of its waste flow quantity drops significantly in 2050. In 2050, buildings only contribute to 10% of the total copper waste flow. In another word, even if it's 100% mineable, the copper stock embedded in buildings is not expected to make significant contribution as a source for urban mining. It is expected that most of the copper waste will be released by the infrastructure and transport stock in 2050. Therefore it would be more interesting to set the focus product from one of these two categories. More specifically, electric vehicles and the electricity distribution network are the two copper-containing products that are considered most significant as the target for urban mining activities mainly because of their high level quantity. The distribution network for electricity is not only expected to generate most copper waste, the copper embedded in the grids also makes up a big part of the copper urban mine in 2050. The distribution network is therefore chosen as the case study in Part 2.

4.2 Benchmarking with other cities

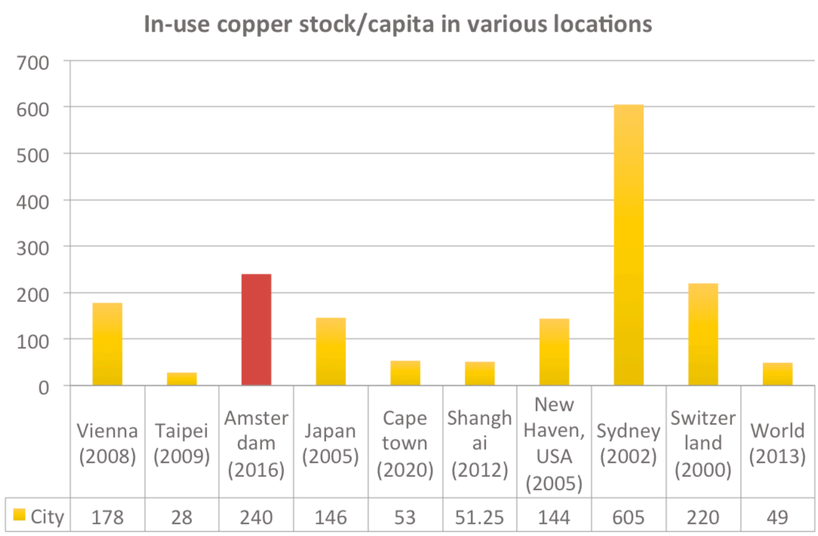

Fig. 29. Comparing in-use copper in different cities (unit: kg/capita) (Vienna and Taipei: Kral et al., 2014; Japan: Daigo et al., 2009; Cape Town: van Beers and Graedel, 2003; Shanghai: Zhang et al., 2014; New Haven, USA: Drakonakis et al., 2007; Switzerland: Wittmer, Lichtensteiger, and Baccini, 2003; World: Gloser et al., 2013)

To get an idea of where Amsterdam stands among different part of the world in terms of the copper stock, a comparison of in-use copper stock per capita is conducted based on findings from recent years. The comparison shows that Taipei has the lowest copper in-use stock per capita (28 kg/cap) and Sydney city center dwarfs any other cities (605 kg/cap), following by Amsterdam. Many possible reasons could lead to the differences in results, for example, electrification rate, lifestyle, transportation system, building types, climate, industry type, energy structure. In addition, the timeline of these studies also attributes to the level of copper in-use.

4.3 Preliminary conclusion

Based on the results of the copper urban mine estimation, the following preliminary conclusions are drawn:

- The amount of in-use copper in Amsterdam grows by 40% from 2016 to 2050, making the city growing richer in copper urban ore.
- Carbon policy is the main driving force for the introduction of copper-intensive products. Transition towards renewable energy system and zero emission transportation system are expected to boost the copper usage.
- From 2016 to 2050, the largest contributor to the copper waste stream shifts from the residential buildings to power distribution system.
- Given the large shift in copper waste composition, the level of annual discarded copper remains quite stable through 2050.
- Amsterdam still needs more copper than the amount of copper waste it generates, but the difference is becoming smaller.
- This research estimates the copper stock from the perspective of raw materials. The added value of recovering the urban mine with repair and reuse is not accounted for in this estimation because it's estimated simply by calculating the weight. Without the detailed properties of the product, such as the suitability to be repaired for resale, it is hard to gauge the potential on an economic scale.

PART 2: Envision and assess urban mining in action

In Part 1, the quantification results identified the electricity distribution system to be the largest contributor to in-use stock and demand in 2050. As the demand for the distribution network continues to rise, the pressure for demand for fresh copper also grows along. Given this trend, this study is done in order to answer a series of questions as listed below to identify the current practice and if the current actions are on the right track to achieve the ambition.

Research questions in Part 2:

B1: What would an urban mining system look like?

B2: What are the key activities for an urban mining system?

B3: What information is required in mining urban copper stocks?

B4: What is the knowledge gap of copper urban mining?

B5: What are some of the leakages for copper cycle in the urban system?

CHAPTER 5 / URBAN MINING SYSTEM

Section 5.1 depicts the general setting of the urban mining system within the context of circular economy. First, the definition of urban mining and its values are reviewed for Amsterdam. Second, barriers and opportunities for urban mining of copper are identified based on studies of the material cycles in Amsterdam. Finally, an ideal urban mining system in action is then depicted based on the seven principles of the circular economy in the policy agenda and initiatives to lift the current barriers for urban mining.

Section 5.2 investigated the power cable as a case study for an urban mining system. The existing practices of urban mining activities for power cables in Amsterdam are studied. Further, an institutional condition is reviewed for urban mining.

5.1 Urban mining in action

5.1.1 Amsterdam as an urban mine

In Part 1, the urban mine of copper in Amsterdam is characterized by estimating copper-containing products in use until 2050. I defined urban mining as reusing or recycling the urban copper waste generated from anthropogenic activities. The target in this estimation is focused on the in-use stocks that are actively serving their functions in the economy. With the quantification result in Part 1, it is now possible to describe the urban mining system in Amsterdam with more precision based on its unique features.

Definition: What is urban mining in Amsterdam?

The goal of urban mining is to retain the value of copper to the largest extent after it reaches the end of its economic life to close the material loop and to have minimal environmental and social impact in its life cycle. To achieve this goal, urban mining seeks to recapture the materials from the EOL product stream (in the form of raw material or product) and return it to the heart of the market by recycling or reusing the product. Besides enhancing the recycling scheme for material recovery, value based on the copper-containing product's function should also be taken into consideration in urban mining. For example, instead of recycling all the end of life products, repairing the products for reuse could not only extend the product lifetime, it also bypasses the stages of refining and remanufacturing to deliver the same functions. Therefore, transition towards product service based system could also facilitate the goals of urban mining.

According to TNO, circular economy is already happening in the Netherlands for the metal and electrical sector. This is because the schemes of recycling, repairing, renting and leading, and secondhand market trading are widely applied to products in these sectors (TNO, 2014). From a future perspective, the smooth transition toward a circular economy through urban mining copper is determined by the development of the urban mine in Amsterdam.

The development of Amsterdam's urban mine towards 2050 shows a strong shift towards the use of renewable energy, increase of power grid capacity, and electrification of transport tools. This makes the energy and distribution system in infrastructure and transportation the most relevant categories in urban mining. Based on the expected lifetime for solar panels, in 2050, the amount of copper in solar panels generated from the waste stream will be 100 times larger than today's level. This implies that the composition of copper waste in 2050 will look vastly different than today. Recyclers need to be equipped with the technical capacity to handle this type of waste in sorting, disassembling, and refining this material.

However, this study does not take into account the logistics or the promotion of localizing productions. While closing the material loop is an important part of the goals of urban mining in the circular economy framework, it doesn't mean that the loop has to be located on a local level. Learning from the existing practices of labor division on an international level gains advantageous positions to modernize metal recycling system (Reck and Graedel, 2012).

What's the value of urban mining?

Financial implications

From the perspective of raw materials, urban mining presents the roadmap to sustain the physical economy with finite resources. However, it is difficult to translate the material quantity into monetary values with precision because of its wide application and the various ways value could be calculated. For a robust urban mining system, both reuse of product and recycle of materials need to be considered. As copper is embedded in a wide variety of modern technologies along with a massive list of materials, it is impossible to single out the value of copper that brings to a single device for the function it serves. And estimating the value of copper solely based on the raw material value also runs the risk of underestimating the economic potential it brings since the value of services it provides would be much higher than the raw material price.

With this being said, it is possible to look at the physical economy with a birds-eyes view and estimate the potential economic benefits from circular economy based on the product values instead of raw material basis. In 2013, TNO conducted an analysis to estimate the economic benefits that a circular economy would bring for the metal sector and the electrical sector in the Netherlands. With feedback loops to retain values of the products and materials, it was estimated that transition towards a circular economy for the electronic, electric, and metal products brings the Netherlands an additional 573 million Euro and 10583 new job opportunities (TNO, 2013). For Amsterdam, the

Environmental implications

Urban mining copper not only secures the sources of secondary raw materials, it also reduces carbon emission. According to BIR (2008), production of secondary copper saves 65% of CO2 emission comparing with fresh copper. To explore the implications of the carbon emission through employing more secondary copper to fulfill the demand in Amsterdam through 2050, three scenarios are compared in Figure xx. The gray bar stands for the CO2 emission produced when using all the copper waste to supply copper demand. When the copper waste is lower than demand, primary copper is used. The bars in blue stand for the CO2 emission produced when 100% primary copper supplies the copper demand without recycled copper in Amsterdam. Currently, about 50% of the copper used is secondary copper in Europe, according to the International Copper Study Group (ICSG).

Assuming half of Amsterdam's copper demand is supplied by secondary copper, the orange bars represent the CO_2 emission in copper production. The UM supply scenario is used as base of 1 to calculate the potential CO_2 emission saving under different scenarios. Fully utilizing the secondary copper from urban mining activities saves 50% carbon emission comparing with the 0% recycled scenario in 2050. In addition, comparing with 50% secondary copper supply scenario, it saves 40% of carbon emission.

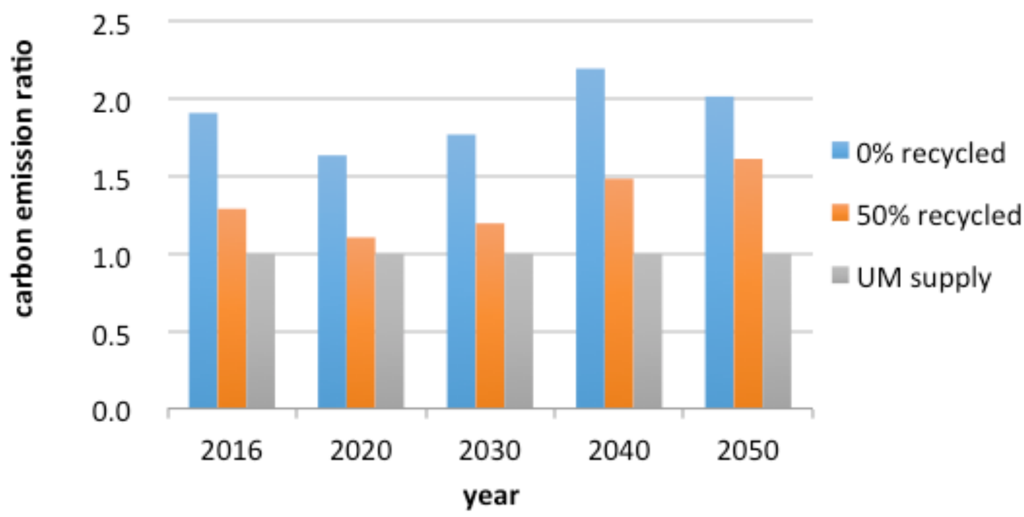

Fig. 30. Carbon emission level with three urban mining scenarios

Barriers and opportunities for urban mining in Amsterdam

This section identifies barriers and potential opportunities for urban mining copper in Amsterdam. Four types of barriers are summarized in Table 9: laws and regulations; culture, technology, and market. To lift the barriers, cross-sector cooperation is often required. But policy could play a significant role in leading the actions.

Table 9. Barriers for urban mining

Types	Description
Policy barrier	• Financial burdens for scrap dealer taking in materials containing restricted chemicals • Carbon emitting recycling activities punished by ETS • Waste shipping rules lacks strict enforcement to prevent illegal cross boundary shipping
Cultural barrier	• Lacking cross-sector network to respond to opportunities • Material efficiency not part of consumer's considerations when dealing with EOL products • Repaired products associated with less quality for some consumers
Technical barrier	• Increasing complexity of material composition • Certain metal impurities difficult to separate in smelters
Market barrier	• Market mechanism unclear for consumers to take back EOL products

- Lacking incentives for product owners to recycle products
- Investment on urban mining does not return to the investor

(1) Policy Barrier

Regulations or policies sometimes create legal uncertainties or challenges to businesses when decisions need to be made to carry our urban mining activities. Without further clarification of the legal status or financial consequences, these rules often cause disruption in the operation. Not only do the policy barriers disrupts urban mining activities, the policy barriers could also lead to other environmental impacts.

Three regulations were identified to potentially pose as policy barriers for businesses that engage in urban mining activities: chemical regulations, the carbon trading system, and waste shipping rules. However, according to a survey to the industrial associations on policy barriers on circular economy, most of the barriers are formed by a combination of regulations instead of one single regulation (Wilts, 2016).

First of all, the EU directives of REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) heavily regulate chemicals that are listed as substances of very high concern (SVHCs). Once a chemical is listed as SVHC, it could be included in the authorization list, making it illegal to be placed on the market after certain date. Unless the use of such chemical is exempted from authorization, a company needs to apply for authorization to use the chemical. However, the financial consequences of authorization process are severe especially to small or medium size companies. According to European Copper Institute (2015), scrap dealers could avoid buying EOL products that have higher possibilities of containing REACH authorization materials to avoid compliance cost, impacting the smelters' raw materials access at a competitive price. As a consequence, more and more scrap materials could be exported to regions with less stringent regulatory pressure.

Another aspect of the regulatory barriers is the lack of enforcement of the waste shipping regulations. Illegal shipment of the scraps to countries such as China not only weaken the raw material security, it also bears the risks of outsourcing the environmental impacts to countries with lower capacity to properly recover the materials. Finally, companies also argue that some existing practices of recycling involve burning the insulation layer as fuel during the copper recovering process, which is punished by the European Carbon Trading Scheme.

(2) Cultural barrier

For businesses, working with different sectors to promote circular economy of copper could be challenging. Without existing business networks across different sectors, it is difficult to enhance efficient material use (Circle Economy, 2015). On the other hand, businesses are not always able to account for the materials embedded in the products that have a long lifetime when making decisions, such as buildings (Circle Economy, 2015). Buildings are designed to last for 50 years, but the uncertainty of the market condition in 50 years is too high and this implies unforeseeable benefits within fast business revenue cycles.

For consumers, when they handle EOL products, they do not always take into account the performance of material efficiency from the perspective of raw materials. For consumers, the behaviors are often driven by considerations of functionality of products and the services they provide. For example, separation of household waste is a field that needs great improvement to avoid useful materials going into waste stream in Amsterdam when comparing with other cities.

As a part of urban mining activities, EOL products can be repaired or refurbished to be put back on the market. However, consumers tend to associate the concept of second hand with compromised quality (OPAi, 2014), making it less favorable comparing with brand new product. Also, owning products in general has positive notions to consumers comparing with leasing product.

(3) Technology barrier

From manufacturing, sorting, to recycling, technological barriers for urban mining appear in many stages in the copper cycle. Product characteristics that are desired by the consumers might be a pain point for the companies that does disassembling. For example, seamless cases, large glass displaying screens and ultra thin computers are difficult for companies to recycle or repair (Bonnington, 2014). For the recycling companies, they are now facing challenges of separating materials with increasing complexity, which impacts the quality and quantity of recovered copper (European Copper Institute, 2015). Metals such as zinc, iron, silicon and aluminum are easier to be separated from copper while other metals have greater difficulties to be separated (e.g., bismuth, antimony and arsenic) (European Copper Institute, 2015). Overall, the lack of information and communication across the supply chain forms obstacles for material recovery and brings uncertainty to technological processes.

(4) Market barrier

For some products, the market is well established for clearly defined actors such as infrastructure companies that manage grids. However, for some products the market is not always clearly defined or even present. For example, electronic products such as used CD players can be taken back to stores for recycling. However, consumers do not receive financial rewards for taking back the EOL products for repair or recycling. Even if there is a market for the material, the lack of financial incentive for certain actors exclude the consumers or owners to be a player on the market, leading to demotivation to urban mining activities.

Also, along the supply chain, the investment that promotes urban mining does not always return to the actor that makes the investment. It is likely that other members in the supply chain may benefit from the circular investment instead of the investor itself. For example, designing products that are easy to dismantle will benefit the sorting facility by reducing the time and efforts to extract the valuable material. However, the company that puts efforts into improving the material efficiency has no way to benefit from the improvement unless the company also handles the extraction of valuable material from its own EOL products.

Opportunities for urban mining

On the national level, the existing recycle scheme and the second hand trading market for reuse prove that the Netherlands has taken the path towards a circular economy and there are potentials to advance the circular economy (TNO, 2013). Furthermore, the citizens in general hold a positive attitude to participate in circular activities. As for Amsterdam, two specific areas of opportunities for urban mining in a circular economy are identified.

(1) Circular economy-related policy

While urban mining involves a wide spectrum of actor, the role of government remains significant to lead the direction to make the market and policy environment friendly for urban mining. Material use efficiency has been on the top of Amsterdam's policy agenda since 2010. Instead of waiting for policies such as the circular economy package to kick-in, the municipality could take measures to move forward with circular economy. The city government supports circular economy and provides free zones as testing grounds for initiatives that promote sustainability. In addition, in the procurement procedures, the municipality sets the ambitions for circular procurement contracts. The municipality implements the concept of circularity within its own organization and acts as a "launching customer". This provides the policy environment and market for urban mining activities to take place with the government.

The relatively clear policy goal also provides an opportunity for Amsterdam. While the city aims at achieving an seemingly difficult goal to cut the carbon emission and transforming the landscape and mobility system with steep upwards slope, the transition pathway also gives visibility to where the majority of the future copper stock will be located. Furthermore, the most relevant flows for urban mining originate from products that are not difficult to trace based on the product characteristics and existing EOL handling protocols.

For the power distribution system, the DSO that operates the power grid keeps the detail registration of the power cables. For the electricity generation system, the government programme plays an important role in energy transition towards renewable system and therefore the traceability is relatively feasible for EOL solar panels and wind turbines. For the electric vehicles and electric motorcycles, the vehicle registration system keeps record of the product in use. The system in place gives Amsterdam an advantage position to target the stakeholders for future waste flow for urban mining activities. The policy dissemination efforts should target relevant stakeholders such as Amsterdam inhabitants with solar panels installed on their roofs. Urban mining takes cooperation between different stakeholders. If the goals and achievements of urban mining for circular city can be better communicated to the people who are sitting on the urban mine, it is also more likely that the urban mining could take place.

(2) Internet of Things: lowering consumption & allocating material resources

Another opportunity that is rooting in the economy for urban mining is the Internet of things (IoT). IoT connects the built environment with the Internet and captures human activity information as usage data and the conditions of the device, enabling better coordination of resource allocation overall. The concept of IoT is being promoted by the municipality of Amsterdam, with business networks being rapidly formed to gather momentum to more connectivity in various parts of the city. For example, the "boat water detector" notifies owner via SMS and Maintenance Company that the water is coming in the boat, preventing the boat from further damages and extends the lifetime of the boat (EIP-SCC, 2016). Another example is Peerby, in which product service owners to track their lent items locations and the use conditions (EIP-SCC, 2016). Other potential applications for IoT can be seen in Fig. 31 by Libelium.

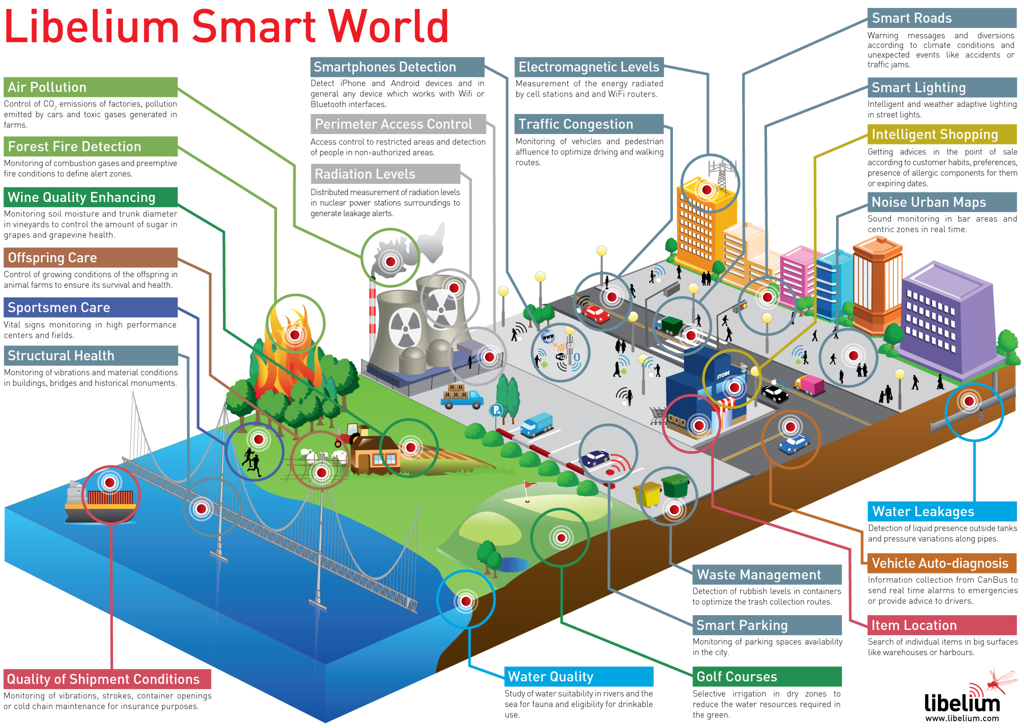

Fig. 31. Applications of IoT (Libelium, n.d.)

So how are these related to urban mining? From the perspective of the materials that are embedded in the products, the connectedness has the potential of optimizing the usage of the device and extends its lifetime. The demand for new product to replace the existing devices can therefore be lowered. In addition, the traceability of the product, and therefore the raw material, is increased with the possibility to track and locate the device. On the societal level, it is also possible to aggregate the data from individual devices to have an idea of the current in-use stock and how much material is approaching its end-of-life stage. The potential to locate the device implies the spatial information can be captured for material collection and material recovery.

With higher traceability, the IoT would also amplify the potential of sharing economy. Business models based on product service systems are given more certainties to keep the products in good condition.

Vision for urban mining system

A general setting of an urban mining system for copper is described in this section based on the circular economy principles from Amsterdam's sustainable agenda (Fig. 32). The description is made to depict a future circular system in action that seeks to retain the value of copper by various actors. The system takes into account the current status of the policy barriers identified in the previous section for improvements. Also, the current recycling rates of certain EOL products are used as an example to seek to improve possible leakages in the copper cycle.

Overall, enhanced information transparency is put forth along the supply chain, allowing a clearer picture of anthropogenic copper mine to be drawn on a societal level. Also, the urban mining activities engage a wide spectrum of actors to return the EOL copper to the heart of the market through incentivizing the urban miners. With the information being more transparent, real-time material accounting can also be made possible on a societal level.

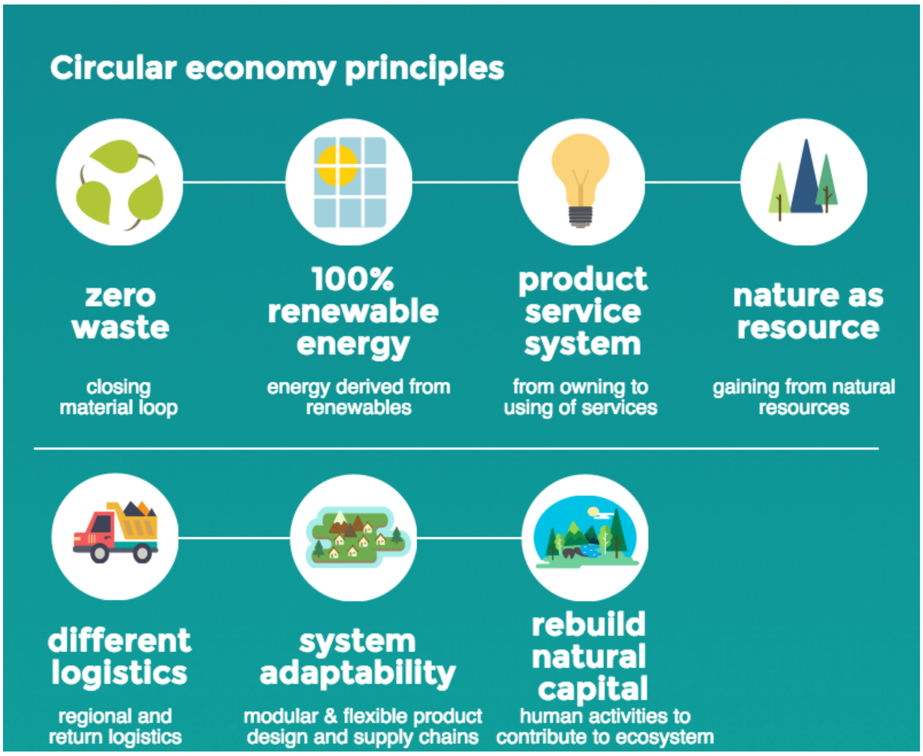

Fig. 32. Seven principles of circular economy in Amsterdam's sustainable agenda

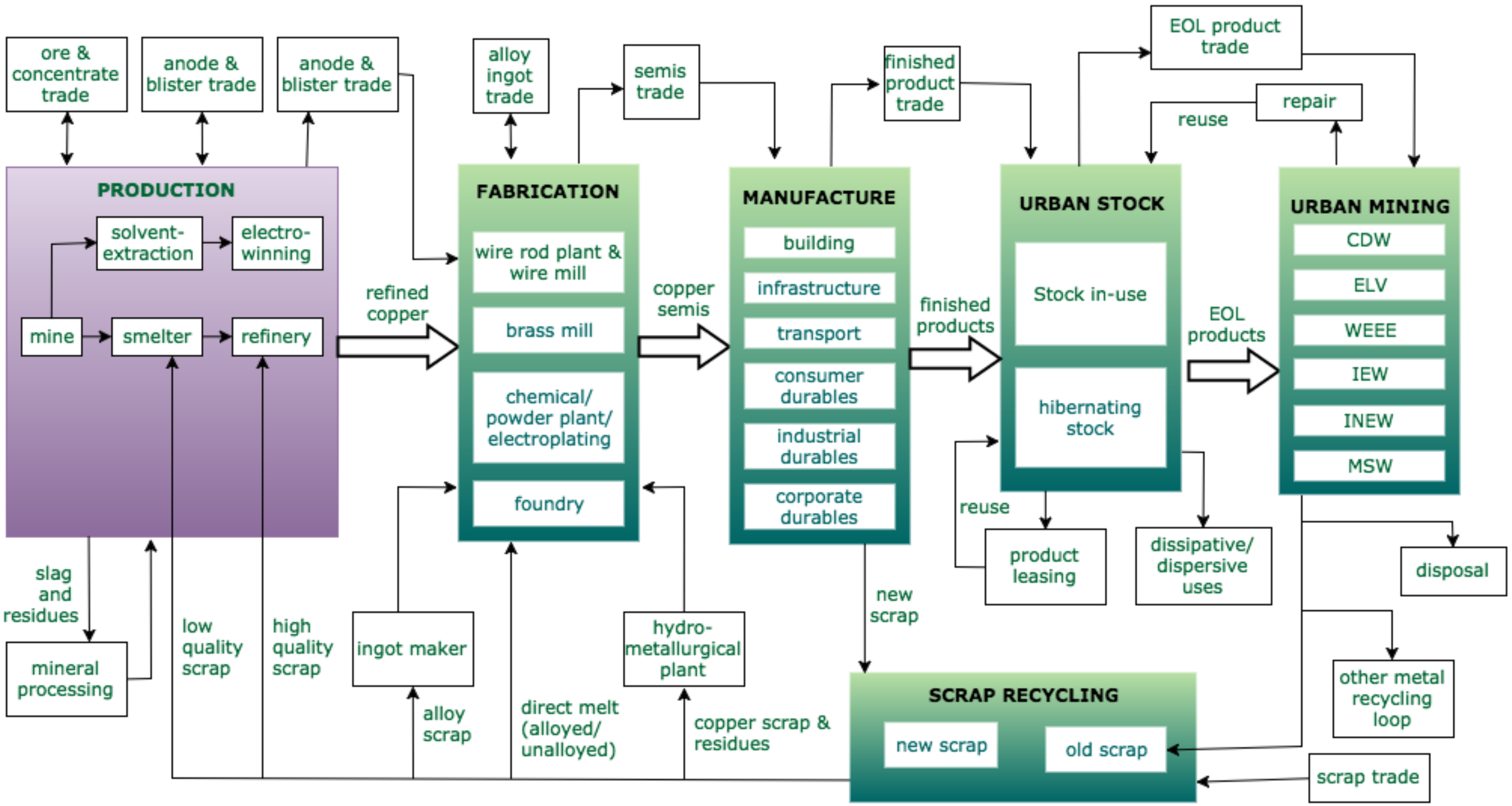

Fig. 33. Urban mining in a copper cycle. Adapted from UNCTAD (2014) (CDW: Construction and Demolition Waste, INEW: Industrial Non-Electrical Waste, IEW: Industrial Electrical Waste, ELV: End-of-Life Vehicles, WEEE: Waste Electric & Electronic Equipment, MSW: Municipal Solid Waste)

Key elements in a robust urban mining system

Design for recyclability

First of all, the recyclability of products to some degree is already determined at the design stage. Therefore the products are designed with consideration of recyclability. This makes the in-house recycling/reuse practice easier; especially with more and more product leasing services being established and customer take back product scheme being put in place. For leasing companies, product ownership means responsibility of maintenance. The customer take back scheme returns the product back to the manufacturers for product refurbishment or recycling. With easier disassembling, manufacturers will be able to separate the materials more easily and extract the valuables.

Manufacturer: Generating material passport

A passport that details product material composition and handling in its life cycle should be generated along the supply chain with all products or semi-finished products. In fact, some companies nowadays already generate recycle passport or material passport for their products. The recycling passports list the material compositions (weight %, metal grades, etc.), regulatory compliance (regulations, standards conformity, etc.) and the instructions of how to handle the materials after it becomes waste (reuse, recycle, product hazards, etc.). With the material passport, sorting facilities will be able to better separate materials according to their metal grades before selling to scrap dealers.

Consumer: Pay back scheme

Consumer's engagement in urban mining can be illustrated using current WEEE challenges as an example. Currently the material recovery of electronic waste suffers from inappropriate waste handling behaviors. Although the electric and electronic products go through mandatory registry by law, large amount of waste stream is lost. In addition, according to CBS (2015), every year 20,000 to 40, 000 tonnes of electric and electronic wastes end up in waste bins instead of official collections. In 2012, out of the 368,000 tonnes of WEEE generated in the Netherlands, only 34% is collected (CBS, 2015). 11% of the WEEE was thrown away into the waste bins and 55% of the WEEE was lost in the cycle (CBS, 2015). To avoid valuable materials ending up in waste bins or becoming hibernating stocks, consumers should be given incentives to bring back the copper-containing products.

In addition to current stations that collect EOL appliances from consumers, businesses that buy back waste products from consumers should be set up. When consumers receive financial incentives, they will be encouraged to bring back the products to waste collection points. Such a system is also supported by the study conducted by the municipality. City of Amsterdam

(2014) collaborated with the former City of Amsterdam's Environmental and Building Department (DMB), the Department of Physical Planning (DRO), Waternet and AEB to identify desirable characteristics of future cycles of waste and other areas. Providing financial reward to Amsterdam inhabitants to better sort the waste with tax benefits is listed as a measure to enhance the sorting.

Consumer: Repair shop buy back

With technology advancement, consumers have been presented with better technologies on the market. As a result, products are often thrown away and replaced before it reaches the end of life in order to enjoy better product functions, making product reuse an increasingly stronger alternative to recycling. Therefore, repair shops that buy used products from consumers and repair for resale can have great potential in extending product lifetime while providing consumers with incentives to bring back the products. By either repairing for reuse or collecting product with financial incentives to product owners (consumers), the value of the products are retained on the market and EOL products are prevented from ending up in the waste bin or incinerators.

Limitations to mineability

Ownership: For the copper stock that is owned by the private sector has more uncertainties for their mineability due to ownership. The decision to mine the EOL product is made by the owners. From the resource management point of view, the municipality might not be able to account for these stocks as a part of the urban mining system when developing relevant capacities to tap into urban copper mine. However, it does not mean that these corporate assets cannot be mined. It only implies that the government has less influence over these resources. Similar challenges also exist for consumer products that are privately owned.

Hazardous materials: The EOL material in contact with asbestos, or the copper is embedded in buildings that used asbestos, the copper is unlikely to be recovered due to health risks. The global circulation of commodities also bears the risks of banned substances being embedded in components in a copper-containing product and imported into the Netherlands. This could create potential impact to recycling facilities, smelters, and any waste facilities that handle the EOL products.

Economic feasibility: Another limitations to mineability is whether the investment to mine the urban stock can be recovered. Even if recovering copper from EOL product can reduce the environmental footprint comparing with linear economy, it has to be economically justifiable for organizations to mine the urban stock. However, with technological updates and the transition of energy system, products on the market might be increasingly difficult to recycle because recycling facilities also need to be adapted to the product characteristics and invest in machineries that are able to sort and disassemble the products. The upfront investment creates business uncertainties to innovative actors. Economic and policy support is therefore needed for these actors to build a business case for the urban mine in transition.

5.1.2 Urban mining case study: power cables

Case study: Alliander

In Amsterdam, the power grid is operated and maintained by the distribution system operator (DSO) Alliander. The company is currently looking into various issues such as the designs of power cables, end-of-life treatment, circularity, etc. This section presents the current practices taken by Alliander through literature review.

According to Alliander (2009), when the cables and pipelines are taken out of service, the current regulations require the operator to remove the cables. When the cables are put in the ground or disconnected, the operator (Alliander) also documents the spatial information and registers the information according to the Act on Information Exchange on Underground Network (WION) (Alliander, 2009). However, there are still end-of-life cables that were previously disconnected but stayed in the ground because the old disconnection practice did not involve cable removal. These underground end-of-life cables are registered as abandoned cables. Because the cables might pose risks for the environment in the future if they continue to stay underground. These abandoned cables are still going to be removed at some point in the future. According to Alliander (2009), removal work is likely to happen when maintenance work take place in order to keep the environmental disturbance at the minimum level. In addition, this practice is listed as one of the social performance indicator in Alliander's company guidelines.

According to CE Delft (2016), which conducted a life cycle assessment on power cables commissioned by Alliander, the end-of-life copper cables are put on the market. But further information regarding the treatment the copper scrap receives after it was sold on the market is not available and the source of the metals for power cables is also unknown (CE Delft, 2016).

The current handling of end-of-life copper is addressed in the GRI Index (Alliander, 2009) under the environmental performance indicator: Disclosure of management approach and specific explanations. Alliander strives to have all metal waste recycled in the Netherlands, or exported to Sweden, or Germany. According to Alliander (2009), copper theft is also a concern in the arrangement of the handling because the company bears a risk of financial loss if the end-of-life treatment is not properly handled.

Besides the EOL cable handling, Alliander has been working with one of its cable providers Prysmian to explore power cable using circular economy as the design concept since 2014 (Sluijer et al., 2015). By integrating the material purchase, material lifetime, material reusability, and EOL material recovery, the companies initiated the cooperation to create more sustainable products.

Handling copper waste in Amsterdam: waste facility AEB

To gain more knowledge into what happened with the end-of-life copper-containing products in Amsterdam, the capacity to deal with copper waste in the waste facility in AEB is described below.

AEB is the waste treatment facility that handles municipal and hazardous waste in Amsterdam. Currently AEB is recovering copper from bottom ash (94% recovery rate, 3% bottom ash is metal, half copper and half aluminum), and from dismantling EOL products such as cables (shredding) and fire extinguishers (by hand). The material is then sold to copper smelters in Germany or Netherlands (Residue to Products (R2P) project, 2008; Duijn et al., 2011; AEB, 2015; WasteKIT, 2010).

Since 2012, AEB has been working with City of Amsterdam on recycling electric cables. The cables are shredded, peeled by machines to separate the copper and the insulation layer. The plastic granulate and copper can both be used again. The quantity of electric cables that AEB processed has been increasing since 2012. According to AEB's 2014 annual report, the cables (total cable weight before retrieving the copper) processed increased from 12 tonnes in 2012, 65 tonnes in 2013, to 103 tonnes in 2014 (see Fig. 34). The cable processing takes place in the Hazardous Waste Depot (DGA), a specialized facility dedicated to collection and processing chemical waste and hazardous waste. Finally, the total amount of copper recovered in DGA comes to 29.6 tonnes in 2014 (AEB, 2015).

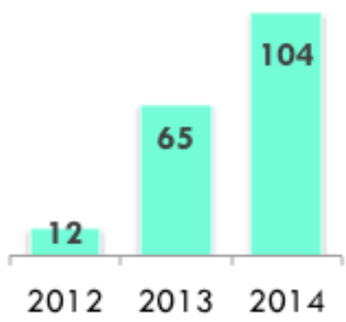

Fig. 34. Weight of EOL cables processed by AEB's DGA (tonnes)

Another AEB department that processes copper waste is the Regional Sorting Center (RSC) in Westpoort. EOL products such as water meters and refrigerators are collected from six collection points in Amsterdam. The wastes are sorted, disassembled, and processed for material recovery.

According to AEB (2016), up to 80% of the materials received at the RSC are still usable. In addition, the cooperation between AEB and municipality goes beyond waste collection. Under the collaboration between Amsterdam municipality and Milieuwerk, the workforce is established through a social employment program at AEB's Regional Sorting Center. This employment program is designed to give the people who are less likely to find careers in the job market to have equal opportunities.

5.1.2 Grid development and urban mine

How would the transition towards future grid shape the urban mine?

In Part 1 of this study, the quantification results show that the copper in the power grid forms the largest copper stock in Amsterdam in 2050. Power grid also creates the largest demand and discarded copper compared with other copper-containing products in the estimation. Having that in mind, the future development of the grid could hold the key to the size of the urban mine and how the copper inflow, outflow behaves. The following section goes further in-depth as an attempt to pinpoint the elements in the power grid development that could characterize the copper urban mine in Amsterdam.

While the ambitions for renewable energy system was clearly set in the city's sustainable agenda *Sustainable Amsterdam*, the development for power grids has not reached a concrete goal on how it could develop into. This has to do with the bottom-up nature of decentralized energy generation systems. Two on-going power grid development trends that are often seen are discussed here as the basis for discussion: direct current (DC) grids and smart grids.

Development direction 1: DC grids

First of all, the material demand in electricity distribution system and the future energy landscape go hand in hand. To look into the factors that affect the material demand with in the distribution system, it is also necessary to characterize the energy production. On the electricity production side, a challenge is expected to emerge as the city of Amsterdam strives to foster its capacity in renewable energy production, especially the decentralized renewable energy generations. Most renewable energy systems produce electricity in direct current (DC), but the current grid system is on alternative current (AC).

When electricity is produced in a renewable energy production system, it needs to be converted from DC to AC before being transmitted onto the AC grid. However, loss of electricity takes place during the AC/DC conversion. Moreover, the majority (~80%) of the devices and appliances we use today function on DC. Therefore the devices need an adaptor to convert the electricity from the AC grid to DC to power the device. The conversion from DC to AC, then from AC to DC lead to electricity loss twice. The loss of electricity can be reduced if the grid can be changed from AC to DC and the conversion can be eliminated. In addition, the elimination of the need of conversion saves copper, according to an Energy Post (2015) interview of Professor Ad Van Wijk, a Professor for Future Energy Systems at Delft University of Technology.

The current policy in Amsterdam has yet to address specifically to what level would the city be covered by smart grid systems that regulates electricity supply and demand better while support the decentralized renewable energy production. However, the DSO Alliander is looking into implementing smart grids on DC. Van Wijk pointed out that it's hard to say if the speed of the introduction of DC smart grid is going to be fast in Europe (Energy Post, 2015); however, in the coming 5 to 10 years it can be expected to have DC smart grid implemented in some buildings for low voltage grids, especially for new urban areas in development.

Alliander (2015) is looking into the possibilities to install DC grids near Lelystad Airport with developers in order to support the local plans for sustainable energy systems, including solar, wind energy, charging stations for electric cars, battery storage systems, and public lighting by LED. Although DC grid will increase the energy efficiency for renewable energy systems on a local level and saves materials at the same time (Alliander, 2015), barriers also lie ahead to bring DC grids into practice. Relevant regulations have not been introduced to allow such development for relatively new DC grid technology, as everything is done in AC currently. Alliander (within Netbeheer Nederland) the Ministry of Economic Affairs, and Authority for Consumers & Markets (ACM) are working together to tackle the legislative challenges (Alliander, 2015).

Development direction 2: Smart grid

The development of smart grid is predicted by the copper industry to drive up the copper demand. In order to ready the grids to support the locally generated renewable energy sources that are expected to have a strong growth, Alliander is investing in smart grids to support the energy development and digitising the grid system (Alliander, 2015). Smart grid usually refers to integrating more communication, control, and sensing systems on various levels in the electricity distribution system to deliver a secured energy supply (MIT, 2011; Ekanayake et al., 2011). Smart grid could include a wide range of technologies such as smart meter, substations (distribution stations) that manage the intermittency of power generation, controller, regulator, energy storage, distribution lines, smart appliances, and information and communication technology, etc.

The demand for copper in smart grid system is expected to require more copper than the traditional grid system due to a few elements involved. These include: sensors, energy storage, cables, and telecommunication system. For example, the electricity storage systems typically contain 0.3 to 4 tons copper per MW of electricity storage capacity (CDA, n.d.). Also, as a key element of the smart grid, information system allows the users activity information to be communicated to optimize the operation and meet the varying electricity demands. But the communication channel uses copper cable (less able to take the signal for shorter distance and need repeater) or optical fiber (able to takes the signal for a longer distance without a repeater) to transmit digital signals (Ekanayake et al., 2011).

Despite that the smart grids are expected to demand more copper than traditional grids to build up the system, that fact that the smart grids allow the users to shift their electricity usage to the off-peak period, reducing the peak load and operational cost could ease the peak load pressure to the grids. In addition, when users have access to real-time information, the electricity usage is reduced. This could in turn reduce the needed capacity for the distribution network and possibly lessen the material demand.

Pilot smart grid in Amsterdam Nieuw West

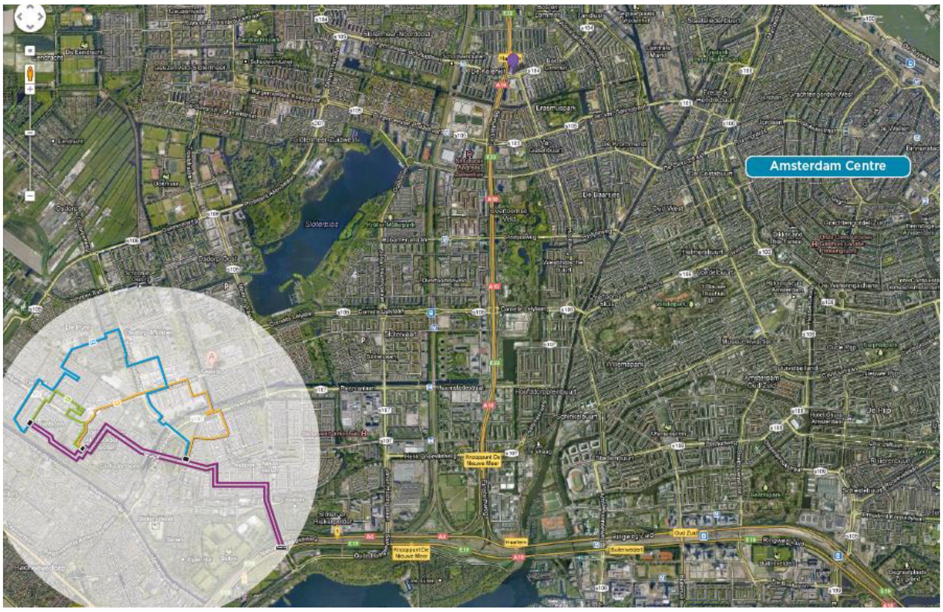

Fig. 35. Smart grid project area of i-Net by Liander (Source: Liander, 2013)

In Amsterdam, the concept of smart grid has been materialized in the district of Nieuw West as shown in Fig. 35. Liander, as a part of the DSO company Alliander, implemented the project i-Net to smarten the medium voltage grid with automation and grid reinforcement since early 2011. The project area is over 18 square kilometers and the power supply requirement is 9 MVA. This area also has the one of the highest coverage for solar panels and smart meters in Amsterdam.

i-Net now connects about 10,000 households. The financial feasibility is made possible by reusing 90% of the old grid system, including primary and secondary substations, 90% of medium voltage grid, and 95% of the low voltage grid (Liander, 2013). The new components include: SA sensor technology components, backbone system, and telecommunication system (Liander, 2013). The newly installed backbone cable is the inner ring in Fig. 23. It is 20 kv cable that is connected to the primary substation. As secondary loops, the existing 10 kv cable forms closed circuits and are connected to the 20 kv backbone through the secondary substations (Heerbaart et al., 2013). According to Heerbaart et al. (2013), bi-directional flow of electricity is enabled in both primary (20 kv) and secondary loop (10 kv).

In terms of material usage during the grid transformation, the newly added 20 kv backbone, sensors, computers, communication cables, and remote control switchgear all require copper to be completed. Therefore smartening up the power grid also drives up the demand for copper.

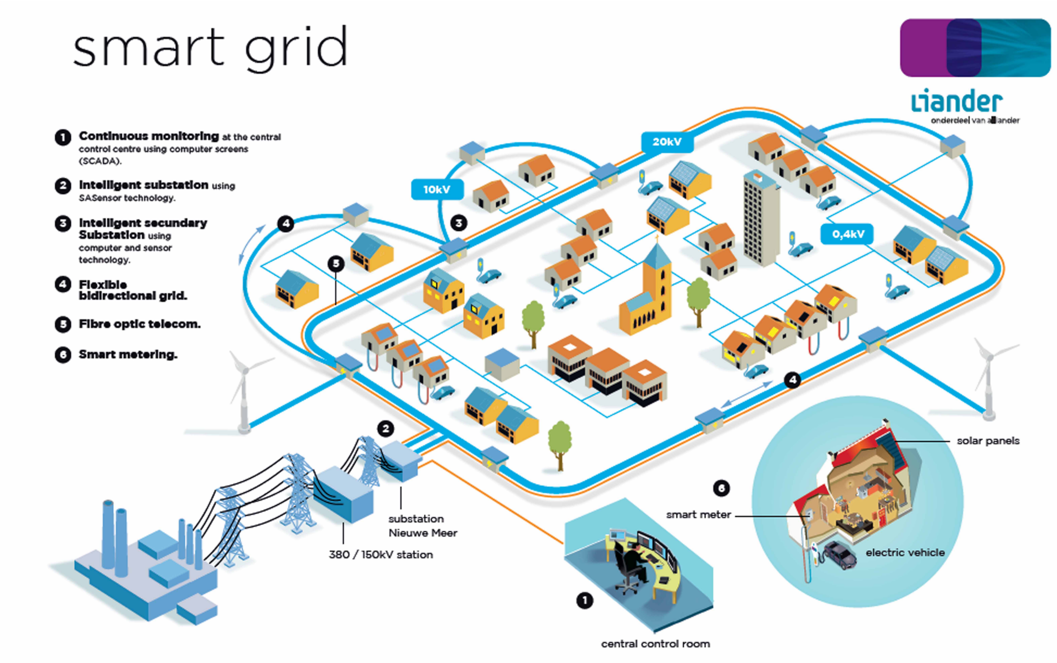

Fig. 36. Smart grid system and its components (Source: Liander, 2013)

Trade-offs: smart grid, material substitution

While smart grid technologies show great promises to a wide range of benefits, including the increase of energy efficiency, enhanced coordination between demand and supply, and the reduction of operational cost, the communication characteristic also accompany trade-offs. A common concern that has been often raised is privacy and cyber safety (IRENA, 2013; Abdallah et al., 2014), the attackers could intentionally drive up the cost of the smart grid system. Other trade-offs include

Some companies are working on reducing the use of copper in smart grid. Siemens (2014) claims to be able to reduce the use copper power distribution cable with enhanced automation on the grid while maintain the supply quality. Another strategy for copper material reduction is by substitution.

Aluminum is a material that is often compared with copper due to its conductivity and lightweight properties. Primary aluminum emits 3 times the CO_2 per unit weight of metal produced comparing with primary copper (BIR, 2008). Secondary aluminum, on the other hand, has the opposite CO_2 implications. According to the study that assesses the environmental impact of the medium voltage cable made with copper and aluminum by CE Delft (2016), recycled aluminum performs better environmentally across the board. In terms of CO_2 emissions, producing one kilogram of copper cable equals to the emission of 370,000 km mileage for a Dutch car while the emission equivalence by aluminum is only one third (CE Delft, 2016). This result is also different from other studies (BIR, 2008).

On the other hand, the conductivity of aluminum is only 60% of copper, making the performance less attractive. Also, the fire risk for aluminum cables is 10 times higher than copper. Finally, except for aluminum, other substitution materials are in development. Based on the environmental impacts results of CE Delft's study, substituting copper with aluminum could mean that less negative environmental impact is made. Advantech Corporation, Industrial Automation Group claim that copper cables are expected to replaced with superconductive materials (Frederich & Dove, 2010). So what does material substitution means for the urban mine? For the urban copper stock, if the substitution takes place before the end of the cable's service life, it means that the city is creating more Cu outflow. Since the new cables put in will be aluminum (or other materials), the new cables won't have copper, which shrinks the overall Cu inflow. The net flow of Cu will be negative, meaning a smaller urban mine for copper is expected if substitution takes place.

5.2 Institutional conditions

The policy environment shapes the conditions to facilitate urban mining activities. In order to understand the institutional conditions for urban mining, this section provides an overview of the public and private policies that are relevant with urban mining initiatives. A review of the status of resource efficiency is done as that basis to position the urban mining possibilities in Amsterdam within the framework of circular economy.

5.2.1 Overview of EU resource efficiency

In June 2016, EEA published a report *More from less – material resource efficiency in Europe* that reviewed the current status of resource efficiency on the EU level, national level, and some regional level. The report provides an overview of the current institutional arrangements from the public and some private sector on material resource efficiency and the circular economy with a goal of enhancing the experience learning opportunities among EEA countries.

Decoupling taking place for material use and economic growth in EU

Between 2000 and 2014, the resource productivity (relationship between GDP and domestic material consumption) increased by 34% while the use of resources has decreased by 12% in EU-28, signaling economic growth and resources use level no longer go hand in hand (see Fig. 37 and Fig. 38). The financial downturn that began in 2007 slowed down the construction activities and reduced the material use significantly. On the other hand, the GDP has suffered relatively minor impact from the financial crisis. The resource productivity was therefore improved, making the main challenge now to continue to improve resource efficiency and maintain the decoupling of material use and economic growth (EEA, 2016).

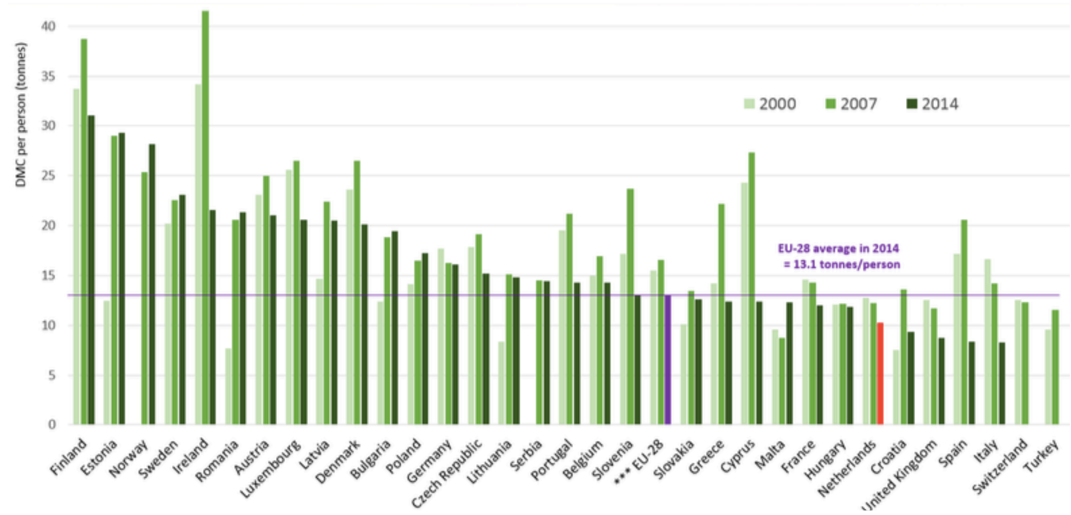

Fig. 37. Per capita material use for EU28 and participating countries (Source: EEA, 2016)

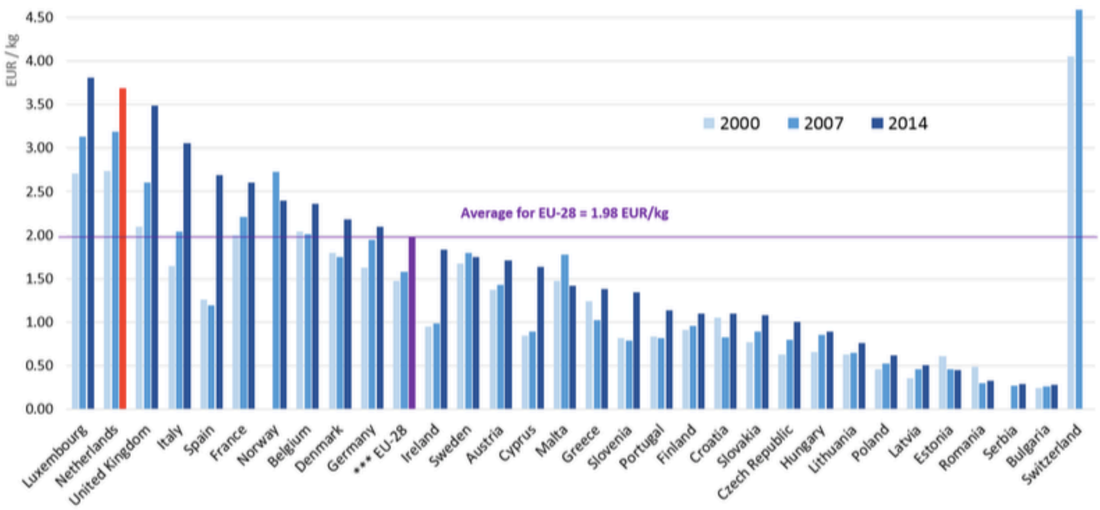

Fig. 38. Resource productivity (GDP/DMC) for EU28 and participating countries (Source: EEA, 2016)

National strategies and plans

Three countries developed strategies on a nation level to improve material efficiency, including Austria, Finland, and Germany, according to EEA. However, instead of developing national strategies that are solely dedicated for material resource efficiency, most European countries combine the use of materials and resource efficiency in other policies such as sustainable development, environment, waste, energy, and industrial development. Some countries also have strategies on a regional instead of national level. To achieve better performance in material resource efficiency, recycle, waste management and prevention, secondary raw material use are the major themes on a national level.

Another theme besides waste management, waste prevention, and recycling plans to improve material resources efficiency is energy. Although energy is usually an independent policy for most countries, initiatives on the use and efficiency of energy and renewable energy are also incorporated into the national policy for material resources efficiency.

What's driving forward material efficiency?

Economic, environmental, and regulatory factors are the top driving forces for countries to work on material resource efficiency. Economic interests are considered to be the most important driver of the issue. Drivers specifically focused on the competitiveness, the raw material security, material independence, and energy were reported by countries. Other economic drivers include production efficiency improvement and energy sector performance, creating green jobs. On the other hand, environmental drivers include the environmental impact reduction, improvement of waste management and using secondary raw material.

Priority sector for material efficiency

Manufacturing sector is considered the top priority sector when it comes to material efficiency. While the service sector represents two thirds of the European economy, it is not often considered to have much influence on resource efficiency. A more systematic approach is called upon to further the knowledge of how materials are circulated and the issues. Good practices shared by most countries mostly focus on waste prevention and recycling.

To measure material resources efficiency, Eurostat indicators that are developed based on MFA to measure material resource efficiency are often used. Other used indicators include materials that are based on waste generation and waste management.

Closing the material loop in a circular economy

Although the circular economy and closing material loop are already on some countries' priority policy list, they are not commonly recognized as a driver to improve material resource efficiency. The Netherlands is one of the three countries that developed a strategy to close the material loop. Waste regulation on the EU level often influences the national policies on closing material loop.

Institutional set up

Countries set up institutional structure that involves various ministries for policy development on resource efficiency. Usually more than one governmental agency is involved. Various types of stakeholders' involvement are being arranged. For example, cooperating among value chain members, establishing agreement on a voluntary basis, and forming stakeholders groups to tackle certain-issues.

Countries have made various progresses in identifying economic priority materials and developing plans on a national level. The Netherlands and Switzerland already looked into the materials that are important economically. Other countries are currently looking into the economic priority materials. When it comes to setting the target to reduce using primary materials, none of the countries planned to set such targets. However, reduction of energy use and improvement of energy efficiency targets are common targets. For individual sectors, material use reduction targets are rarely established. More and more government agencies on different levels are working on initiatives and setting targets to increase material resource efficiency, for example, energy use reduction in public sectors buildings, improving transportation sustainability, and reducing paper use.

5.2.2 Overview of Dutch resource efficiency

According to Eurostat (2016), The Netherlands is one of the few countries that showed a consistent reduction of domestic material consumption from 2000, 2007, to 2014 (see Fig 24-25). Transition toward a circular economy is the main focus for the Netherlands. A national policy for Green Growth (2013) is established by the Ministry of Economic Affairs. With elements to use market incentives in a smart way, a legislative framework promoting dynamism; innovation, and the government's involvement as a part of the network. Some initiatives aiming to use waste as resource were introduced to further the circular economy in The Netherlands. For example, a sector that shows promising results is chosen to carry out a pilot project for circular economy in order to learn from the transition process. On the consumer's end, a strategy is also proposed to engage consumers to contribute to resource efficiency. Waste policy to reduce the raw material consumption is set up to target green growth.

- Circular economy programme From Waste to Resource (2014)
- Research studies on materials critical for the Dutch economy
- Green Growth Policy in the Netherlands (2013)

Policy ambitions on material efficiency and sustainability

In 2011, the Dutch government issued a memorandum on raw material (grondstoffennotitie) that is consisted of three agendas to ensure the security and sustainability of supply; to impose restrictions on the demand and to enhance its sustainability if possible; improve the efficiency and sustainability of raw material use.

In 2012, The Dutch cabinet signed an agreement towards circular economy and to promote the reuse of scarce raw materials. The program of *From Waste to Resource* by Dutch Ministry of Infrastructure and the Environment (Rijkswaterstraat, 2014) shaped the measures to transition towards a more circular economy, taking into account the steps along the supply chain by sector. The programme gears the Dutch economy towards a circular economy by developing incentives, product design, promote resource free business, and develop a system that allows quantification with indicators and metrics. With the leading ministries of Infrastructure and the Environment, the Dutch government is currently developing a Government wide Programme on Circular Economy with ministries of Economic Affairs, Foreign Affairs, and Interior and Kingdom Relations. The Dutch Cabinet sets a goal of 75% separation for domestic waste by 2020, with less than 100 kg per capita annually, aiming at reducing material losses of 50% (EEA, 2016).

The Waste Management Plan (LAP3) that is currently under development is expected to be issued at the end of 2016. In addition to the full coverage of EU Waste Framework Directive (WFD), LAP3 is also set to be connected the circular economy programme, including developing a material plan with strategies to enhance resource efficiency.

Identify the priority materials and products

The impacts of raw material price volatility on the cost price on sectors are identified by TNO (2014). For transport, metal products, and electrical, electronic equipment are larger than the impacts on the end use products due to the level of copper content presents.

TNO (2015) conducted a research that identified copper as one the materials that has the highest material supply insecurity in the long term in the Dutch economy, along with Sb (antimony), Ge (germanium), In (indium), Ga (gallium), and other rare earth metals. In addition, copper is also one of the materials that have the top economic impacts in the Netherlands (TNO, 2015).

Underground power cables, wires, and pipes for the infrastructure are on the list of products that are subject to a value-chain approach. Stakeholder within the supply chain are engaged to seek for a common goal and to come to agreement on the approaches to achieve economic results while accomplishing a design for more durable products with better recyclability and less chances of ending up in the waste dump. The government agencies often function as a facilitator in these initiatives (TNO, 2015)

Public-private partnership

Although many regulatory instruments are in place today, according to EEA (2016), before introducing regulatory instruments, it is traditionally preferred for stakeholders to cooperate on a voluntary basis. These legal instruments on material resources efficiency include issuing a ban on landfilling recyclable/incinerable products; introducing laws for producer responsibility such as WEEE, packaging, EOL cars, etc. Besides the regulatory instruments, bettering the current regulations is an ongoing process within the Dutch ministry of Economic Affairs. The government agencies set up a taskforce to identify regulations that might prevent businesses from taking more circular practices. Work on the government side includes clarifying the rules and rule amendment to increase feasibilities.

Example of stakeholder partnership is the Realisation of Acceleration towards a Circular Economy (RACE) is a coalition of non-profit organizations and governmental agencies that carry out projects to accelerate achieving the goal of reaching circular economy by introducing designs, upscale the reuse of materials of high value, and to address the barriers towards the goal. This coalition is formed under the programme Nederland Circulair!

The "Nederland Circulair" programme, a collaboration between the Ministry of Infrastructure and the Environment, CSR Netherlands , Circle Economy , Green Business , ClickNL Design , Green Brain , Sustainable Finance Lab and RVO.nl, identified a list of value chains based on their economic, environmental impacts, taking into consideration their potential to preserve the values and transition (EEA, 2016). The list corresponds to the quantification results quite well, including the automotive and the maritime industry are both estimated to contribute to the in-use stock and demand in the City of Amsterdam.

Financial instruments that encourage organizations to invest in a more environmental friendly way are in place (e.g. Vamil, MIA), through which investors are rewarded with investing in sustainable technologies with resource efficiency standards. Also, individuals who invest in green investments might also be eligible for lower tax rates.

Infrastructure sector joining force: Fair Infra

Ambitie 2020 is a programme launched by the Dutch government to gather businesses to form a coalition to create a binding ambition on a national level towards a circular economy and inclusive economy. Under this umbrella programme, companies will be leading the initiatives while the

Dutch government serves as a contact point (MVO Nederland, 2014).

With the Ambitie 2020 as a starting point, a coalition was formed between seven leading infrastructure firms, Enexis, Alliander, ProRail, Stedin, Gasunie, TenneT (energy), and KPN. These companies signed a document named "Fair Infra Mission Statement", listing the ambitions to work together to reduce energy use and emission, increase the circularity of materials and network maintenance and management.

A platform called "Groene Netten" was launched to host the knowledge base for the partners of the infrastructure service providers (Groene Netten, 2016a). Besides setting a goal of reducing energy consumptions by 9.6 TWh/year jointly, the coalition will green the energy use to reduce CO_2 emissions. The companies will increase the use of renewable resources and recycled materials. Maximization of social impact of the collaboration is a goal between the infrastructure service providers.

Each of the infrastructure manager will carry out one or more iconic project on the innovation of circular materials, saving energy, or greening material use. The implemented projects will also function as supportive experience for upcoming policy changes. In addition to the publication of annual progress. The results from the projects are going to be shared among the coalition members to maximize the experience sharing. The iconic projects include: (1) circular cables, (2) circular track, (3) greening the energy, (4) Fair IT, (5) sharing assets.

Circular cable as iconic project under Groene Netten Platform

Together, the members of the Groene Netten own a significant amount of cables. The platform members initiated an iconic project to increase their circular purchase. The ambition of the Circular Cable icon project (Groene Netten, 2016b) is to reduce the network losses, increase the recyclability, and reuse the cables. The members cooperate to explore strategic procurement, and linking asset management. In addition, technical knowledge exchange on network losses reduction as well as cable redeployment are also initiated by the members. Alliander is one of the key partners on the commitment to reduce the use of freshly mined materials in cables and the research to increase recyclability.

The Groene Netten project found out that the cables in the Netherlands are by default made from primary material while there are examples made by secondary materials elsewhere (Roijackers, 2016). According to OSGP report (2016), besides the circular cables, the Groene Netten also initiated *The Fair Meter Projects* between Alliander and Stedin to retain the values of energy meters and to explores the possibilities of material reuse from end-of-life meters (e.g., the rail tracks.) (OSGP, 2016).

What about private policy?

Besides binding rules enforced by the governmental agencies, private companies also have internal rules that shape the behavior of stakeholders. For the case study product, power cables, Alliander enforces internal standards and also external code of conduct for its suppliers. The Supplier Code of Conduct provides a generic set of guidelines that the supply chain partners are expected to be in compliance with. Suppliers should commit to waste prevention with their best effort. In addition, Alliander also requires its suppliers to research the recycling alternatives and implement as possible. Finally, a reversed-cycle arrangement is also put in place, requiring the suppliers to accept the returned EOL products for responsible handling of materials.

Overall, the company currently recycles about 90% of its waste and has a circular grid management policy. Alliander sets a goal of achieving at least 40% of circular procurement for its technical materials and recycling all the materials it consumes so nothing goes to waste.

Despite it is not clear whether the close loop policy apply to Alliander's procurement for copper power cables, and the goals for waste management are not clearly defined in the supplier code of conduct, the company claims to request the information from suppliers regarding the origin and recyclability of the materials. In addition, raw material passport is used for offices in Duiven and Arnhem as an example of its closed loop material use.

The overall environment in the Netherlands seem to be moving towards the path for a more circular economy. From the public-private partnership to encourage ambitions for circular economy, to the company's internal rules and goals for recycle EOL materials, to some level it can be said that the awareness for companies are on the rise. However, how can the awareness for a circular economy be encouraged for companies to invest in urban mining activities? And what could incentivize companies for being more circular besides financial return?

Let the money speak: influence from financial institutions

Profundo (2015) conducted an analysis on Dutch financial institution's initiatives on urban mining. It was concluded that financial institution can influence companies' behaviours and they can stimulate urban mining activities by including the concepts of circular economy and material efficiency improvement for the banking and insurance sector to consider during the risk and credit assessment (Profundo, 2015). Furthermore, financial institutions can provide advice and create networks for relevant actors for urban mining (Profundo, 2015). Profundo (2015) suggested that besides engaging the companies in urban mining, transparency in investment and benchmarking how far off the current investment is from the institution's policy and how improvement can be made to be in line with the policy.

Besides financial incentives, companies that take the initiatives of urban mining could also benefit from the following aspects: greening the corporate image, value retention from putting the EOL product on to the market, and create frontrunner advantage in the market. Some of these benefits can be easily translated to monetary terms while some are more difficult to be monetized.

5.3 Towards 2050: Envision urban mining in action

This section explores a vision of urban mining in action for the case study selected for Part 2 of this study, power cables. As more and more grids being smartened up, a network of diversed components are expected to be deployed, meaning more copper-containing products are needed to be installed to power the society in a smart way. The urban mining activities for the power cables are not expected to be much different from today, considering the existing regulation already require the DSO to remove the underground power cables during grid replacement operations. Even if there are abandoned cabled left underground from old times before the law comes into force, it would still be mandatory for the DSO to register the exact location of the abandoned cables for future removal. In addition, it is known that the existing waste is being placed on the market for material recovery within The Netherlands, Germany, or Sweden. It is therefore not expected that the copper scrap for cables to have a leakage in its life cycle within these clearly defined practices. In other words, business as usual in this case might not be a derogative term in the case of power cables in Amsterdam.

CHAPTER 6 / DISCUSSIONS AND CONCLUSIONS

In this section, the main findings of this study are recollected and summarized to answer the Part 2 research questions. Conclusion and recommendations are made to address the possibilities to further the knowledge in urban mining based on this research.

6.1 Re-check the ambition for circular economy

While this study sets the focus on urban mining, it needs to be discussed under the framework of circular economy to allow ourselves for an evaluation of the events taking place with broader perspectives. The stock estimation in Part 1 shows that the urban mine for copper in Amsterdam is an artificial mine in the making. By 2050, the in-use copper will be 40% richer in weight comparing with today's (2016) level, growing from 240 to 307 kg/capita. As the quantity of the copper scrap discarded by the society still weighs less than the quantity needed every year to satisfy the urban development, the societal use of raw materials will continue to challenge the physical limits of the global copper reserve.

On the good note, the copper urban mine does not show endless expansion. The general trend shows that the overall amount of copper consumed by Amsterdam is going to gradually decrease passing 2020 while the amount of copper discarded every year slowly increases, implying an urban mine that is on its way to stabilization.

The sustainable agenda for Amsterdam asks the city to step up its effort to decarbonize the energy and transport system, which calls for a societal transition towards electric vehicles and renewable energy technologies. Producing solar and wind energy system uses 25 and 3 times more copper per kwh, respectively, comparing with coal-fired power plants. Building an electric vehicle costs four times more copper than a car running on gasoline. In addition, to power the transport system and connect the decentralized energy sources, the infrastructures will need to be built to accommodate the transition. To phase out the fossil fuel based power plants and vehicles, copper intensive technologies are employed, causing a growing appetite for copper to meet the policy goals. Of course, as a critical reminder, it shouldn't be ignored that fossil fuels are not reusable, and copper is a material that can theoretically be recycled infinitely.

This transition towards low carbon society shows that a closed material loop for copper cannot be achieved in terms of quantity unless the demand for copper can be lowered to close the inflow/outflow gap. As the role of copper becomes increasingly more important, this usage trend gives an indication to the possible scale of impacts that could be made. As a geologically copper-poor country, The Netherlands relies on a global market of copper to sustain the economy. The situation that some economies take advantages of economies lacking sound management, making socially, economically, and environmental unsustainable practices preconditions for global circular economy (Velis, 2015). While the City of Amsterdam achieves its 80-90% carbon reduction ambition in 2050, will the carbon footprint for primary and secondary copper production be exported to other countries? Top five countries for The Netherlands to export copper scrap to are Germany, China, Belgium, USA, and UK (CBS, 2006). Knowing possible discrepancies in environmental standards under different jurisdictions, will the copper scraps exported to other countries be properly handled before being made into new products? Are the tangible benefits such as improvement of air quality and economic prosperity of circular economy exclusively reserved for citizens within the boundary of Amsterdam? The sustainability agenda not only underpins a future of low carbon economy, it also challenged itself to answer to the reality check for the real cost that's embedded within the complex global copper supply chain.

Tacking the near term challenge on closing the material loop: what are the options?

As it can be seen that closing the material loop would not be feasible until after 2050, the near term challenges to close the material loop can be tackled with two strategies: (1) restrain the use of copper; (2) increasing the copper recovered from urban mining. Reducing the demand could be achieved with lower societal stock of products and/or lower copper content of product. To reduce the number of products means more sharing or less usage. It is less likely that less usage would be an option that would receive support. Finding ways for product users to share would be worth exploring as an alternative since successful business cases have been established. It is also possible for informal product sharing schemes to be coordinated, such as car-pooling.

The second option is to lower the copper content of the products. For this to happen, manufacturers would have to have enough motivation to change the design to substitute or reduce the copper level. This will require research capacity and change in production line, which means the investment needs to be worthwhile. It is possible to be triggered by either high material price or rising taxes.

The other aspect is to maximize the copper recovered from urban mining. While this treatment alone will not be able to close the gap between inflow and outflow, it is a well-recognized strategy for the waste prevention and value recovery. Closing the material loop would require both strategies to be adopted, however, it is questionable that the gap can be really closed with both strategies going full force.

6.2 Filling the knowledge gap

To pinpoint the knowledge needed to handle the transition towards the future envisioned in the current policy for copper urban mining initiatives. For the selected case study, as the current practices already demand the DSO to remove end-of-life cables by law, material extraction is already achieved since the spatial information of the copper power cables is available. Furthermore, the suppliers take the end-of-life products back for waste treatment or material recovery. Since the urban mining system seems to be in place, perhaps it is relevant for circular economy to look beyond urban mining and rewind to the life stage of power cable production.

Coming back to the life cycle stage before the power cables are deployed, the current research programs initiated by distribution system operator (Alliander), cable provider (Prysmian, etc.), and other infrastructure companies such as Enexos are looking into enhancing the circularity of their products and practices. This includes examining the environmental impact of materials and applying the circular economy concept to the design of power cables. The formula below shows how Alliander calculates the circularity of material. Circularity calculation asks information regarding the percentage of reused or recycled materials, the material recyclability in percentage, and the percentage of materials used out of the materials that are purchased (CE Delft, 2016). According to CE Delft (2016), the material origin of the assessed power cable is not known. To fill in the knowledge gap of how the product performs in terms of circularity, the DSO would need to look into the origins and properties of the raw materials used in the product. Furthermore, as discussed in the previous section, socially and environmentally responsible practices should be validated throughout the supply chain in order to be in-line with the circular economy ambition. (

$$\text{Circularity (\%)} = \frac{\text{recycled material used (\%)} + \text{material recyclability (\%)}}{2} \times \text{material use efficiency (\%)}$$

[Note: recycled mat used (%) is the percentage of recycled or reused material being used in the cables; material recyclability (%) is the percentage of material that is recyclable at the end of its service life; material use efficiency (%) is how much purchased material (by percentage) is eventually used]

6.3 Conclusions

The following conclusions are drawn from the findings from Part 1 and Part 2:

- **Growing urban mine**: Until 2050, Amsterdam is growing into an urban mine 40% richer than today. Per capita in-use stock grows from 240 kg Cu/capita in 2016 to 307 kg Cu/capita.
- **Policy-driven copper use**: The implementation of carbon policy is the main driving force for the introduction for copper-intensive products. The policy aiming at transformative renewable energy system and zero emission transportation system is expected to cause increase use of copper.

- **Shift of copper waste stream composition**: The power distribution system is the source of the largest copper waste stream in 2050. In 2016 the largest copper waste stream comes from residential buildings.
- **Stable copper waste level**: Annual copper waste discarded by the urban mine is remains quite stable through 2050.
- **Inflow larger than outflow**: The copper demand remains larger than the discarded copper until 2050, meaning that material cycle cannot be closed.
- **Narrowing gap between copper inflow and outflow**: From 2016 to 2050, the gap between the amount of discarded copper and the amount of copper demand becomes smaller.
- **Highest outflow growth in infrastructure and transport**: Infrastructure grows 70% in discarded copper while the transport grows 38%.
- **Highest in-use stock growth in infrastructure and transport**: The per capita copper in-use stock in infrastructure grows 65%, followed by transport with 20% growth.
- **Highest inflow growth in transport and infrastructure**: The per capita copper inflow in transport grows 23%, followed by infrastructure with 13% growth.
- **Even higher copper demand for grids to go smart**: Increasing smart grid connection calls for more copper-containing products. However, benefits of loss reduction and electricity use reduction by smart grid could be an opportunity to lower the load capacity and therefore copper demand.
- **Tapping into the urban mine:** The transition towards a renewable energy system and a low carbon transportation system invites Amsterdam to tap into these copper stock that is highly relevant to the inhabitants' lifestyles. Tapping into the urban mine would require dissemination of circular economy concept to citizens, companies, and knowledge institutions to bring actors together to facilitate cross-sector cooperation.
- **Urban mining power cable already in place**: As a standard practice, the grid operator Alliander in Amsterdam removes end-of-life power cables and puts the copper cables on the market for material recovery.

- **Opportunities**: Concepts of urban mining and circular economy are getting noticed in Amsterdam and there are already some recycling, reuse scheme, and second hand trading market in place. The transition towards renewable energy system and electromobility need complementary urban mining capacities to handle the outflow of copper after the service life of the products and infrastructure.

- **Corporate initiatives**: Financial institutions can encourage investment in urban mining by adding material efficiency and circular economy concept in the their policies. Connecting relevant actors and giving advice to companies in urban mining activities can also facilitate the awareness in urban mining.

- **Lack of life cycle information to build a circular economy for power cables**: Information about secondary material use (%) in products and EOL treatment missing. Circular initiatives from companies are being introduced to fill the knowledge gap.

6.4 Recommendations

Recommendations for urban mining actors

Municipality: Results from this study provide a basis to identify the largest potential source for urban copper mine in Amsterdam towards 2050. Through the efforts of the copper stock quantification with bottom-up method, the material implication of the renewable energy ambition set by the sustainable agenda is found to be on the rise. The rising demand might be translated into various social and environmental impacts across the globe and beyond the border of Amsterdam. As a part of the follow-up efforts to evaluate how this development might mean for a circular economy, some foresight work should be done to assess if the consequences are aligned with the ambition.

The public sector should stimulate the development of innovative businesses in the recycling technology and sharing to handle the product streams that are expected to be introduced in the economy on a large scale. Funds should be made available to foster the technical and business feasibility to kick off the initiatives. Investments need to be encouraged to go towards the innovative technologies/business owners that can close the material loop.

Infrastructure sector: R&D work is needed to further the knowledge on bringing down the copper demand for smart grid development along the supply chain for the wide spectrum of components needed to smarten the grid. For grid operators, information disclosure and greater transparency in operations should be more open to the public. The material use could be studied on the pilot smart grid neighborhood in order to provide a more solid ground for the material implications on a national level for copper with wide smart grid coverage.

Waste sector: The results generated by this study can also be used to target the product waste streams expected to be discarded based on their lifespan to plan for material recovery. In order to foster an environment that favors systematic use of anthropogenic copper from urban mining, cross-sector cooperation is needed among manufacturers, waste sector, and the infrastructure sector.

Future studies

(1) According to World Bank (2016), about 85% of world population have access to electricity. For places that do not have a complete coverage of electricity grid, emerging technologies such as DC grid could show great potential of material use reduction while delivering renewable energy to households. Life cycle assessment for DC could offer more quantified evidence of material demand for a sophisticated estimation on energy demand.

(2) For countries that already have good electrification coverage, many challenges might be the decision for systematic shift for DC grid. Whether material intensity could be a deciding factor for the shift of the system can only be understood with the copper intensity for DC grid.

(3) This study explores different categories of copper-containing products and the results provide an idea of the scales of urban mining sources. However, evaluating the feasibility of mining these waste streams will require further characterization of the urban mine such as interviewing and ground level truth finding by sample collecting.

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APPENDIX 1: Data and Assumptions

1. BUILDING

1.1 Residential buildings

Table A1. Residential housing copper content

Copper in household dwellings			
Building type	Copper content	Country	Source
family house	195 kg/unit	Australia	(van Beers and Graedel, 2006)
shared living complex	110 kg/unit	Australia	(van Beers and Graedel, 2006)
unspecified type	152.5 kg/unit	Australia	Average of family and shared living complex
unspecified type	80 kg/c	Switzerland	(Wittmer & Lichtensteiger, 2007)
unspecified type	60 kg/c	Stockholm	(Wittmer & Lichtensteiger, 2007)
unspecified type	70 kg/c	-	Average of Switzerland and Stockholm
Lifespan	25 years	Germany	(Schimschar et al. 2011)
Renovation/newly built	2	Netherlands	(Meijer et al., 2009)

Table A2. Residential housing development based on Dashboard Housing Plan (City of Amsterdam, 2016)

Year	- to build (1- House)	- to build (2- apartment)	- to build (3-uncertain)	- to build (Total)	- to demolish
2014	376	2,926	0	3,302	913
2015	481	3,949	0	4,430	1,249
2016	879	5,236	0	6,115	381
2017	1,121	9,874	0	10,995	1,090
2018	507	5,721	479	6,707	843
2019	423	7,387	1,137	8,947	1,107
2020	47	6,845	2,345	9,237	942
2021	136	2,039	1,113	3,288	678
2022	159	1,965	5,732	7,856	943
2023	0	1,746	3,918	5,664	1,522
2024	0	404	2,617	3,021	124
2025	0	370	1,940	2,310	120
2026	0	330	1,800	2,130	100
2027	0	290	1,700	1,990	110
2028	0	250	1,600	1,850	100
2029	0	220	1,500	1,720	90
2030	0	200	1,400	1,600	80
2031	0	180	1,300	1,480	70
2032	0	160	1,200	1,360	60
2033	0	150	1,100	1,250	50
2034	0	140	1,000	1,140	52
2035	0	120	900	1,020	40
2036	0	105	800	905	40
2037	0	100	700	800	40
2038	0	100	600	700	40

Assumptions

[1] Assuming the renovation/newly built ratio is 2 in Amsterdam (Meijer et al., 2009)
[2] Housing stock from 2039-2050: Using the population growth divided by the household person as the increase house stock
[3] Housing stock from 2035, 2030, 2020, 2015, 2014, 2007-2011 are from CBS. 2012-2013, 2016-2019, and 2021-2029 are calculated by interpolation.
[4] Housing stock from 2025-2038 are calculated by the housing stock 2012 (CBS) and the housing plan of building development and demolitions.1.2 Service buildings
[5] The annual demolitions of residential buildings from 2039-2050 are taken from the annual average of existing demolition plans from 2014-2038. (This might be an over-estimation for demolitions since demolition is unlikely to take place without the need to build new houses. As long as the houses are livable, it is likely to continue as it is without renewal of stock).

1.2 Service buildings

Table A3. Residential housing copper content

Development Plan				
Timeline	Area		Location	Source
2015 completed	32500	m^2	Zuid	(Hello Zuidas Foundation, 2016)
2016 under construction	155000	m^2	Zuid	(Hello Zuidas Foundation, 2016)
2016 start to build	85000	m^2	Zuid	(Hello Zuidas Foundation, 2016)
To develop - service	700000	m^2	Zuid	(Hello Zuidas Foundation, 2016)
To develop - service	45 000	m^2	NDSM	(Circular Buiksloterham)
To develop - service	200000	m^2	Buiksloterham	(Circular Buiksloterham)
2016-2022 for hotels	37000	m^2	Overhoek	(City of Amsterdam, 2014)
By 2020	421700	m^2	Amsterdam	(City of Amsterdam, 2014)
After 2020	529600	m^2	Amsterdam	(City of Amsterdam, 2014)

Copper in service buildings			
Building type	Copper content	Country	Source
Unspecified	0.5 kg/m^3	Germany	Kleemann et al., 2016

Table A4. Building copper content

Assumptions

[1] The development plan follows current vision of the area published by the municipality, development foundations, and consultants
[2] The lifetime of the copper content in buildings are assumed to be the same as the electric wires (Schimschar et al. 2011)
[3] Office area in 2015 is 7322000 m2, adopted from OIS Amsterdam (2016) http://www.ois.amsterdam.nl/
[4] Assumes the electricity generation remains the same throughout the lifecycle

Sources:

- Metabolic. (2014). Circular Buiksloterham
- Schimschar et al. (2011). Panorama of the European non-residential construction sector. ECOFYS.
- City of Amsterdam. 2014. Zoning rule of Overhoek, City of Amsterdam http://ftp.ruimtelijkeplannen.amsterdam.nl/DRO/plannen/NL.IMRO.0363.N1501BPGST-/NL.IMRO.0363.N1501BPGST-OW01/t_NL.IMRO.0363.N1501BPGST-OW01.html
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2. INFRASTRUCTURE

2.1 Electricity generation

2.1.1 Solar Energy

Table A2. Residential housing development based on Dashboard Housing Plan (City of Amsterdam, 2016)

Copper in solar panels			
Parameter	Value	Unit	Source
Copper content	4	tonne/MW	(Copper Alliance, 2012)
Lifetime	30	years	(Díaz, 2014; NREL, 2012)

Table A3. Solar energy implementation plan

Solar Energy Goal (City of Amsterdam, 2015)		
Year	Capacity	Unit
2013	9	MW
2014	11	MW
2015	13	MW
2016	25*	MW
2018	75*	MW
2020	160*	MW
2040	1,000*	MW

* ambitions in the current policy plan

Assumptions:

[1] Based on current technology of panels of 250 Wp per panel and 1900 kWh consumption / Amsterdam (City of Amsterdam, 2015).

[2] The policy ambition and past generation capacity is adopted from Schaalsprong Sun, Implementation Programme 2016 - 2018 (City of Amsterdam, 2015)

[3] The solar energy is obtained by a formula derived by the existing capacity in 2013-2015 and the target capacity in 2016, 2018, 2020, and 2040. The

generation capacities for the years in between that fit into the equation are interpolated.

[4] Assumes the electricity generation remains the same throughout the lifecycle

Source:

- Copper Alliance. (2012).Copper: powering an energy efficient, low carbon Europe. from: http://copperalliance.eu/docs/default-source/resources/summer-2012---european-copper-institute-news.pdf?sfvrsn=0
- City of Amsterdam. (2015). SouSchaalsprong Sun, Implementation Programme 2016 - 2018 https://www.amsterdam.nl/publish/pages/765329/schaalsprong_zon.pdf
- Díaz, A.C. (2014). Energy Life Cycle Assessment (LCA) of silicon-based photovoltaic technologies and the influence of where it is manufactured and installed. Master's Thesis. University of Barcelona.
- NREL. (2012). Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics.

2.1.2 Wind Energy

Table A4. Data for wind energy

Copper in solar panels			
Parameter	Value	Unit	Source
Copper content	3	tonne/MW	(USGS, 2011)
Lifetime	25	years	(USGS, 2011)

Table A5. Solar energy implementation plan

Wind Energy Goal (City of Amsterdam, 2015; City of Amsterdam, 2016)		
Year	Capacity	Unit
2015	67*	MW
2016	25*	MW
2020	85*	MW
2025	250*	MW
2040	400*	MW

* Ambitions in the current policy plan Sustainable Agenda

Assumptions:

[1] Assuming linear growth between 2015-2020, 2020-2025, 2025-2040, growth is evenly spread out.

[2] From 2040-2050, assuming wind power capacity growth continues at 10 MW annually as in 2025 - 2040

[3] Wind turbine lifetime is 20-30 years. An average of 25 years is assumed here.

[4] Based on the assumption in page 12 of USGS study (2011). The wind turbine generates 3 MW of electricity. The generation system include a mix of technologies, include rotor blades, steel-concrete towers, etc, that could use composite materials. The technology also assumes 80% double-fed induction generator with 20% permanent magnet.

[5] Assumes the electricity generation remains the same throughout the lifecycle

Source:

- City of Amsterdam. (2015). Sustainable Agenda
- City of Amsterdam. (2016). Wind power in Amsterdam. from: https://www.amsterdam.nl/gemeente/volg-beleid/agenda-duurzaamheid/windenergie/
- USGS. (2011). Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030. from: http://pubs.usgs.gov/sir/2011/5036/sir2011-5036.pdf

2.1.3 Biomass

Table A6. Data for biomass

Copper in solar panels			
Parameter	Value	Unit	Source
Copper content	0.028	g/kWh	(Frischknecht et al., 2005)
	0.0278	kg/MWh	-
Lifetime	25	years	(BPA, 2016)

Assumptions:

[1] Assuming 10 MW output in electricity (current maximum capacity), the annual electricity generation in BPA is 87600 MWh.

[2] Assuming Amsterdam Biomass Power Plant (BPA) is the only biomass power generation plant. http://www.akef.nl/en/folio/biomass-power-plant-amsterdam/

[3] Assumes that BPA starts its electricity generation in 2016 and ends in 2041 with the current lifetime assumption.

[4] Assumes the electricity generation remains the same throughout the lifecycle

Source:

- BPA. (2016). Biomass Power Plant Amsterdam. from: http://www.akef.nl/en/folio/biomass-power-plant-amsterdam/
- Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2005). The ecoinvent database: Overview and methodological framework, *International Journal of Life Cycle Assessment* 10, 3–9.

2.1.4 Coal

Table A7. Data for coal-fired power plant

Copper in solar panels			
Parameter	Value	Unit	Source
Copper content	0.021	g/kWh	(Frischknecht et al., 2005)
Lifetime	40*	years	(SEO, 2016)

*In operation since 1994.

Assumptions:

[1] Assumes 650 MW output in electricity (current maximum capacity), the annual electricity generation in Hemweg 8 is 5694000 MWh.
[2] Hemweg 8 started operation in 1994. Assumes it ends the service in 2034 as adopted from report of SEO (2016).
[3] Assumes the electricity generation remains the same throughout the lifecycle.
[4] In 2043, the copper in the power generation system becomes scrap when the service ceases.

Source:

- Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2005). The ecoinvent database: Overview and methodological framework, *International Journal of Life Cycle Assessment* 10, 3–9.
- SEO. (2016). Sluiting kolencentrales. from: https://www.natuurenmilieu.nl/wp-content/uploads/2016/04/2016-18-Sluiting-kolencentrales.pdf

2.1.5 Gas

Table A8. Data for gas power plant

Copper in solar panels			
Parameter	Value	Unit	Source
Copper content	0.007	g/kWh	(Frischknecht et al., 2005)
Lifetime	30	years	(Siemens, 2006)

Assumptions:

[1] Assumes 440 MW output in electricity (current maximum capacity), the annual electricity generation in Hemweg 9 is 3854400 MWh. (Hemweg 9, 2016)
[2] Assumes the electricity generation remains the same throughout the lifecycle
[3] Hemweg 9 in operation until 2042 according to Siemen's product guides with 30 years of lifetime. In 2042, the copper in the power generation system becomes scrap.

Source:

- Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2005). The ecoinvent database: Overview and methodological framework, *International Journal of Life Cycle Assessment* 10, 3–9.
- Hemweg 9. http://powerplants.vattenfall.com/hemweg-9
- Siemens. (2006). Lifetime Extension for SIEMENS Gas Turbines. from: http://www.energy.siemens.com/co/pool/hq/energy-topics/pdfs/en/gas-turbines-power-plants/5_Lifetime_Extension_for_Siemens.pdf

2.1.6 Waste to energy

Table A9. Data for waste to energy

Waste to energy			
Parameter	Value	Unit	Source

Copper content	0.028	g/kWh	(Frischknecht et al., 2005)
Annual electricity generation	1,000,000	MWh	(AEB, 2015)
Electricity generation capacity	114	MW	(AEB, 2015)
Lifetime	25	years	(BPA, 2016)

Assumptions:

[1] Assumes AEB waste to energy system has same copper content and lifetime as biomass power generation

[2] Assumes AEB waste to energy plant continue to receive same amount of waste from the city of Amsterdam, neighboring region, and from abroad as fuel.

[3] Assumes the electricity generation remains the same throughout the lifecycle

Source:

- AEB Corporate Brochure. AEB, 2015. from: http://www.aebamsterdam.com/media/1552/aeb-corporatebrochure-en-screen.pdf
- BPA. (2016). Biomass Power Plant Amsterdam. from: http://www.akef.nl/en/folio/biomass-power-plant-amsterdam/
- Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2005). The ecoinvent database: Overview and methodological framework, *International Journal of Life Cycle Assessment* 10, 3–9.

2.2 Electricity distribution

Table A10. Data for power distribution system

Copper in power distribution system			
Parameter	Value	Unit	Source
Copper content	48,000	kg/MW	(Zhang, 2011)
Lifetime	40	years	(Wang and Graedel, 2009

Table A11. Data for distribution capacity

Electricity distribution capacity in 2016		
Power source	Capacity	Source
Biomass	10 MW	(BPA, 2016)
Coal-fire	650 MW	(Hemweg 8, 2016)
Gas	440 MW	(Hemweg 9, 2016)
AEB	114 MW	(AEB, 2015)
Wind power	67 MW	(City of Amsterdam, 2015)
Solar power	13 MW	(City of Amsterdam, 2015)
Total	1294 MW	

Assumptions:

[1] 2015-2033, and 2050, the distribution capacity is the combination of all the electricity generation at its maximum because grid system is designed to handle the maximum electricity generation load.

[2] Between 2034 and 2049, the distribution load is assumed to be evenly distributed.

[3] 2034-2049, due to the closure of the coal-fired power plant Hemweg 8, the distribution capacity goes down, which does not fit into reality. The distribution infrastructure is estimated to remain in place. Therefore, the distribution capacity is assumed to be growing until it reaches the projected 2050 capacity.

Source:

- AEB Corporate Brochure. AEB, 2015. from: http://www.aebamsterdam.com/media/1552/aeb-corporatebrochure-en-screen.pdf
- BPA. (2016). Biomass Power Plant Amsterdam. from: http://www.akef.nl/en/folio/biomass-power-plant-amsterdam/
- City of Amsterdam. (2015). Sustainable Agenda
- Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2005). The ecoinvent database: Overview and methodological framework, *International Journal of Life Cycle Assessment* 10, 3–9.
- Hemweg 8. (2016). http://powerplants.vattenfall.com/hemweg-8
- Hemweg 9. (2016). Hemweg 9. http://powerplants.vattenfall.com/hemweg-9

2.3 Water Infrastructure

2.3.1 Water pipes

Table A12. Data for water pipes

Copper in water pipes			
Parameter	Value	Unit	Source
% of copper	6.71%	%	(Waternet, 2016)
pipe weight	2.2	kg/m	(Hamel Metaal, 2007)
total pipe length	2,800	km	(Waternet, 2016)
lifetime	35	years	(Schimschar et al., 2011)

Assumptions:

[1] For 2015, the current length of pipelines and the pipe dimensions are used to calculate the total copper stock.

[2] For 2016-2050, assuming the copper stock/capita in water pipeline is the same. Use that as a basis to extrapolate copper in-use stock in relation with the population development.

Source:

- Hamel Metaal. (2007). from: http://www.hamel.nl/Files/File/Assortiment%20pdf/WEB_KOPER.pdf
- Schimschar et al. (2011). Panorama of the European non-residential construction sector. ECOFYS.

- Waternet. (2016). Personal communication through Elena Hooijschuur with Waternet.

2.3.2 Service connection

Table A13. Data for service connection

Copper in service connection			
Parameter	Value	Unit	Source
Length (22 mm)	105	km	(Waternet, 2016)
Length (28 mm)	36	km	(Waternet, 2016)
Unit weight (22 mm)	0.64	kg/m	(Hamel Metaal, 2007)
Unit weight (28 mm)	0.9	kg/m	(Schimschar et al., 2011)
Lifetime	35	years	(Schimschar et al. 2011)

Assumptions:

[1] For 2015, the current length of pipelines and the pipe dimensions are used to calculate the total copper stock.

[2] For 2016-2050, assuming the copper stock/capita in water pipeline is the same. Use that as a basis to extrapolate copper in-use stock in relation with the population development.

Source:

- Hamel Metaal. (2007). from: http://www.hamel.nl/Files/File/Assortiment%20pdf/WEB_KOPER.pdf
- Schimschar et al. (2011). Panorama of the European non-residential construction sector. ECOFYS.
- Waternet. (2016). Personal communication through Elena Hooijschuur with Waternet.

2.4 Public lighting

2.4.1 Traffic light

Table A14. Data for traffic light

Copper in traffic light			
Parameter	Value	Unit	Source
Lifespan	25	25	(Wang and Graedel, 2010)
Height of traffic light	5	5	(Zhang et al., 2012)
Core wire area	0.75	0.75	(Zhang et al., 2012)
Total lamps	21,480	21480	(City of Amsterdam, 2016a)
Total lights	7,160	7160	(City of Amsterdam, 2016a)
Cores/light	4	4	(Zhang et al., 2012)
Average distance between lights	400	400	(City of Amsterdam, 2016b)
Copper density	8,900	8900	–

Assumptions:

[1] From the map, the new housing plan until 2025 have good traffic light coverage. Therefore it is assumed that extra traffic light needed to be installed in the future is limited.

[2] The average distance between lights are measured from the Historic Map of traffic lights (City of Amsterdam, 2016)

Source:

- City of Amsterdam. (2016a). Traffic light: from: https://www.amsterdam.nl/parkeren-verkeer/infrastructuur/verkeerslichten/uitleg_over/
- City of Amsterdam. (2016b) .Historic Map of traffic lights. from: http://maps.amsterdam.nl/verkeerslichten/?LANG=zh
- Wang, J., & Graedel, T. (2010). Aluminum in-use stocks in China: a bottom-up study. *Journal of Material Cycles and Waste Management*, 12(1), 66–82. http://doi.org/10.1007/s10163-009-0271-3
- Zhang, L., Yuan, Z., & Bi, J. (2012). Estimation of Copper In-use Stocks in Nanjing, China. *Journal of Industrial Ecology*, 16(2), 191–202. http://doi.org/10.1111/j.1530-9290.2011.00406.x

2.4.2 Street light

Table A15. Data for street light

Copper in street light			
Parameter	Value	Unit	Source
Lifespan	25	years	(Wang and Graedel, 2010)
Height	9	m	(Zhang et al., 2012)
Core wire area	16	mm2	(Zhang et al., 2012)
Total lights (2012)	126,000	units	(DIVV, 2013)
Cores/light	3	units	(Zhang et al., 2012)
Average distance between lights	35	m	(Zhang et al., 2012)
Copper density	8,900	kg/m3	–
Total length of cables (2013)	470	km	(DIVV, 2013)
Copper in street light	4	kg/unit	-
Copper in cables	142	kg/km	-
Annual cable length increase	15	km	(DIVV, 2013)

Assumptions:

[1] The copper content in each unit of street light is calculate by the height x core wire area x cores per light x the average distance between street lights x density of copper.

[2] Total lighting fixture in Amsterdam from 2005-2015 planning was used for the total lighting fixture unit value (City of Amsterdam, 2007)

[3] The annual stock increase of lighting fixture is obtained from the total lighting fixture from 2013 minus the lighting fixture in 2012. The annual lighting units stock increase is assumed to be 7500 from 2013 to 2020. From 2020 to 2030, it is assumed to increase 3000 annually. From 2030-2040, it is assumed to be 2000. From 2040 to 2050, it is assume to be 1000.

[4] The annual cable length increase is calculated from the cable length in 2013 (470 km) and the cable length in 2012 (455 km). The annual increase is applied until 2050.

[5] The calculation method is adopted from Zhang et al.,2012

Source:

- City of Amsterdam. (2007). Lighting fixtures: Beleidsplan openbare verlichting 2005 – 2015
- DIVV. (2012). Gemeente Amsterdam, Dienst Infrastructuur Verkeer en Vervoer. Jaarverslag 2012
- DIVV. (2013). Gemeente Amsterdam, Dienst Infrastructuur Verkeer en Vervoer. Jaarverslag 2013
- Wang, J., & Graedel, T. (2010). Aluminum in-use stocks in China: a bottom-up study. *Journal of Material Cycles and Waste Management*, 12(1), 66–82. http://doi.org/10.1007/s10163-009-0271-3
- Zhang, L., Yuan, Z., & Bi, J. (2012). Estimation of Copper In-use Stocks in Nanjing, China. *Journal of Industrial Ecology*, 16(2), 191–202. http://doi.org/10.1111/j.1530-9290.2011.00406.x

2.5 Telecommunication

Table A16. Data for telecommunication

Copper in power distribution system			
Parameter	Value	Unit	Source
Wire length	30	meter/household	(Zhang, 2012)
# of wires	4	unit/household	(Zhang, 2012)
Thickness	0.13	mm^2	(Zhang, 2012)
Copper density	8,900	kg/m^3	-
Lifetime	15	years	(Schimschar et al. 2011)

Assumptions:

[1] Copper content of telecommunication is estimated by calculating the total volume of the copper wire (length times the cross section area) times the density of copper. Copper for telecommunication wires is about 140 grams/household.

[2] Data and telephone cable lifetime ranges from 10-15 years (Schimschar et al. 2011)

[3] Thickness is assumed to be the same as in Zhang 2011, 0.13 mm2. This same study assumes 30 m cable per household and 4 wires.

Source:

- Schimschar et al. (2011). Panorama of the European non-residential construction sector. ECOFYS

- Zhang, L., Yuan, Z., & Bi, J. (2012). Estimation of Copper In-use Stocks in Nanjing, China. *Journal of Industrial Ecology*, 16(2), 191–202. http://doi.org/10.1111/j.1530-9290.2011.00406.x

2.6 Rail system

Table A17. Data for rail system

Copper in rail system			
Parameter	Value	Unit	Source
Rail length	238	km	Personal communication, 2016
Copper content of overhead contact line	1.79	ton/km	(TNO, 2014)
Lifetime	15	years	(Schimschar et al. 2011)

Assumptions:

[4] The length of railway is obtained through personal communication with NS staff through PUMA project colleague on Apr 14, 2016.

[5] The copper stock is calculated by multiplying the length of the railway to the copper content per kilometer.

[6] Lifetime of the railway contact line is assumed to be the same as the telecommunication line from Schimschar et al. 2011.

Source:

- Personal communication through Sidney Niccolson. (2016)
- Schimschar et al. (2011). Panorama of the European non-residential construction sector. ECOFYS
- TNO (2014). White paper ‘Circulair Spoor’: Visie op de circulaire economie voor de spoorsector.

2.7 Electric vehicle charging station

Table A18. Data for ev charging station

Copper in ev charging stations			
Parameter	Value	Unit	Source
Copper content	0.94	kg/unit	(Johansen, 2013)
Lifetime	30	years	(Engholm et al., 2013)

Table A19. Electric vehicles charging station plan

EV charging stations		
Year	Units	Source
2015	1,321	(City of Amsterdam, 2016)
2016	2,500	(City of Amsterdam, 2015)
2017	3,250	(City of Amsterdam, 2015)
2018	4,000	(City of Amsterdam, 2015)

Table A20. Electric vehicles charging station plan

Charging station service capacity - car/station-day		
	Unit	Source
Fuel economy	24 kwh/100 km	(IEA, 2013)
Travel	11,500 km/year-cap	(CBS, 2015)
Electricity consumption	2,760* kwh/year	
Charging station power	11 kw	(City of Amsterdam, 2016)
Charging time	251* hours/year	
Charging time	2* Hours/charge	
Charging frequency	115* times/year	
Charging frequency - Equivalent	0.3* times/day	
Service capacity	11* cars service/station-d	

*estimated values

Assumptions:

[1] Assuming fuel economy is 24 kwh/100 km, annual travel distance by car is 11500 km as the Dutch average (CBS, 2015), annual electricity consumption can be calculated by the fuel economy times total travel distance.

[2] Annual electricity consumption divided by the charging capacity is the charging hours needed to make the annual travel distance. The charging capacity of the charging station is 11kw (City of Amsterdam, 2016).

[3] Assuming every charge can last 100 km, the hours needed per charge can be calculated by dividing the fuel economy 24 kwh/100km by charging capacity 11 kw. It takes about 2 hours to complete one charge.

[4] Dividing the annual charging hours needed by the time needed for one charge, the charging frequency can be obtained.

[5] Assumes the charging station stays as busy as it can be throughout the day, the number of cars that one charging station can serve in one day is obtained by dividing 24 hours by the time needed for one charge.

Source:

- CBS. (2015). Transport and mobility 2015. http://download.cbs.nl/pdf/2015-transport-and-mobility.pdf
- City of Amsterdam. (2016). Requesting Static and Dynamic Chargepoint information at Essent. from: http://data.amsterdam.nl/dataset/oplaadpunten-elektrisch-vervoer/resource/77689dc4-706f-4d4f-baa6-6c82b23e3fc7#
- Engholm, A., Johansson, G., Persson, A. Å. (2013). Life Cycle Assessment of Solelia Greentech's Photovoltaic Based Charging Station for Electric Vehicles.
- IEA. (2013). Global EV outlook.
- Johansen , J.S. (2013). Fast-Charging Electric Vehicles using AC. Master's Thesis. Technical University of Denmark

3. TRANSPORT

3.1 Car

Assumptions:

[1] All new cars are assumed to be electric or hybrid by 2025 according to policy
[2] Car ownership is assumed to remain constant until 2050.
[3] In 2040, all conventional cars are assumed to be phased out by policy
[4] City of Amsterdam wants 20000 electric vehicles on the road by 2020.
[5] City of Amsterdam wants 200,000 electric vehicles on the road by 2040
[6] Assume in 2050, all cars are fully electric
[7] Assume the share % of full electric cars in the city of Amsterdam equals to the share of FEVs in the Netherlands in 2016
[8] In 2015, there are 350 fully electric vehicles for public service (Car2GO) (City of Amsterdam, 2015)
[9] The number of FEV plus hybrid is 20752 in Amsterdam, according to Charging Data Amsterdam Electric (2015) http://www.iamsterdam.com/en/media-
[10] Assuming the per capita ownership of vehicles remains the same (0.28 cars/capita) from now until 2050.

3.1.1 Conventional car

Table A21. Data for cars

Copper in cars			
Year	Units	Unit	Source
Copper content	15	kg/unit	(Riotinto, 2013)
Lifetime	18	years	(WBCSD, 2004)

3.1.2 Hybrid car

Table A22. Data for hybrid cars

Copper in hybrid cars			
Year	Units	Unit	Source
Copper content	35	kg/unit	(Riotinto, 2013)
Lifetime	18	years	(WBCSD, 2004)

Table A23. Share of fully electric vehicles and hybrid vehicles in the Netherlands

Share of vehicle type	
Type	(%)
Hybrid	95.30%
Full EV	4.70%

3.1.3 Electric car

Table A24. Data for electric cars

Copper in hybrid cars			
Year	Units	Unit	Source
Copper content	60	kg/unit	(Riotinto, 2013)
Lifetime	18	years	(WBCSD, 2004)

Table A25. Policy goals addressed in Amsterdam electric

Amsterdam Electric (2009)
• 2009-2011: 200 electric vehicles in Amsterdam
• 2012-2015: 10,000 vehicles, or 5% emission-free transport
• 2015-2020: 40,000 vehicles or 20% emission-free transport
• 2020-2040: 200,000 vehicles or 100% emission-free transport

Source:

- City of Amsterdam. (2009). Amsterdam Electric.
- Riotinto. (2013). Riotinto Copper: solving society's challenges. from: http://m2m.riotinto.com/issue/3/article/copper-solving-societys-challenges
- WBCSD. (2004). IEA/SMP Transport Model. IEA/SMP Transport Spreadsheet Model

3.2 Railcar

Table A26. Data for rail cars

Rail car copper content		
Type	Copper content (%)	Source
Metro	3%	(Siemens, 2006)
Heavy rail vehicle	2.50%	(European Commission's DG Climate Action, 2012)

Table A27. Data for rail cars

vehilces	Weight (tonne)	Stock (No.)	Copper/unit (tonne)	Source	Average (tonnes)
Metro	48	62	1.4	(GVB, 2016)	3
	190	28	5.7	(GVB, 2016)	
GVB Tram - Cambino	34	151	1.0	(GVB, 2016)	
11G/12G Tram	37.5	44	1.1	(GVB, 2016)	1
10G/11G	31	16	0.9	(GVB, 2016)	

Assumptions:

[1] Only trams and metro are taken into account because trains are national.

[2] The city is promoting night economy and plans to run 24 hour metro by 2017. Plus metro line will expand to connect north and south, and grow extension of current lines. Metro cars in 2050 are assumed to be 150.

[3] To support night economy, trams also run at night time and will grow by 2 per year.

[4] Stock increase based on: 1) night economy growth 2) densification of urban functions 3) more use of public transportation and less cars 4) connecting AMS and metropolitan area

[5] Metro: Assume the ratio of 48 tonnes and 190 tonnes metro cars are 2:1 until 2050.

[6] Calculated average tram copper content is 1 ton/tram in 2015. Same applied until 2050.

Source

- European Commission's DG Climate Action. (2012). from: http://www.eutransportghg2050.eu/cms/assets/Uploads/Meeting-Documents/Routes-to-2050-II-Task-2-Focus-Group-04-05-11-FINAL.pdf
- GVB. (2016). Tram. from: http://www.gvb.nl/feiten-en-cijfers/tram
- Metronieuws. (2013). GVB wants that driving at night in 2017 metro. from: http://www.metronieuws.nl/binnenland/2013/11/gvb-wil-dat-in-2017-metro-ook-s-nachts-rijdt
- Siemens. (2006). Life cycle analysis of the energy consumption of a rail vehicle. from: https://www.allianz-pro-schiene.de/wp-content/uploads/2015/10/praesentation-stribersky.pdf

3.3 Vessel

Assumptions:

[1] There are five types of vessels that were researched: sea cruise, river cruise, cargo, leisure boat, and canal cruise. Sea cruise and river cruise are not taken into consideration here after investigating the cruise line headquarters' location. It is assumed that the handling of the materials of vessels follows the ownership of the vessels.

[2] After checking through the list and schedules of the sea cruises and the river cruises at the port of Amsterdam and the passenger terminal, it was found that none of the cruise companies are located in Amsterdam. Therefore it is assumed that the material stock does not belong to the urban system of Amsterdam.

Table A28. Boat weight (CASTOLDI, 2016)

Boat	Weight (tonnes)	Type	Copper content (tonnes)
15 m ferry	11	Canal Cruise	0.11
24 m ferry	30	Canal Cruise	0.30
8.24 m Riva Iseo	4	Leisure boat	0.04

Table A29. Data for vessels

	Value	Unit	Source
Copper content (%)	1%	%	(Ruhrberg, 2006)
Lifespan (years)	28	years	(Assumption)

Table A30. Vessel copper content (%)

	Copper content (kg)	Total number	Source
Sea Cruise	735,735	137	(Port of Amsterdam, 2013)
River Cruise	50,000	1,483	(Port of Amsterdam, 2013)
Cargo	77,076	5,205	(Port of Amsterdam, 2013)
Canal Cruise	250	250	(NSRP, 2013)
Leisure Boat(<12m)	37	14,000	(NSRP, 2013)

Table A31. Cruiseline that stop at Amsterdam (Passenger Terminal Amsterdam, 2016; RiverCruise Schedule, 2016)

SEA CRUISE		RIVER CRUISE	
Cruise lines	Countries	Cruiselines	Countries
Holland America Line	USA	Holland America Line	USA
costacruise	Italian	Viking River Cruises	USA
celebritycruises	Malta and Ecuador	Vantage Deluxe World Travel	USA
Pheonix	AZ	Uniworld Cruise	USA
Seabourn	USA	Tauck Cruise	USA
polarcruises	USA	Grand Circle Cruise Line	USA
tuicruises	Germany	Emerald Waterways	Australia
Royal Caribbean International	USA	Avalon Waterways	USA
Residences at Sea	USA	AmaWaterways	USA
quarkexpeditions	USA	Rijfers River Cruises B.V.	Arhnem, NL
cruiseandmaritime	UK	A-ROSA Cruises	USA
silversea	Monaco	Rhine River Cruises	Germany
Crystal Cruises	USA	CroisiEurope	Belgium
Azamara Club Cruises®	USA	Wenniger	Workum, NL
Sea Cloud	Germany	Oceandiva	Germany
Oceania Cruises	UK	APT	Australia
hl-cruises	Germany		
Princess Cruises	USA		
Regent Seven Seas Cruises	USA		
Hurtigruten	Norway		
msccruises	Switzerland		
Lindblad Expeditions	USA		
AIDA Cruises	Germany		
Cruise & Maritime Voyages	UK		
P&O Cruises	UK		
Fred Olsen Cruise Lines	UK		

Cunard Line	UK
Viking Ocean Cruises	USA

Source:

- CASTOLDI. (2016). Passenger Ferries. http://www.castoldijet.it/en/waterjet_en/applications_en/passenger_en.html
- NSRP. (2013). e-harbours. WP 3.5 Application of Smart Energy. Regterschot and Bakker
- from: http://eharbours.eu/wp-content/uploads/3-5-AmsterdamV4-laatste.pdf
- Passenger Terminal Amsterdam. (2016). from: http://www.ptamsterdam.nl/
- Port of Amsterdam. (2013). from: http://www.portofamsterdam.com/beeldbank/Cijferboekjes/Cijferboekje_ENG_binnenwerk_def.pdf
- River Cruise Schedule. (2016). from: http://www.portofamsterdam.nl/Ned/Ligplaatsenreserveringen.html
- Ruhrberg, M. (2006). Assessing the recycling efficiency of copper from end-of-life products in Western Europe. *Resources, Conservation and Recycling*, 48(2), 141–165. http://doi.org/10.1016/j.resconrec.2006.01.003

3.3.1 Vessel: Cargo

Table A32. Data for cargo

Dead weight tonnage/displacement weight ratio (Papanikolaou, 2014)				
Year	Lower Limit	Upper Limit	DWT/Δ (%)	Avg ratio
General cargo ships (Dead weight tonnage-tonnes)	5,000	15,000	65–80	0.73
	25,000	200,000	83–88	0.86
	120,000	500,000	78–86	0.82

Table A33. Data for cargo

Vessels ownership by NL (UNCTAD, 2015)		
#	deadweight tonnage (tonnes)	displacement weight (tonnes)
1,200	17,005,609	23,456,012

Table A34. Data for cargo

Calculating Rotterdam/AMS vessels ratio			
Port of Rotterdam cargo ship arrival (2015)	#	Port of Amsterdam ship calls (2014)	Ratio of Rotterdam/Amsterdam vessel
dry bulk carriers	1,177		
liquid build carriers	8,127		
container ships	7,398		
breakbuld and	10,360		

roll-on/roll-off ships			
Total	27,062	4,927	5

Assumptions:

[1] Assume no change in boat stock until 2050

[2] Sea cruises and river cruises are found not based in Amsterdam. Therefore not taken into account.

[3] Cargo vessel in Amsterdam is calculated by the total cargo vessels owned by the Netherlands from UNCTAD data (2015) and scale it down to Port of Amsterdam by the shipment movement ratio between Port of Rotterdam and Port of Amsterdam.

[4] Total displacement weight of vessels are calculated by conversion through ratio with deadweight of cargo vessels (Pananikilaou, 2014). Total deadweight is adopted from the deadweight of Dutch-owned vessels UNCTAD (2015) and scaled it down to Amsterdam.

Source:

- Papanikolaou, A. (2014). Ship Design: Methodologies of Preliminary Design. Springer Netherlands. ISBN. 978-94-017-8750-5
- Port of Amsterdam . (2014). Port of Amsterdam ship calls. from: https://www.portofrotterdam.com/en/the-port/facts-figures-about-the-port
- Port of Rotterdam . (2015). Port of Rotterdam cargo ship arrival. from: http://www.portofamsterdam.nl/beeldbank/Cijferboekjes/Cijferboekje_ENG_binnenwerk_def.pdf
- UNCTAD. (2015). REVIEW OF MARITIME TRANSPORT 2015. from: http://unctad.org/en/PublicationsLibrary/rmt2015_en.pdf

3.4 Motorcycle

3.4.1 Motorcycle

Table A35. Data for motorcycles

Copper Content		
Type	Copper content (%)	Source
Conventional scooter	1.33%	(Rauch et al., 2007)
E-scooter copper content	16%	(Braconi, 2014)

Table A36. Data for motorcycles

Motorcycles types in NL (CBS, 2012)		
cylinder	Number of motorcycles (#)	%
1 - 50 cc	3,112	0.48%
51 - 125 cc	12,852	1.99%
126 - 175 cc	7,551	1.17%
176 - 250 cc	23,977	3.71%
251 - 375 cc	12,541	1.94%
376 - 500 cc	58,859	9.10%

501 - 625 cc	105,933	16.37%
626 - 750 cc	144,448	22.33%
751 - 875 cc	34,313	5.30%
876 - 1 000 cc	90,638	14.01%
1 001 - 1 125 cc	47,355	7.32%
>= 1 126 cc	105,145	16.25%
Other/unknown cylinder capacity	271	0.04%
Total	646,995	100.00%

Table A37. Data for motorcycles

Vehicle weight (kg)		Cu content (kg)		Share
		Conventional	Electric	
Scooter (50 cc)	80.00	1.06	12.52	0.48%
Scooter (125 cc)	99.88	1.33	15.63	1.99%
Motorcycle (250 cc)	202.00	2.69	31.61	4.87%
Motorcycle (320 cc)	192.00	2.55	30.05	1.94%
Motorcycle (650 cc)	216.24	2.88	33.84	47.80%
Motorcycle (1000 cc)	237.26	3.16	37.13	37.62%
	Average	2.77	32.64	

Assumptions:

[1] Copper content of motorcycles are assumed to be 1.33% (Rauch et al).

[2] Average copper content is calculated by assumed stock share of different types of motorcycles.

[3] All motorcycles are electric after 2040.

Source:

- Braconi, D., (2014). Green two-wheeled mobility. http://www.diva-portal.se/smash/get/diva2:768669/FULLTEXT01.pdf
- CBS. (2015). Transport and mobility 2015. from: http://download.cbs.nl/pdf/2015-transport-and-mobility.pdf
- CBS. (2012). Motorcycles in NL.
- Motorcycle weight from:
  - http://www.mvoa.nl/files/pdf/.pdf
  - http://www.genuinescooters.com/buddy125.html
  - http://www.kymco.com.tw/heavy_scooter/venox260.html
  - https://www.kawasaki.com/Products/2016-Ninja-H2
  - https://www.kawasaki.com/Products/2016-Ninja-H2
- Rauch, Eckelman, and Gordon. (2007). Part A: In-Use Stocks of Copper in the State of Connecticut, USA. from: http://environment.yale.edu/publication-series/documents/downloads/v-z/WorkingPaper10-PartA.pdf

3.4.2 E-bikes

Table A38. Data for e-bike

e-bike Copper Component - Source 1			
Cu%	Component	weight (kg)	Cu content (kg)
13%	battery	2.6	0.338
2%	controller	0.4	0.008
13%	motor	2.7	0.351
		Total	0.697

Table A39. Data for e-bike

Vehicle weight (kg)		Copper content (kg)	Source
e-bike	26.00	2.55	(ADB, 2009)
e-bike 2	23.00	0.70	(Del Duce, 2011)
	Average	1.62	

Table A40. Data for e-bike

Life span			
Types	Value	Unit	Source
scooters	10	years	Assumed
e-bikes life time	50000	km	(ADB, 2009)
annual biking distance	900	km	(CBS, 2015)
e-bikes life time	4	years	(Leuenberger et al., 2010)

Table A41. Data for e-bike

Copper in cars (Rabobank, 2016; Bike-EU.com, 2009; CONEBI, 2015; Engelmoer, 2012)				
Year	NL Total bike sale (#)/yr	E-bike sales (#)	Share (%) of E-bikes sale	AMS total bikes sale (#)/yr
2004	1,324,000	26,480	2%	1,233
2005	1,250,000	25,000	2%	1,164
2006	1,239,000	40,000	3%	1,863
2007	1,323,000	79,380	6%	3,697
2008	1,400,000	124,250	10%	5,787
2009	1,388,000	145,740	11%	6,787
2010	1,281,000	153,720	12%	7,219
2011	1,212,000	181,000	15%	8,568
2012	1,171,000	175,000	15%	8,347
2013	1,035,000	192,000	19%	9,271
2014	1,008,000	223,000	22%	10,896
2015	1,051,000	276,000	26%	13,549

Table A42. Data for e-bike

Estimated e-bikes in Amsterdam

e-bikes (AMS)	50,526	#	
Share of e-bikes stock	6.32%	%	Assumed to be the same as the Netherlands
Bike ownership	0.96	#/cap	Including e-bike and bikes
Lifetime	15000	km	
distance/yr	900	km	Average annual biking distance (CBS, 2015)
battery change	2.75	times	
Lifetime	6	years	(lifetime distance/annual distance)/battery change

Table A43. Data for e-bike

bikes			
types	total stock (#)	Source	Share %
e-bikes (NL)	1,200,000	(Rabobank, 2016)	6.32%
bikes (NL)	19,000,000	(CBS, 2015)	-
bikes (AMS)	800,000	(City of Amsterdam, 2016)	-

Assumptions:

[1] Total in-use e-bike stock assumed to be zero in 2003. The stock is built up since 2004 by the annual e-bike sales estimation.

[2] 2004-2005, the number of e-bikes sale is estimated by multiplying total bike sales with the known % of e-bike sales in the Netherlands. The sales number of e-bikes in Amsterdam is assumed to be proportional to population. E-bikes annual sales is calculated by annual e-bikes sales times the ratio of Amsterdam population and national population.

[3] The in-use stock is built up by the annual sales, assuming the starting stock in 2003 is so low that it's negligible. Using sales number since 2004

[4] The sales data of e-bike per year in 2006, 2007, and 2011-2015 is sourced from Rabobank and marketing statistics.

[5] In years where there's no annual sales data (2009-2010), estimation is made by percentage of market share multiply the total bike sales in the Netherlands. 2009, 2010 percentage of e-bike sales is from Engelmoer (2012).

[6] Second-hand e-bike sales assumed to be negligible.

[7] In 2020, ownership of e-bike is assumed to be 10%, ownership in 2050 is assumed to be15%. Partly because of aging population and the demand for e-bikes, partly because e-bikes function more and more as recreational transport vehicles.

Source:

- ADB. (2009). Electric Bikes in the People's Republic of China. from: http://www.understandchinaenergy.org/wp-content/uploads/2014/01/Electric-Bikes-PRC-Impact-on-Environment-Prospects-Growth-2009.pdf

- Bike-EU.com. (2009).The Netherlands 2008: E-Bikes: Money Machine for Bike Sector. from: http://www.bike-eu.com/sales-trends/artikel/2009/4/the-netherlands-2008-e-bikes-money-machine-for-bike-sector-10110348
- CBS. (2015). Transport and mobility 2015. from: http://download.cbs.nl/pdf/2015-transport-and-mobility.pdf
- City of Amsterdam. (2016). Cycling in Amsterdam. from: http://www.iamsterdam.com/en/visiting/plan-your-trip/getting-around/cycling
- CONEBI. (2015). EUROPEAN BICYCLE MARKET 2015 edition. from: http://www.conebi.eu/?wpdmdl=892
- Del Duce. (2011). Life Cycle Assessment of conventional and electric bicycles. from: http://www.eurobike-show.com/eb-wAssets/daten/rahmenprogramm/pdf/LifeCycleAssessment_DelDuce_englisch.pdf Engelmoer, W. (2012). The E-bike: opportunities for commuter traffic. from: http://www.rug.nl/research/portal/files/14446095/EES-2012-131M_WiebeEngelmoer.pdf
- Leuenberger, M., Frischknecht, R., ESU-services Ltd., (2010). Life Cycle Assessment of Two Wheel Vehicles. from: http://www.esu-services.ch/fileadmin/download/leuenberger-2010-TwoWheelVehicles.pdf
- Rabobank. (2016). Tweewielerspeciaalzaken. from: https://www.rabobankcijfersentrends.nl/index.cfm?action=branche&branche=Tweewielerspeciaalzaken

3.5 Bus

Table A44. Data for conventional bus

Copper in buses			
Year	Units	Source	
Lifespan	18	years	(WBCSD, 2004)
Cu content - Diesel	109	kg/bus	(Cherry et al., 2009)
Cu content - Hybrid	212	kg/bus	(Kärnä, 2012)
Cu content - Electric	219	kg/bus	(Kärnä, 2012)

Assumptions:

[1] Assuming the bus lines are quite saturated currently in the city of Amsterdam and stock growth is limited. Every year 2 new buses are added to the stock (2016-2050).

[2] Amsterdam's public bus fleet will be fully electric by 2025. In 2016 there are 40 electric bus on the road (Eltis, 2015).

[3] Between 2016 and 2025, the electric buses are assumed to be linearly growing

[4] Starting stock is 280 buses (CBS, 2015) in Amsterdam.

Source:
- Cherry, C. R., Weinert, J. X., & Xinmiao, Y. (2009). Comparative environmental impacts of electric bikes in China. Transportation Research Part D: Transport and Environment, 14(5), 281–290. http://doi.org/10.1016/j.trd.2008.11.003
- Macdonald, L. (2015). Amsterdam buses to be fully electric by 2025 (Netherlands). Eltis. from: http://www.eltis.org/discover/news/amsterdam-buses-be-fully-electric-2025-netherlands
- Päivi Kärnä. (2012). CARBON FOOTPRINT OF THE RAW MATERIALS OF AN URBAN TRANSIT BUS. LAHTI UNIVERSITY OF APPLIED SCIENCES Degree Programme in Environmental Technology Environmental Engineering Bachelor's Thesis
- WBCSD. (2004). IEA/SMP Transport Model. IEA/SMP Transport Spreadsheet Model

3.6 Truck

3.6.1 Conventional trucks

Table A45. Data for conventional truck

Copper in trucks			
	Value	Units	Sources
Lifetime	18	year	WBCSD, 2004
Cu content-electric truck	60	kg/unit	assumed to be the same as electric cars
Cu content-diesel truck	20	kg/unit	(van Beers, Graedel, 2003)

Table A46. Data for conventional truck

Registered motor vehicles (CBS, 2015)		
Type	Quantity (#)	Notes
vans	20,009	Assume copper content same as lorries
lorries	1,096	-
tractors	684	-
special vehicles	1,413	Assume copper content same as lorries

Assumptions:

[1] All vans are assumed to be electric by 2040 according to policy. The conventional stock is calculated by total truck stock minus electric truck stock.

[2] Truck category includes vans, lorries, tractors, and special vehicles. Assume all types of trucks have the same copper content.

[3] Assume the total stock of trucks remains the same until 2050.

[4] Assume copper content of electric trucks is the same as electric cars.

Source:
- CBS. (2015). Registered motor vehicles
- van Beers, D., & Graedel, T. E. (2007). Spatial characterisation of multi-level in-use copper and zinc stocks in Australia. *Journal of Cleaner Production*, 15(8-9), 849–861. http://doi.org/10.1016/j.jclepro.2006.06.022
- WBCSD. (2004). IEA/SMP Transport Model. IEA/SMP Transport Spreadsheet Model

4. CONSUMER DURABLES

Table A47. Data for conventional truck

Copper in consumer appliances						
Product	Cu content (%)	Product Weight (kg)	Cu Weight (kg)	Lifespan (year)	In-use stock in 2015 (#)	Source of in-use stock
TV	2.04%	17.14	0.35	5	423,958	(Oguchi et al., 2011)
Refrigerator	3.4%	61	2.07	12	432,610	(Papachristos, 2015)
Washing machine	3%	39	1	10	415,306	(Papachristos, 2015)
PC	0.9%	15	0.14	7	216,305	(Tselekis, 2012)
Laptop	1%	2.9	0.03	7	718,133	(Tselekis, 2012)
Cellphone	0.3%	0.11	0.0033	4	834,925	(Nation Master, 2016)
Printer	3.2%	5.6	0.18	7	289,849	(Papachristos, 2015)
Microwave	6%	15	0.96	13	363 392	(Papachristos, 2015)
Other appliances	-	-	5.65	9	432,610	assumed

a: Average product weight (Oguchi et al., 2008); b: Average copper content (Oguchi et al., 2011)
c: Ratio between CRT and LCD (NMR Group Inc., 2012); d: Copper content of product. (UNEP, 2013a)

Assumptions:

[1] The in-use stock of consumer appliances in Amsterdam is estimated by applying the penetration rate in the Netherlands to the population in Amsterdam. It is assumed that the ownership rates of these products in Amsterdam are the same as the rest of the Netherlands.

[2] It is assumed that all the appliances have the same copper content, lifetime, and product weight until 2050.

[3] Ownership of products in 2050:

- TV: ownership the same in 2016 and 2050
- Refrigerator: ownership the same in 2016 and 2050
- Washing machine: ownership the same in 2016 and 2050, assuming every house has one washing machine (2015 ownership: 0.94/HH)
- Laptop: ownership assumed to grow from 2015 ownership 1.62/HH to 1 laptop per capita in 2050. Growth assumed to be linear.
- PC: PC are assumed to be phased out in 2050 and replaced by laptop. Ownership assumed to decrease from 2015 ownership 1.62/HH to 1 laptop per capita in 2050. Growth assumed to be linear.
- Microwave: ownership assumed to grow from 2015 ownership 0.82/HH to 1 microwave per household in 2050.
- Printer: ownership assumed to grow from 2015 ownership 0.65/HH to 1 printer per household in 2050.
- Cellphone: ownership assumed to be the same from 2015 until 2050 (1.006

cellphone/capita)

- Other appliances: assumed to be the same as refrigerator.

4.1 TV

Table A48. Data for conventional truck

Type	Weight (kg/unit)	Copper content %	unit Cu weight (kg)	Life span (year)
TV - LCD	7.9	0.80%	0.06	7
TV - CRT	31	3.90%	1.21	12
Average TV (LCD:CRT = 3:2) (NMR Group Inc., 2012)	17.14	2.04%	0.52	9

Assumptions:

[1] Assuming household ownership of TV remains the same from 2016-2050

[2] Average TV weight and copper content is calculated by a ratio of LCD:CRT = 3:2, in reality, the ratio will change, LCD is going to be a bigger share in the future.

[3] 2013 and 2014, stock/HH increase 0,4 annually.

4.2 Other appliances

Table A49. Data for appliances (UNEP, 2013b)

Type	Cu content (g)	Cu content (kg)	unit/HH	copper content (kg)
large appliances (excluding cooling and heating appliances)	1,736	1.74	1	1.736
mediam appliances	956	0.96	1	0.956
small appliances	484	0.48	2	0.968
consumer electronics (DVD, stereos)	423	0.42	2	0.846
electric tools	1,075	1.08	1	1.075
leisure appliances	23.58	0.02	1	0.02358
lighting equipments	2.76	0.00	15	0.0414
Average Cu content (kg)				5.65

Source:

- Nation Master. (2016). from: http://www.nationmaster.com/
- NMR Group Inc. (2012). *Massachusetts Residential Retail Products: Consumer Electronics Saturation; Sommerville*, MA.
- Papachristos, G. (2015). Household electricity consumption and CO 2 emissions in the Netherlands: A model-based analysis. Energy and Buildings, 86, 403-414.
- Oguchi, M.; Murakami, S.; Sakanakura, H.; Kida, A.; Kameya, T. A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. *Waste Manag.* 2011, 31 (9-10), 2150–2160; DOI 10.1016/j.wasman.2011.05.009.

- Tselekis, K. (2013). Energy savings potential from simple standby reduction devices in the Netherlands. Master thesis. Utrecht University.
- UNEP. (2013a). *Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles*; A Report of the Working Group on the Global Metal Flows to the International Resource Panel. van der Voet, E.; Salminen, R.; Eckelman, M.; Mudd, G.; Norgate, T.; Hischier, R.
- UNEP. (2013b). Metal Recycling: Opportunities, Limits, Infrastructure.

5. INDUSTRIAL DURABLES

Table A50. Residential housing copper content

Copper in consumer appliances			
Product	Value	Unit	Source
Copper stock in industrial durables	7	kg/capita	Rauch et al., 2007
Lifetime	8	year	Rauch et al., 2007

Assumptions:

[1] Due to the lack of accessibility in industrial sector's private assets, it is assumed that the copper intensity per capita is the same as Connecticut from Rauch et al.'s research.

Source:

- Rauch, Eckelman, and Gordon. (2007). Part A: In-Use Stocks of Copper in the State of Connecticut, USA. from: http://environment.yale.edu/publication-series/documents/downloads/v-z/WorkingPaper10-PartA.pdf

6. CORPORATE DURABLES

Table A51. Corporate durables copper content

Copper in consumer appliances						
Product	Cu content (%)	Product Weight (kg)	Cu Weight (kg)	Lifespan (year)	In-use stock in 2015 (#) (City of Amsterdam, 2016)	Source
Refrigerators/freezers	3%	84.5	2.535	15	23,936	(Rauch et al., 2007);
Mini fridges (hotels)	3%	15	0.45	15	26,287	
Washing machines (heavy duty)	2.40%	225	5.4	7	1,772	(Truttmann & Rechberge, 2006);
Dryers (heavy duty)	2.40%	225	5.4	15	1,772	
Dishwashers (heavy duty)	2.50%	60	1.5	7	7,528	
Stove/oven	0.20%	80	0.16	15	15,056	Horecaworld, 2016; Rauch et al. 2007
Microwaves	3.90%	15	0.585	15	18,781	(Rauch et al., 2007)
Computers	6.6%	9.9	0.6534	3	402,032	EPA, 2015

Televisions	5%	5.1	0.255	5	44,487	(Truttmann & Rechberge, 2006);
Telephones	9%	0.2	0.01784	5	294,792	(WRAP, 2012)
Stereo/Radio	3%	3	0.09	7	15,316	(Rauch et al., 2007)
Automotive tools by # repair shops	5%		10	15	1,692	(Rauch et al., 2007)

Source:

- City of Amsterdam. (2016). from http://www.ois.amsterdam.nl/.
- EPA (2015). Waste Reduction Model (WARM) Version 13. Personal Computers.
- Horecaworld. (2016). Gasfornuis vierbranders gasoven. from: http://www.horecaworld.biz/gasfornuis-4-branders-gasoven
- Rauch, Eckelman, and Gordon. (2007). Part A: In-Use Stocks of Copper in the State of Connecticut, USA. from: http://environment.yale.edu/publication-series/documents/downloads/v-z/WorkingPaper10-PartA.pdf
- Schipper, N., 2015. Slechtere onderwijsresultaten door verkeerd gebruik computers http://www.trouw.nl/tr/nl/4556/Onderwijs/article/detail/4142779/2015/09/15/Slechtere-onderwijsresultaten-door-verkeerd-gebruik-computers.dhtml
- Sint Lucas Andreas Ziekenhuis (2015) De financiële gezondheid van de ziekenhuizen in en rond Amsterdam. from: http://www.sintlucasandreasziekenhuis.nl/sites/default/files/ziekenhuizen_vergeleken_in_cijfers_editie_2014.pdf
- Truttmann, N., & Rechberger, H. (2006). Contribution to resource conservation by reuse of electrical and electronic household appliances. *Resources, Conservation and Recycling*, 48(3), 249-262.
- WRAP. (2012). Electrical product material composition. Waste & Resource Action Programme.

Assumptions:

[1] The copper in-use stock in corporate durables in 2015 is 402,822 kg, which equals to 0.486 kg/capita. It is assumed that the per capita copper intensity in corporate durables does not change until 2050. The in-use copper stock is calculated by the per capita copper in-use stock times the total population. The lifetime is assumed to be 8 years (Rauch et al., 2007).

APPENDIX 2: Detailed results

APPENDIX 2

1. BUILDING

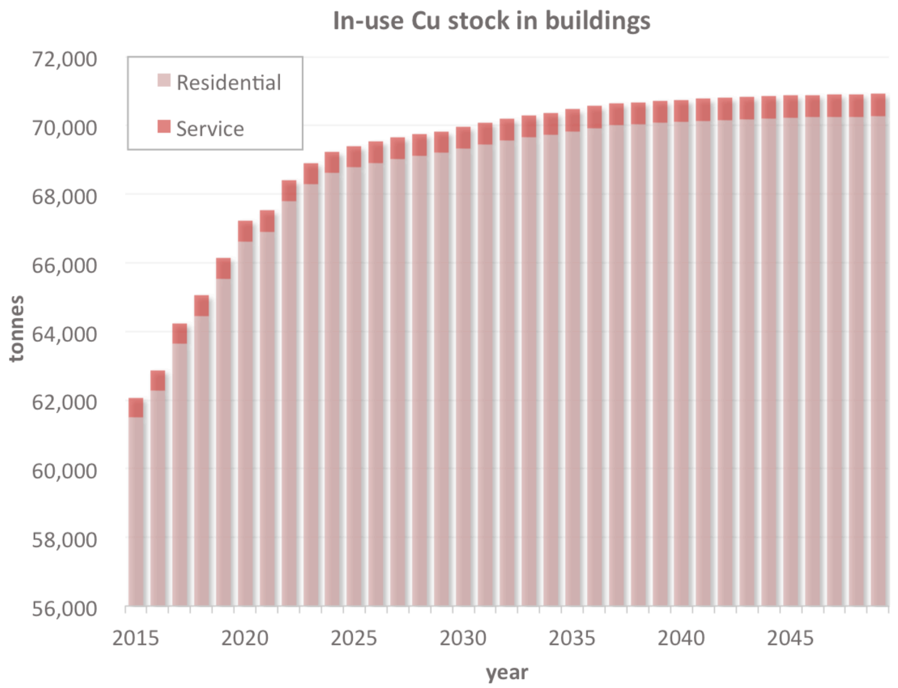

Figure 1. In-use Cu stock in buildings

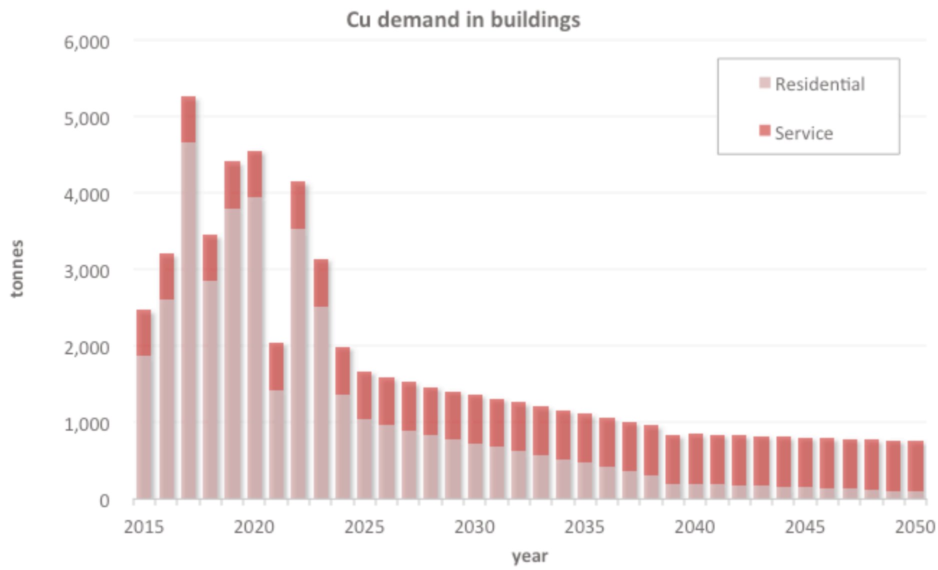

Figure 2. Cu demand in buildings

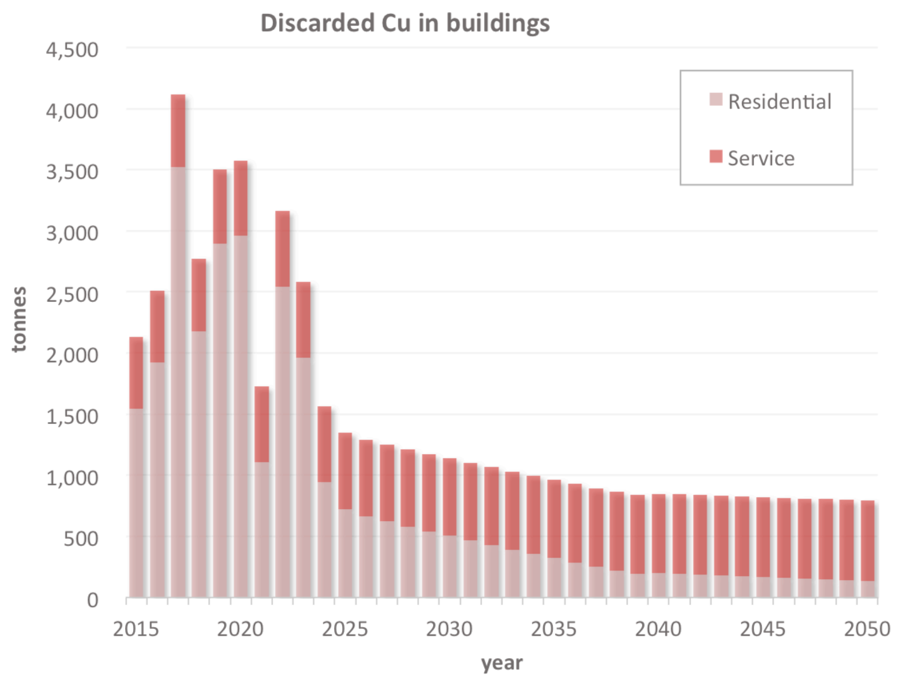

Figure 3. Discarded Cu in buildings

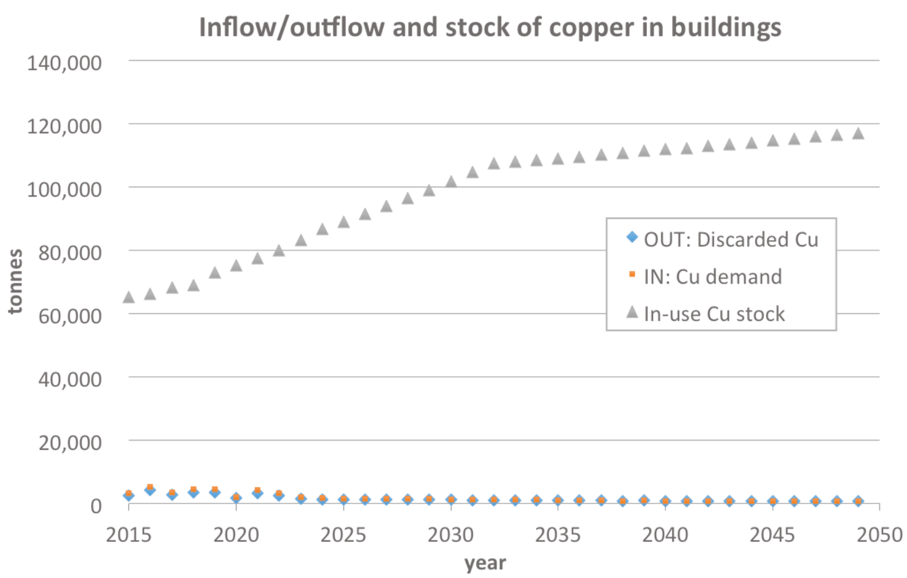

Figure 4. Inflow, outflow, and in-use stock of Cu in buildings

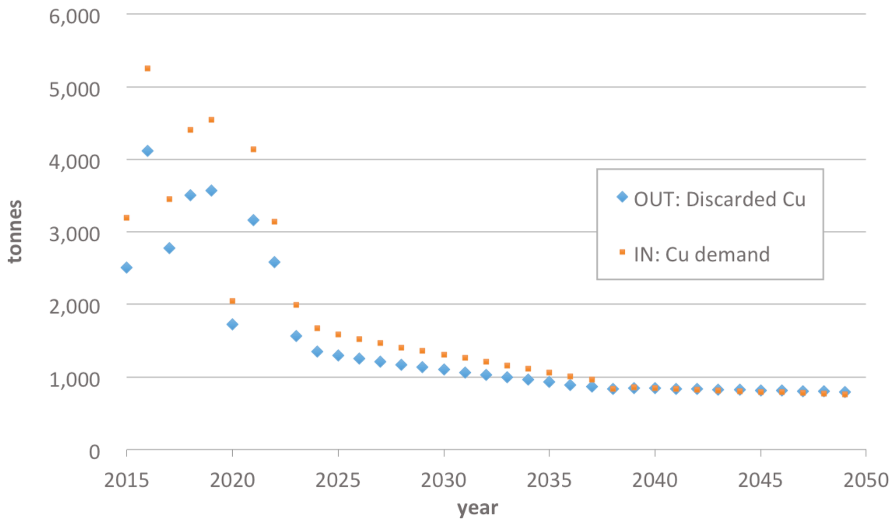

Figure 5. Inflow and outflow of Cu in buildings

2. INFRASTRUCTURE

2.1 Electricity generation

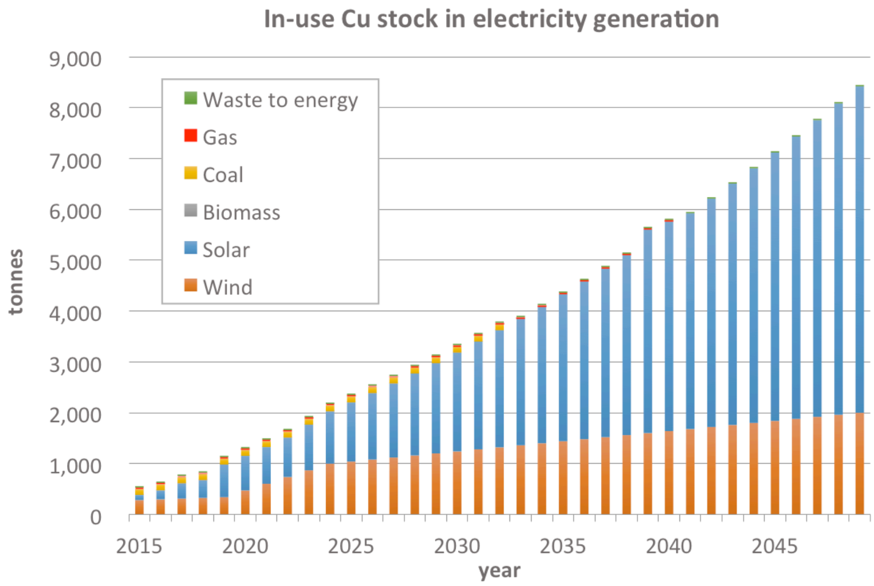

Figure 6. In-use Cu stock in electricity generation

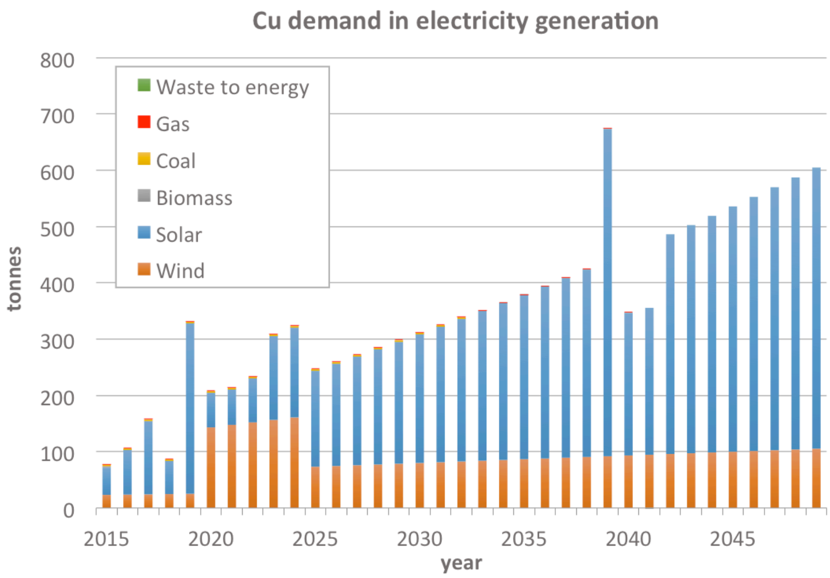

Figure 7. Cu demand in electricity generation

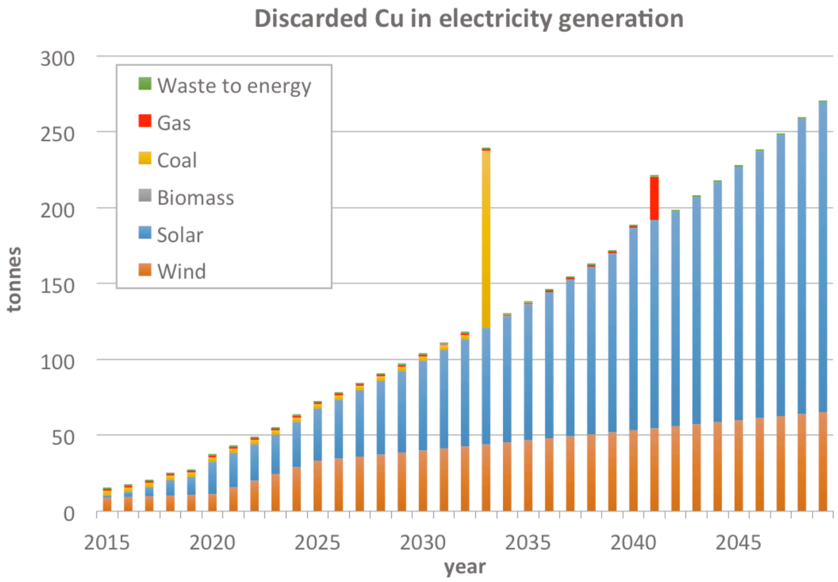

Figure 8. Discarded Cu in electricity generation

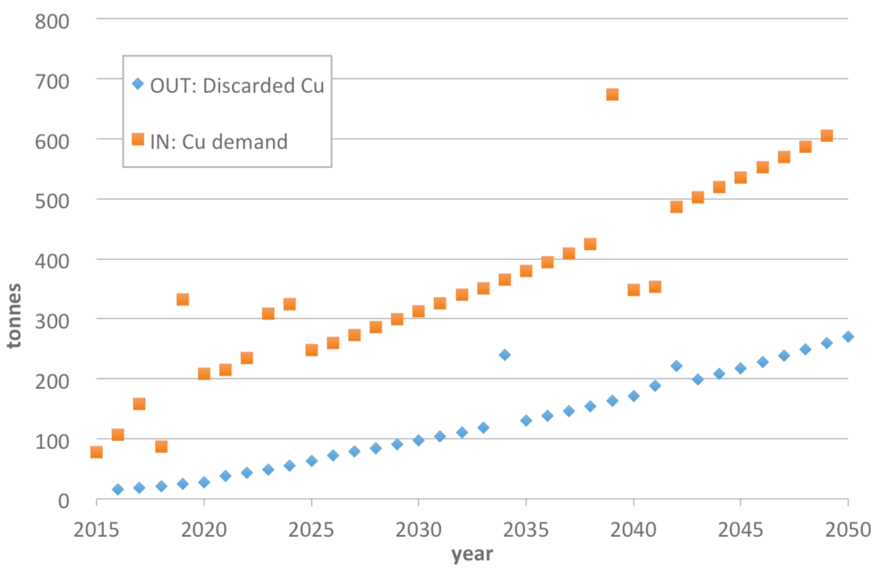

Figure 9. Inflow and outflow in electricity generation

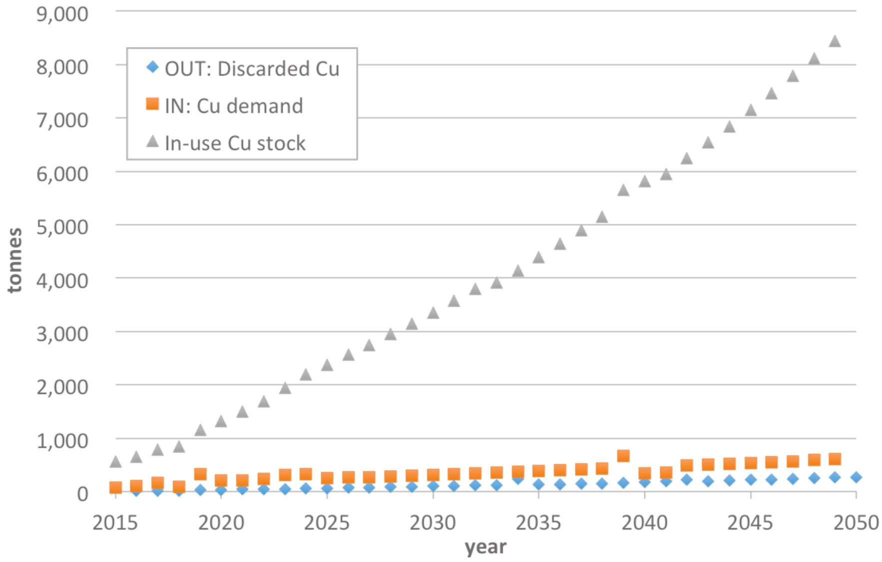

Figure 10. Inflow, outflow and in-use stock of copper in electricity generation

2.2 Electricity distribution

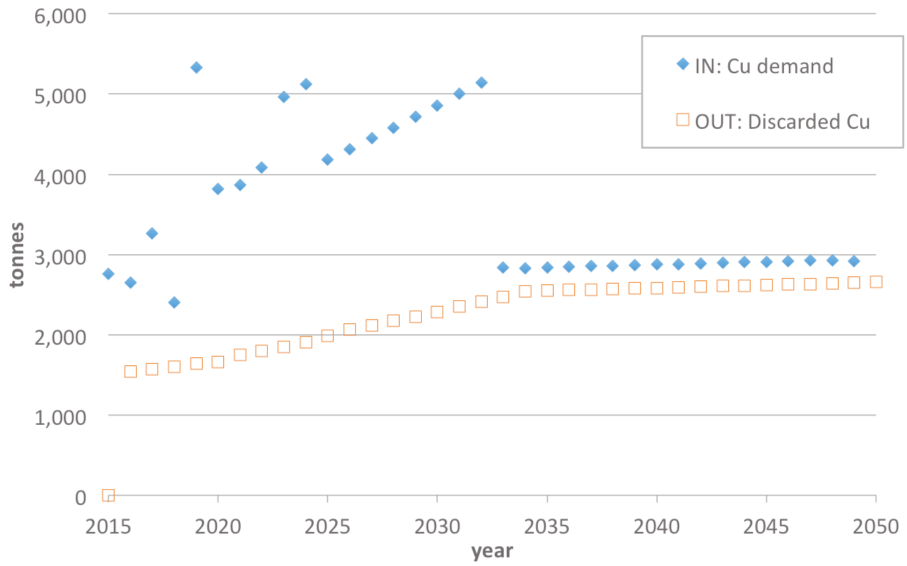

Figure 11. Inflow and outflow of copper in electricity distribution

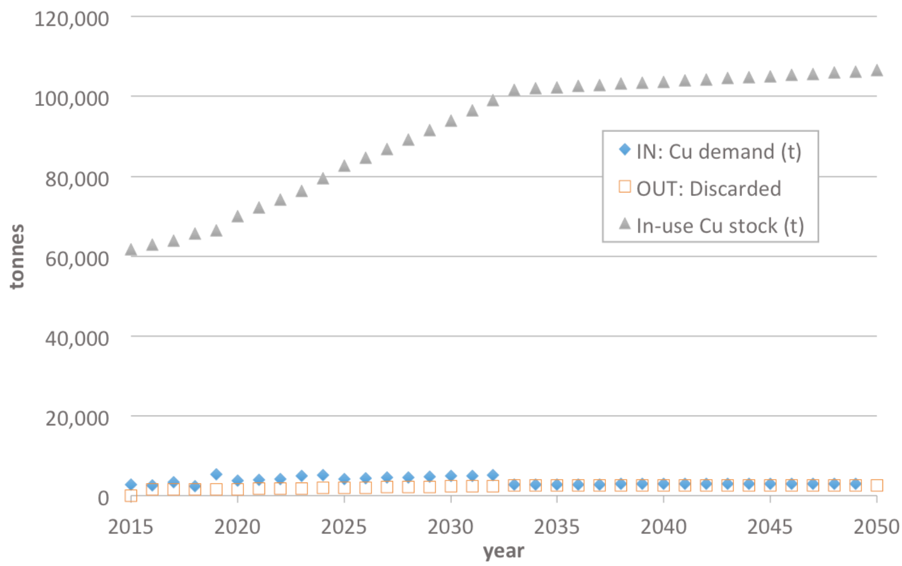

Figure 12. Inflow, outflow and in-use stock of copper in electricity distribution (tonnes)

2.3 EV charging station

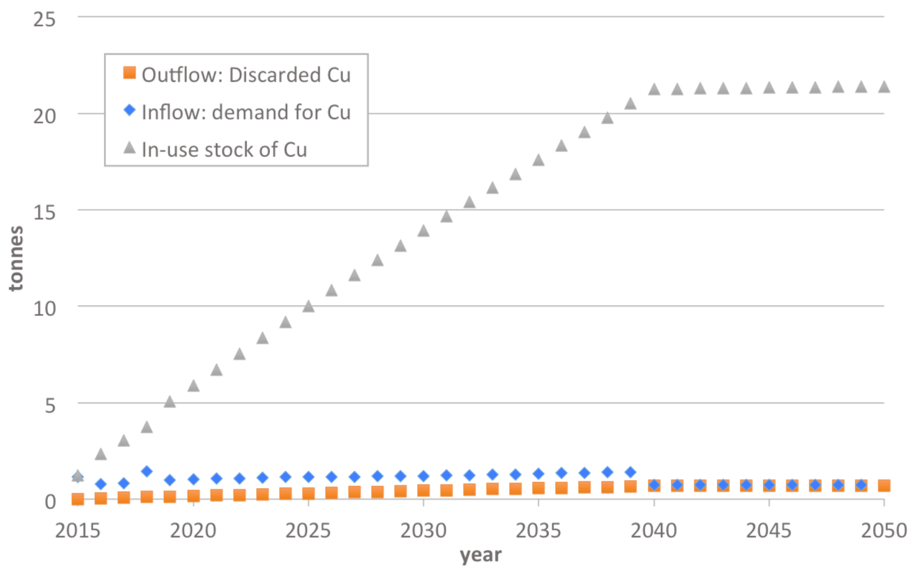

Figure 13. Inflow, outflow and in-use stock of copper in EV charging stations (tonnes)

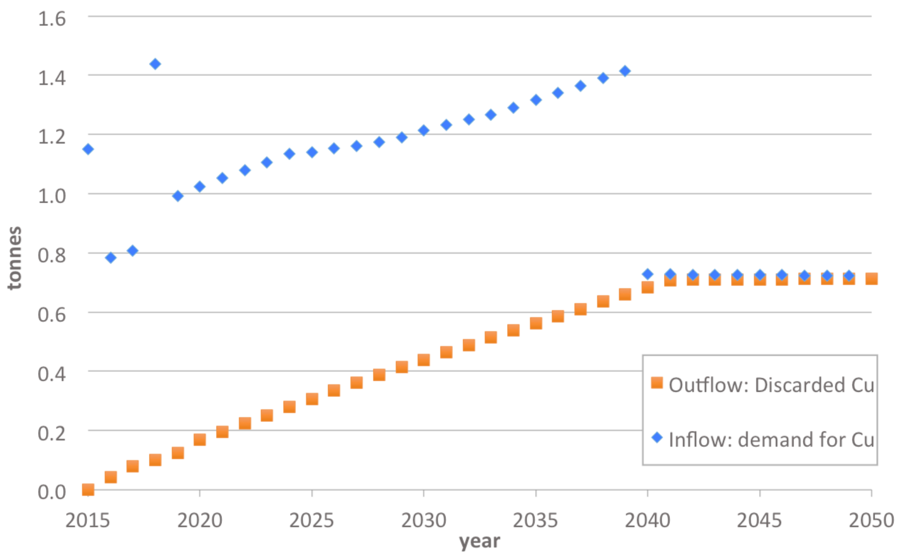

Figure 14. Inflow and outflow of copper in EV charging stations (tonnes)

2.4 Water infrastructure

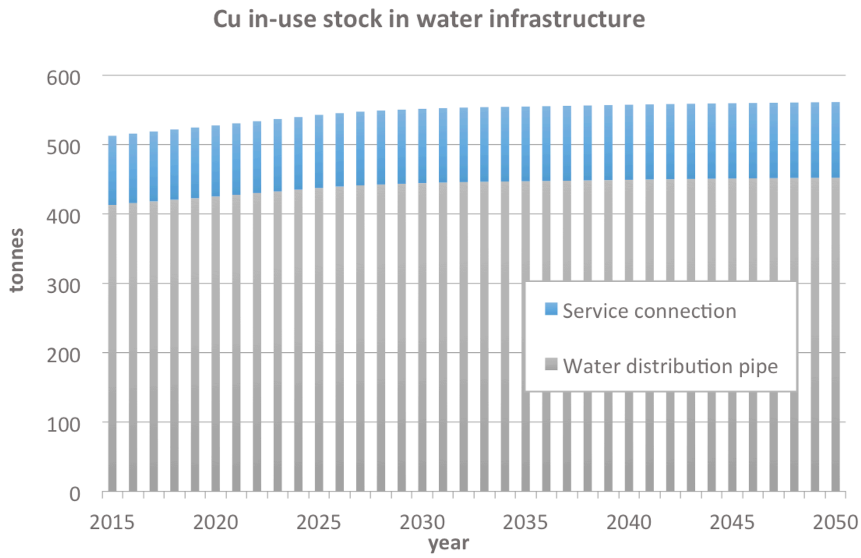

Figure 15. In-use Cu stock in water infrastructure

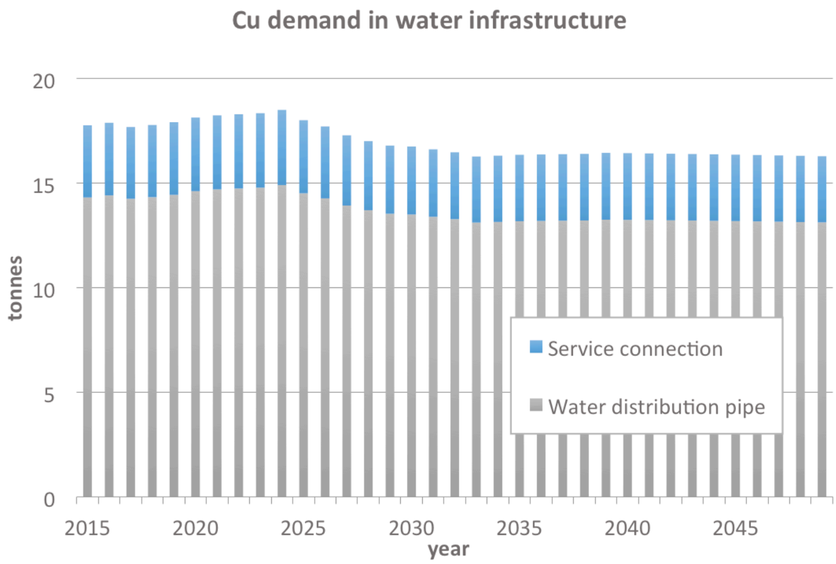

Figure 16. Cu demand in water infrastructure (tonnes)

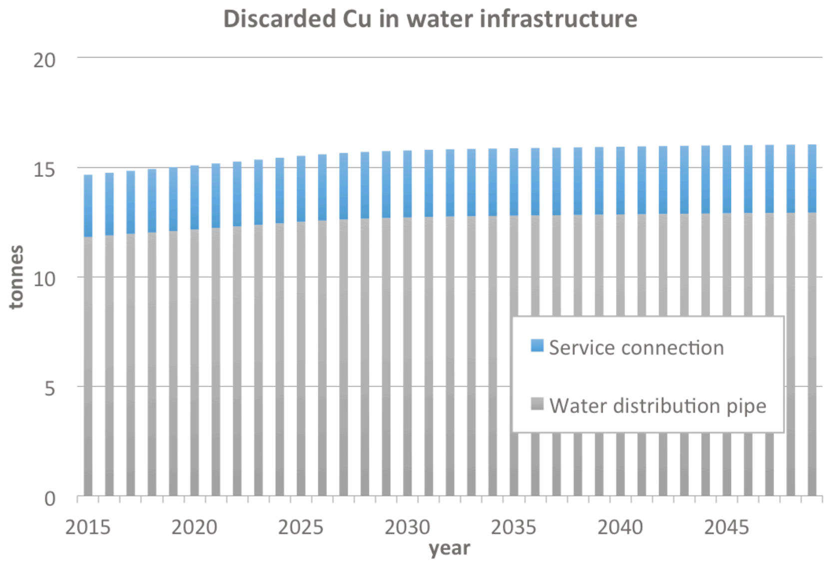

Figure 17. Discarded Cu in water infrastructure (tonnes)

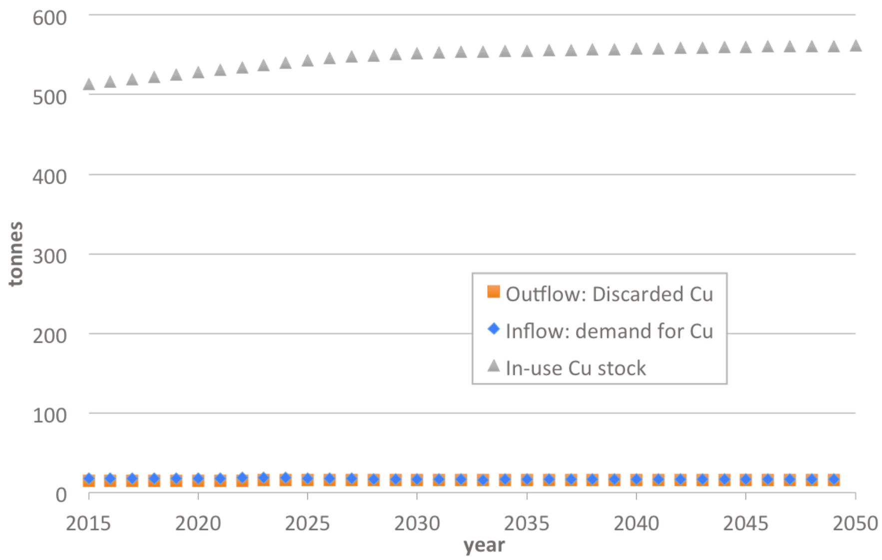

Figure 18. Inflow, outflow and in-use stock of copper in water infrastructure (tonnes)

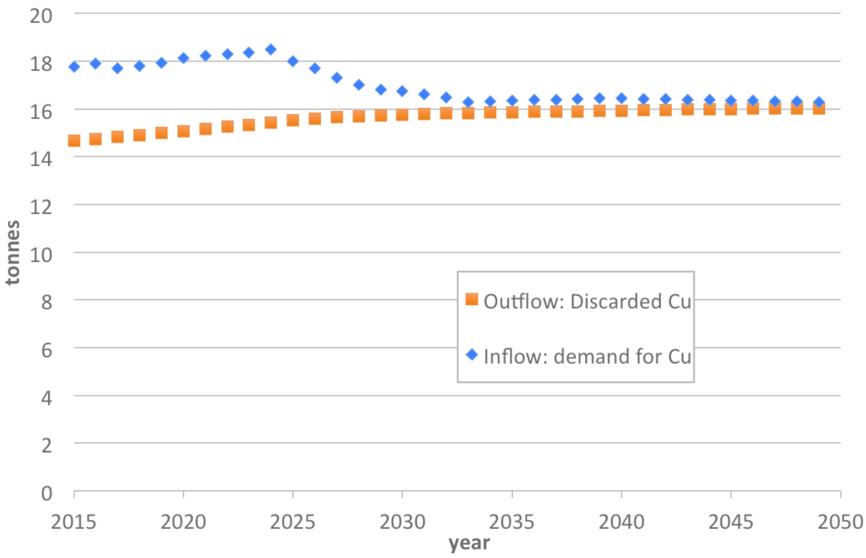

Figure 19. Inflow and outflow of copper in water infrastructure (tonnes)

2.5 Telecommunication

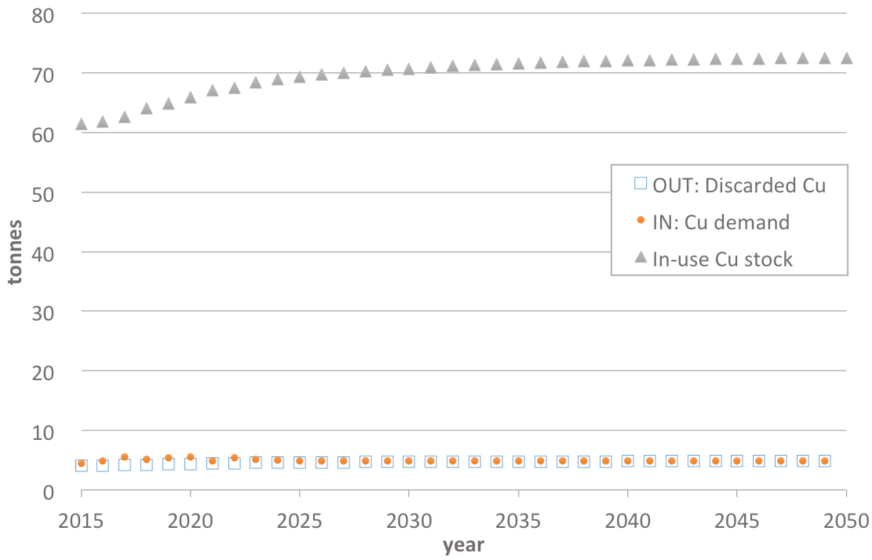

Figure 20. Inflow, outflow and in-use stock of copper in telecommunication (tonnes)

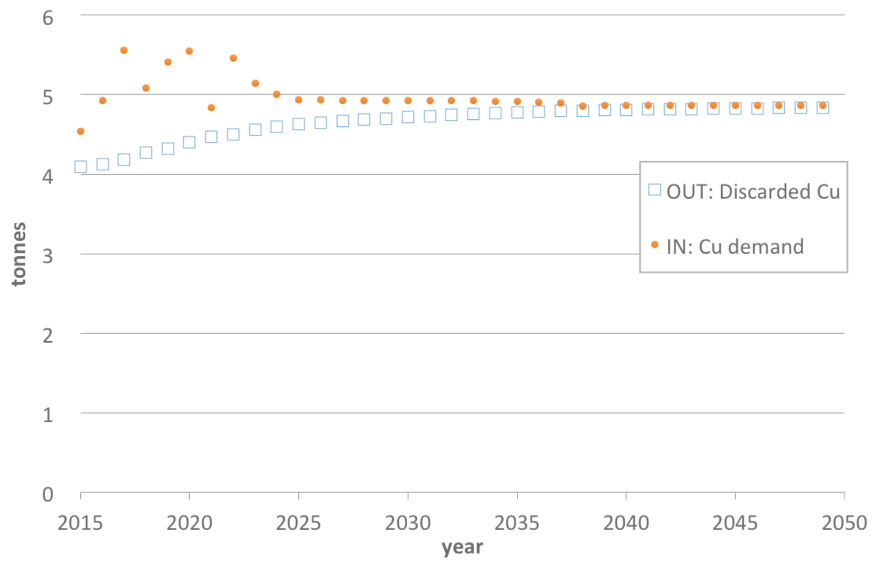

Figure 21. Inflow and outflow of copper in telecommunication (tonnes)

- **Public lighting**

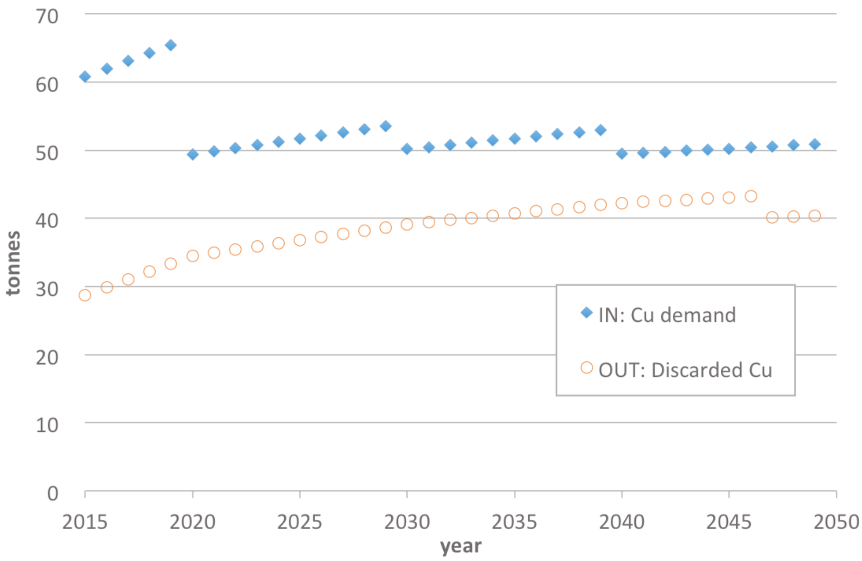

Figure 22. Inflow and outflow of copper in public lighting (tonnes)

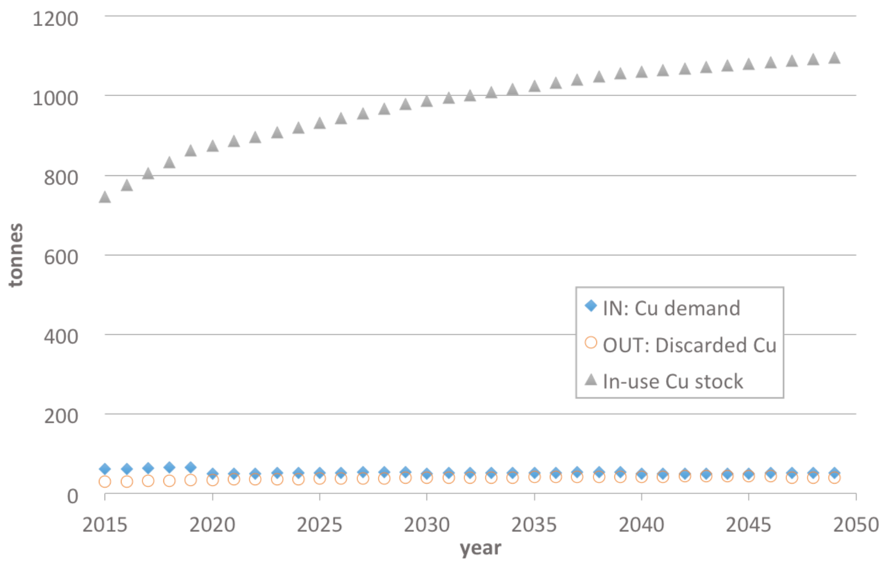

Figure 23. Inflow, outflow and in-use stock of copper in public lighting

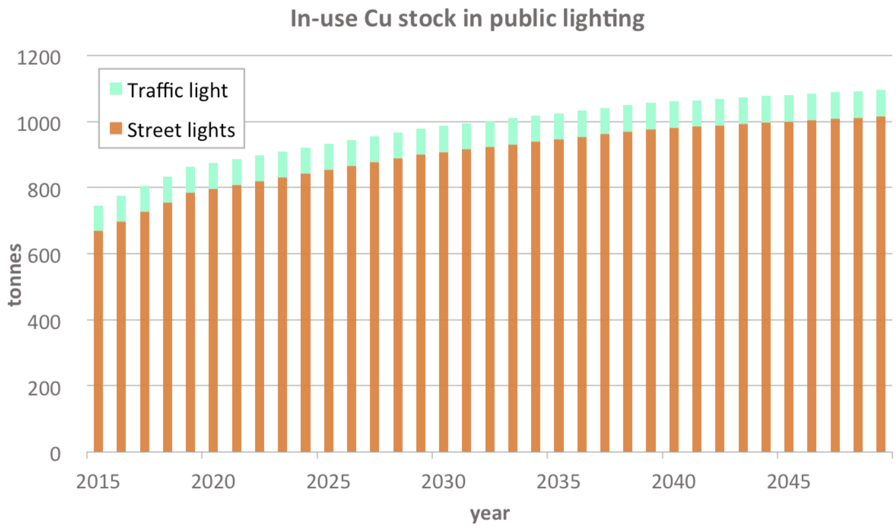

Figure 24. In-use Cu stock in public lighting

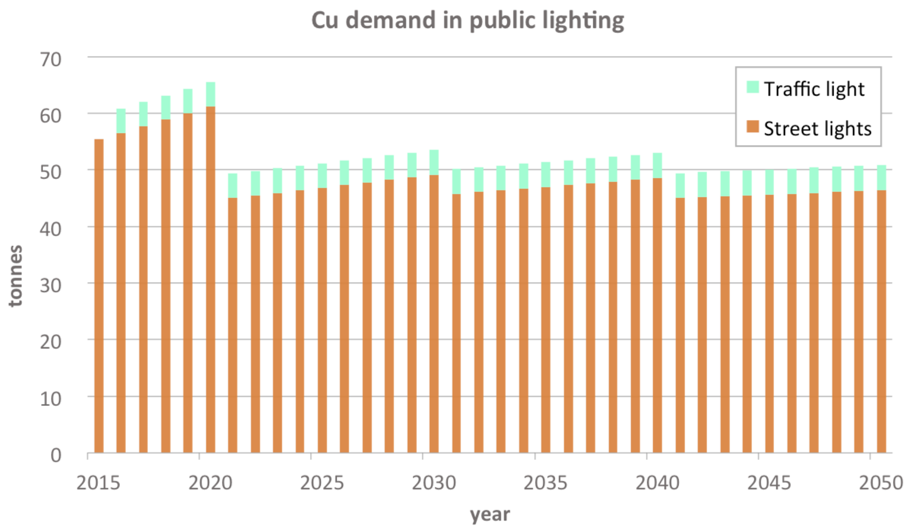

Figure 25. Cu demand in public lighting (tonnes)

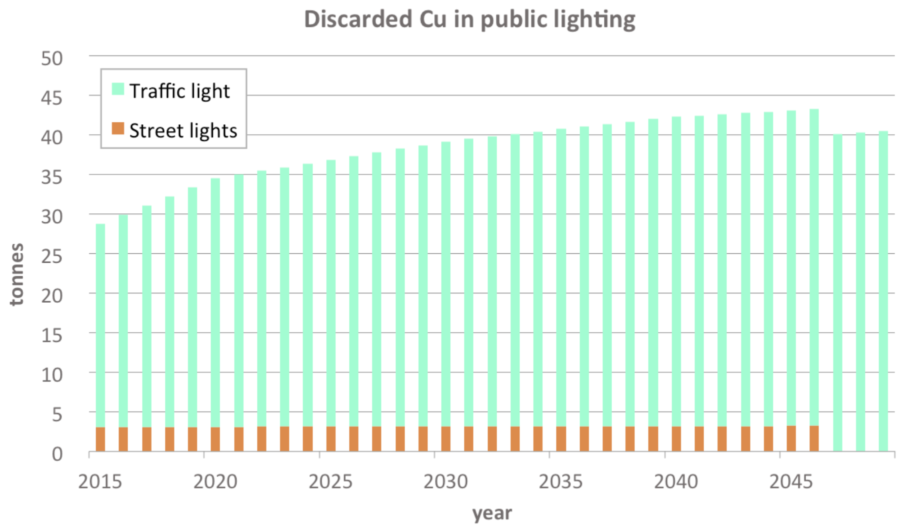

Figure 26. Discarded Cu in public lighting (tonnes)

- **Rail system**

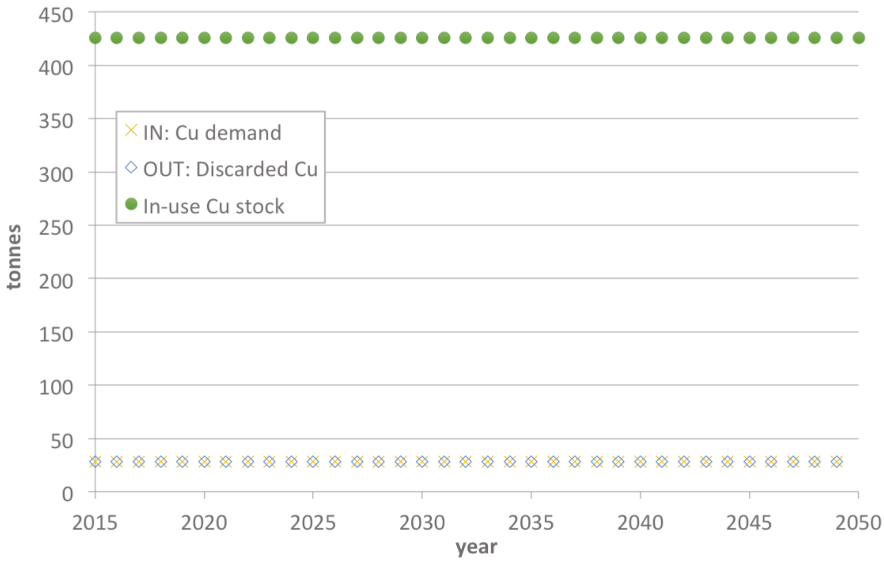

Figure 27. Inflow, outflow and stock of copper in rail system (tonnes)

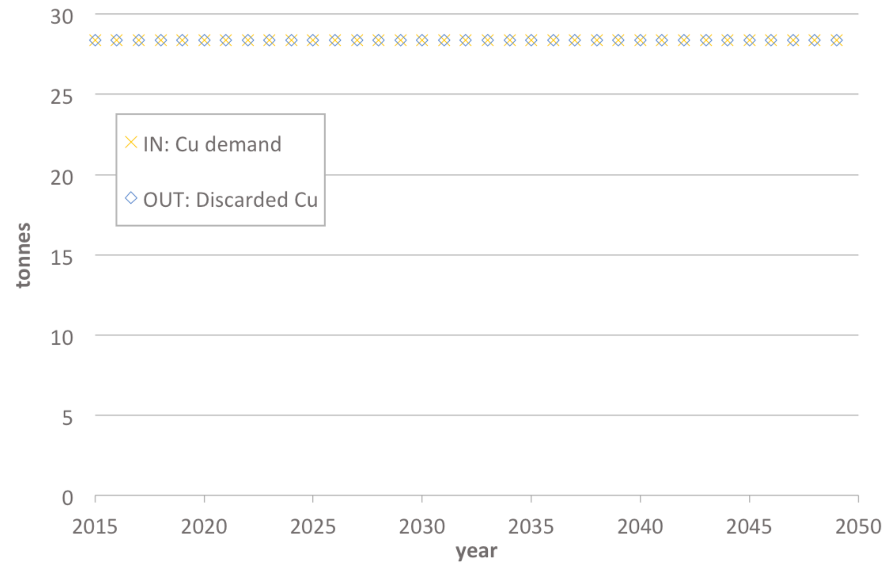

Figure 28. Inflow and outflow of copper in rail system (tonnes)

3. TRANSPORT

- **Cars**

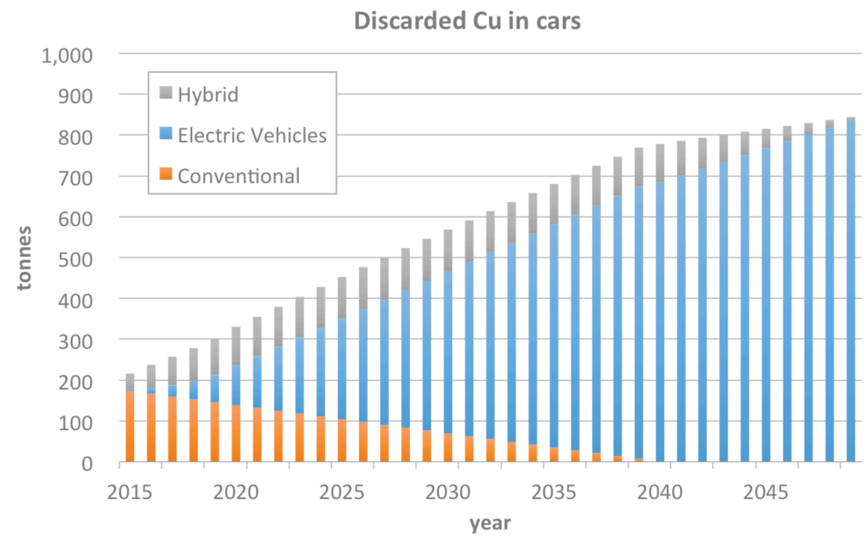

Figure 29. Discarded Cu in cars (tonnes)

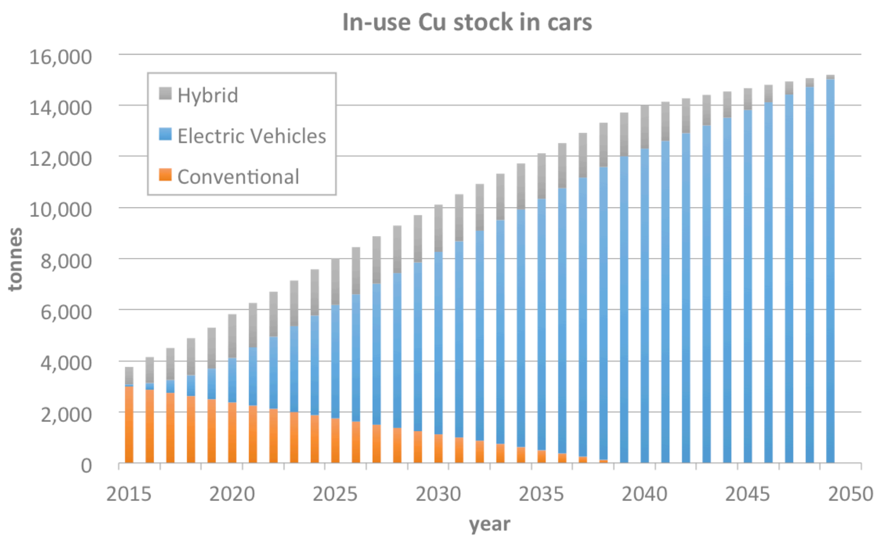

Figure 30. In-use Cu stock in cars

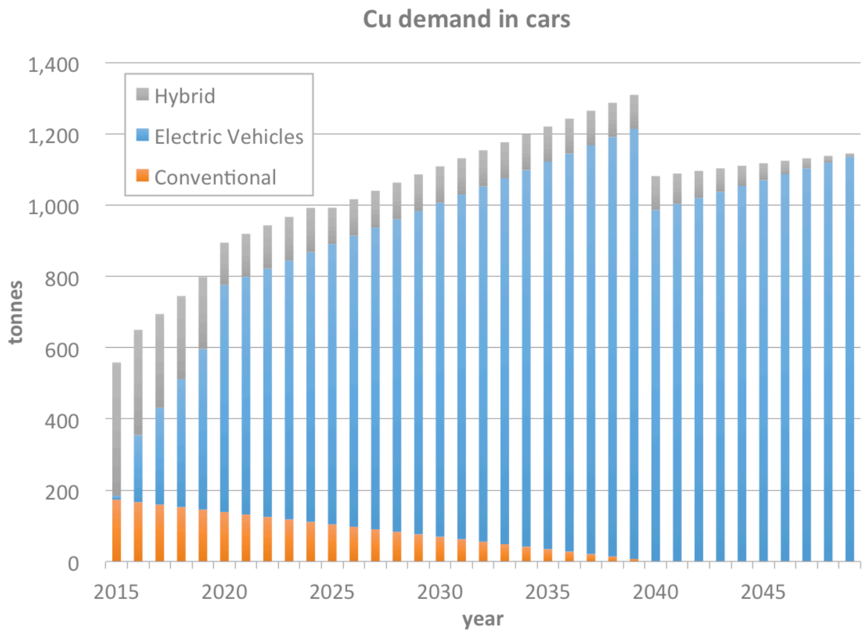

Figure 31. Cu demand in cars (tonnes)

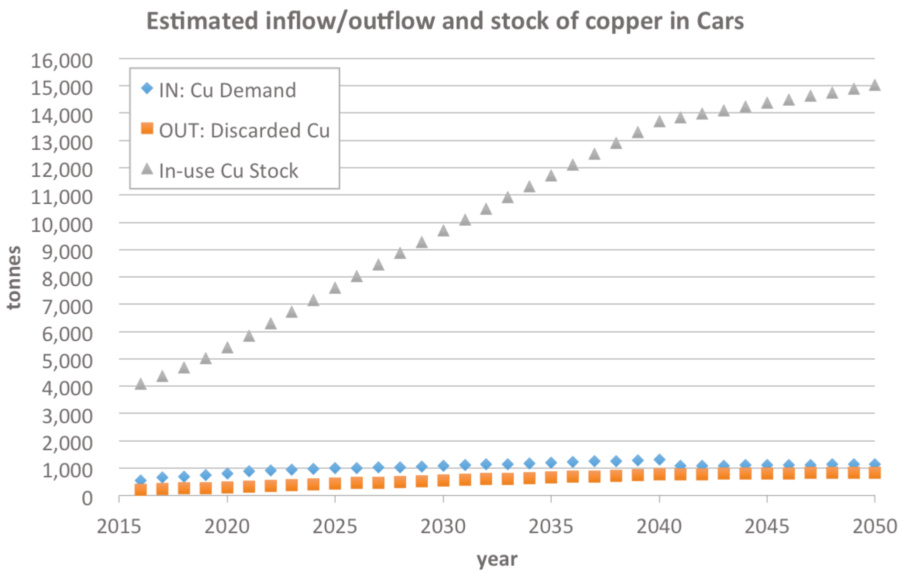

Figure 32. Inflow, outflow and stock of copper in cars (tonnes)

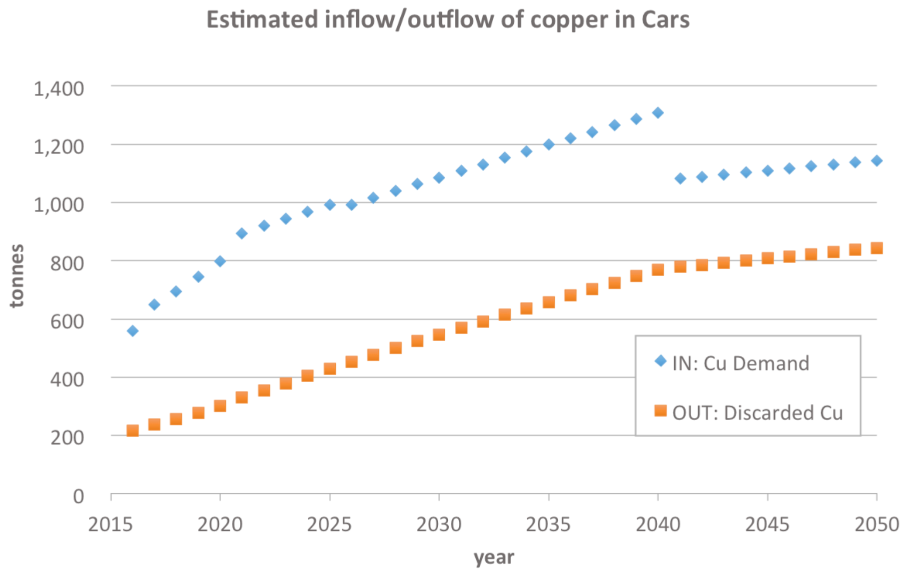

Figure 33. Inflow and outflow of copper in cars (tonnes)

- **Vessels**

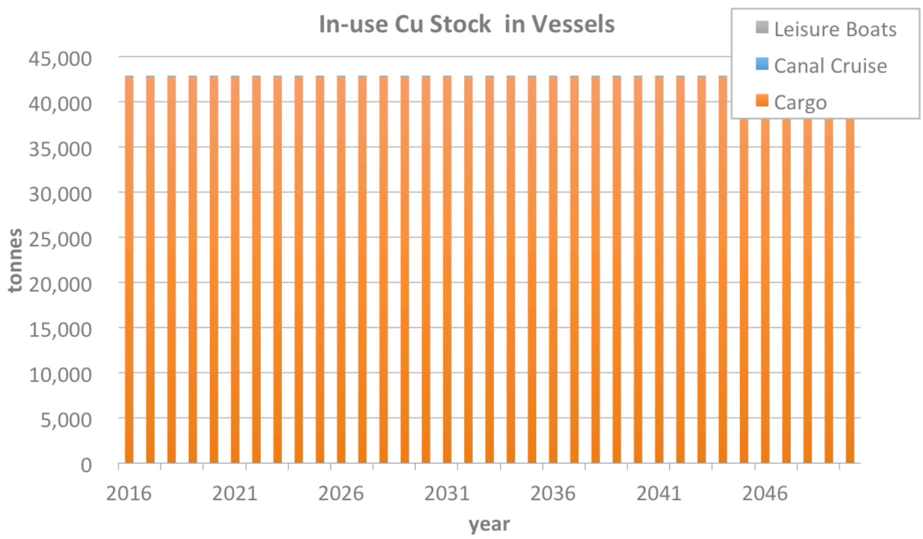

Figure 34. In-use Cu stock in vessles

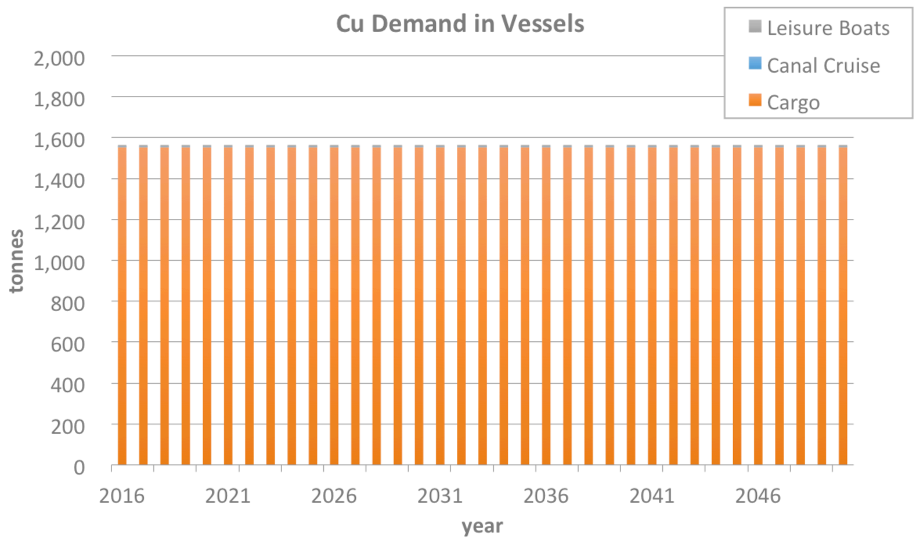

Figure 35. Cu demand in vessels (tonnes)

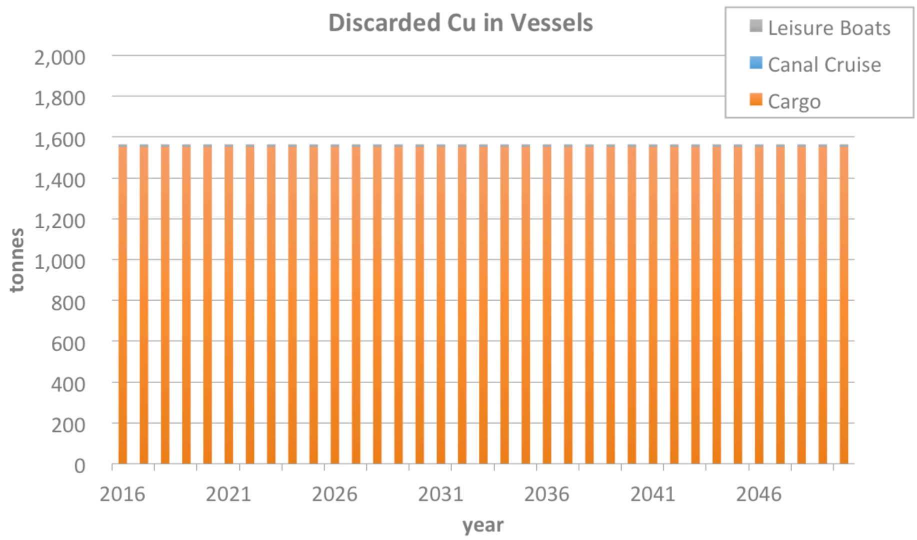

Figure 36. Discarded Cd in vessels (tonnes)

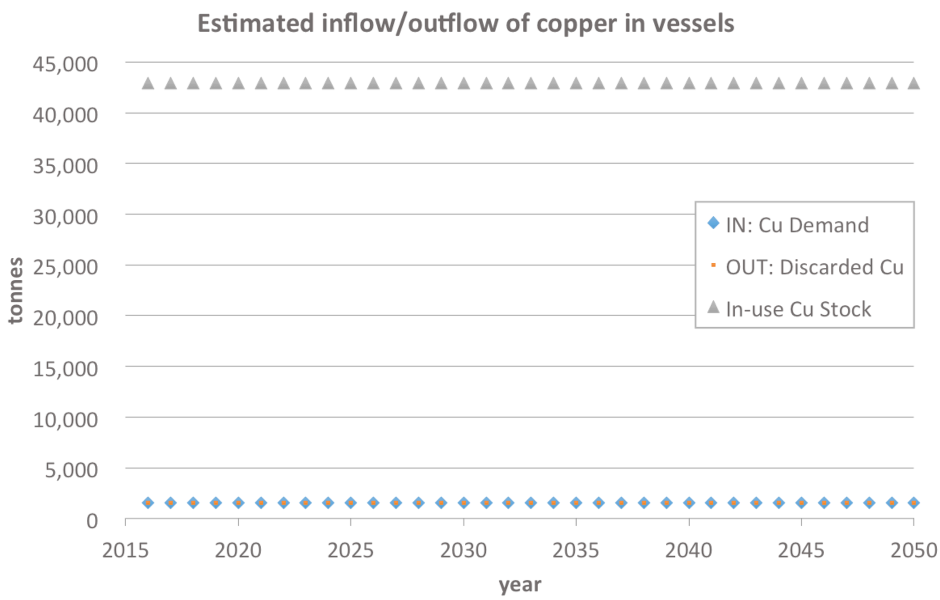

Figure 37. Inflow and outflow of copper in vessels (tonnes)

- **Truck**

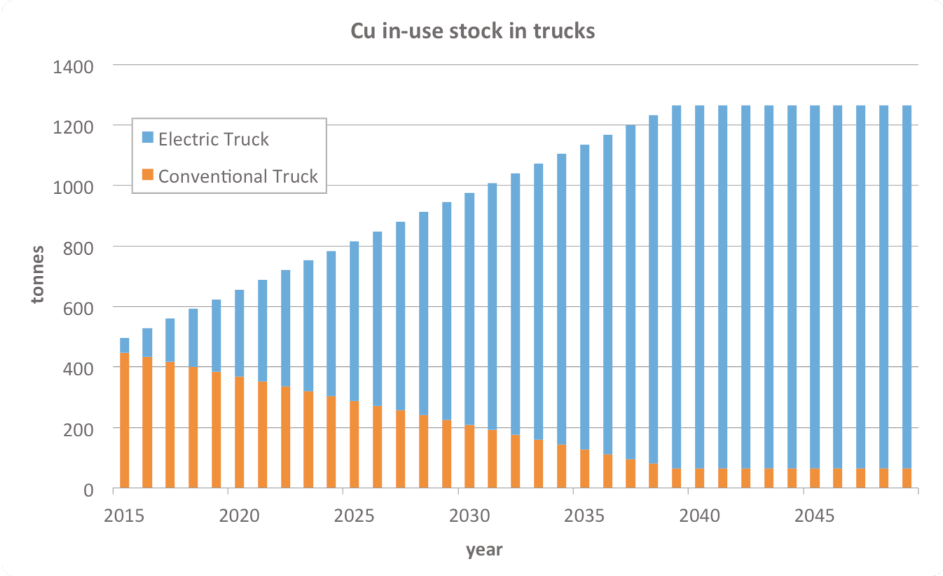

Figure 38. In-use Cu stock in trucks

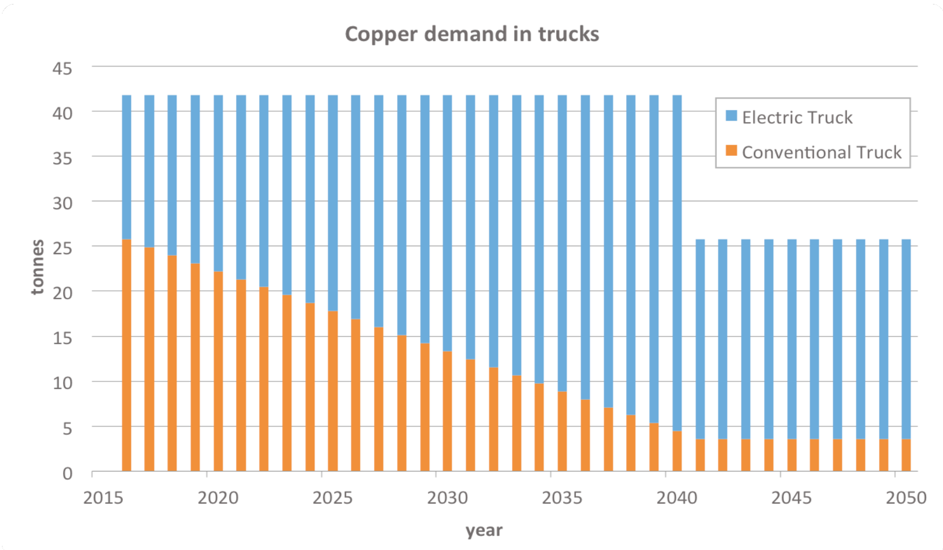

Figure 39. Cu demand in trucks (tonnes)

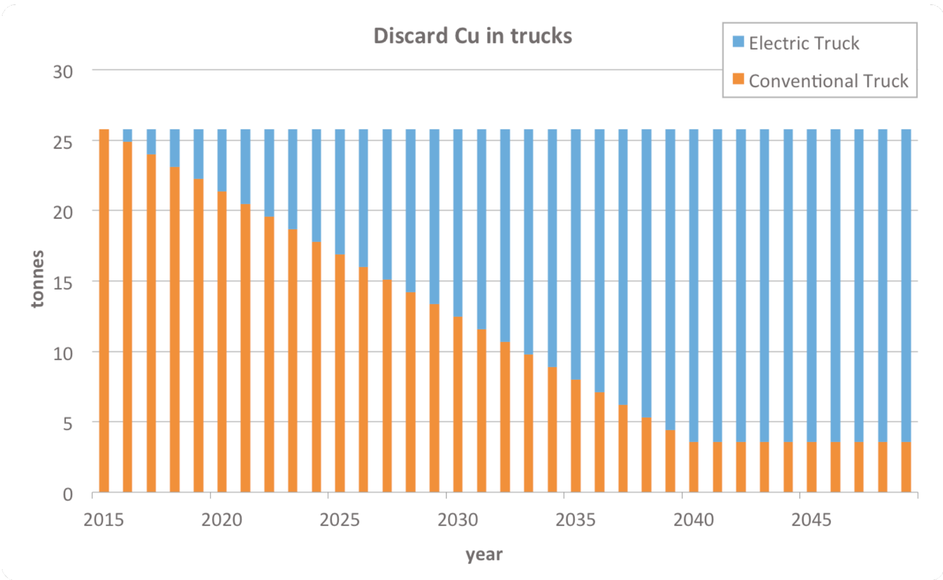

Figure 40. Discarded Cu in trucks (tonnes)

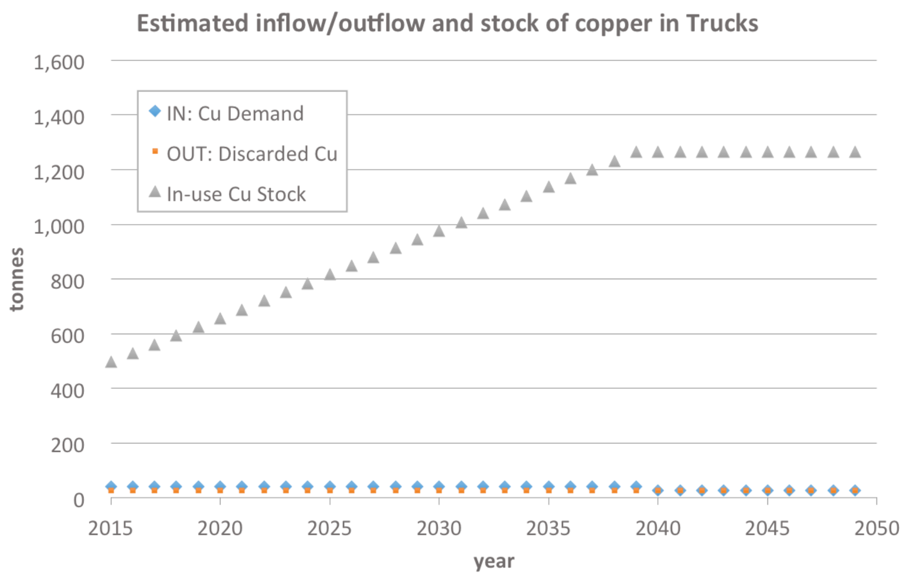

Figure 41. Inflow, outflow and stock of copper in trucks (tonnes)

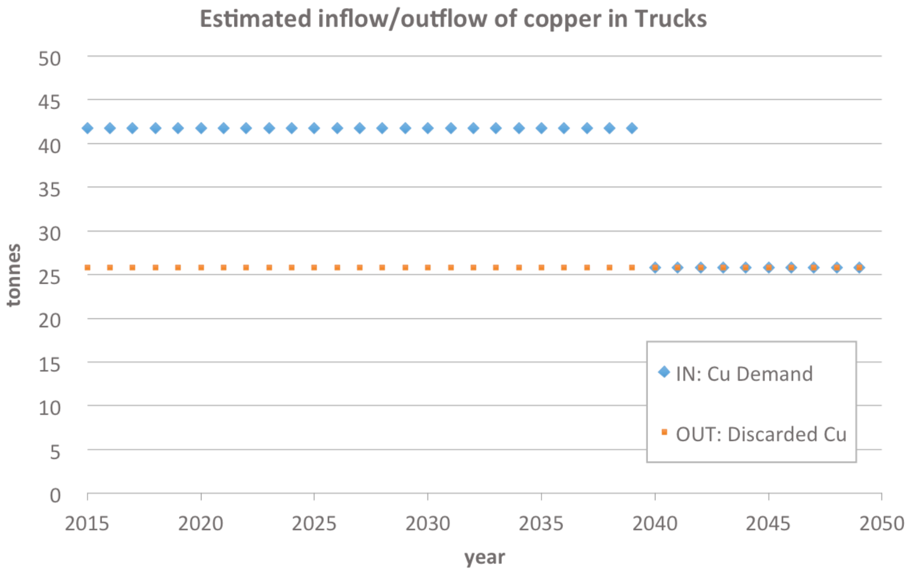

Figure 42. Inflow and outflow of copper in trucks (tonnes)

- **Motorcycle**

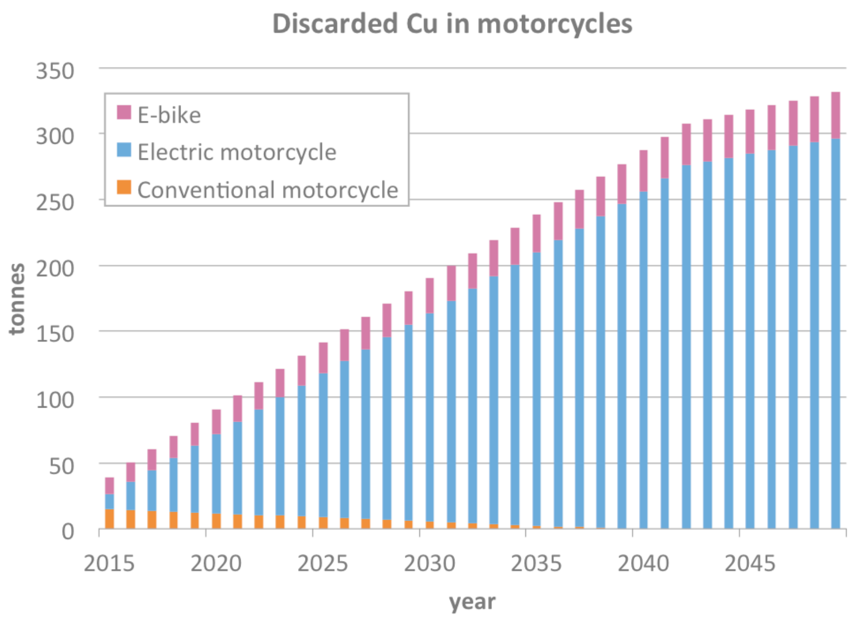

Figure 43. Discarded Cu in motorcycles (tonnes)

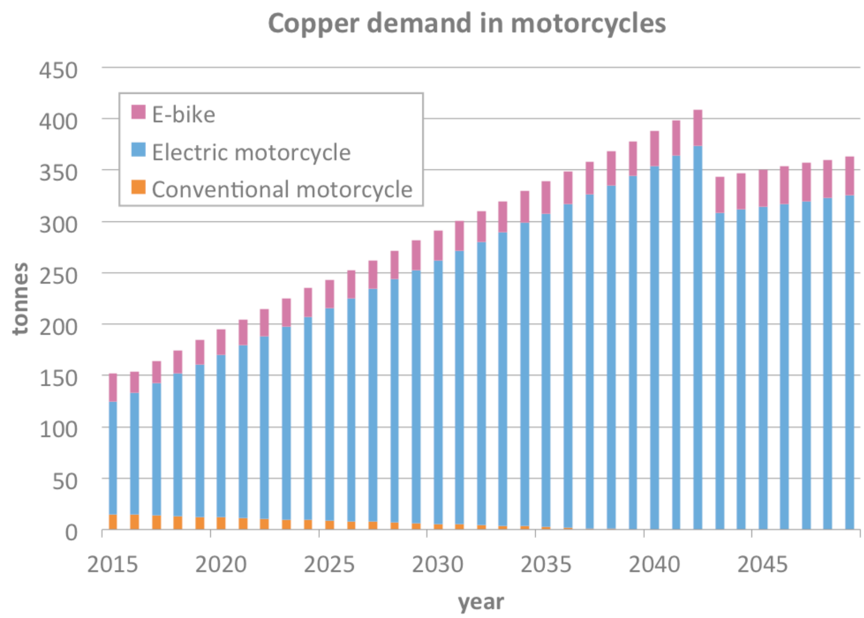

Figure 44. Cu demand in motorcycles (tonnes)

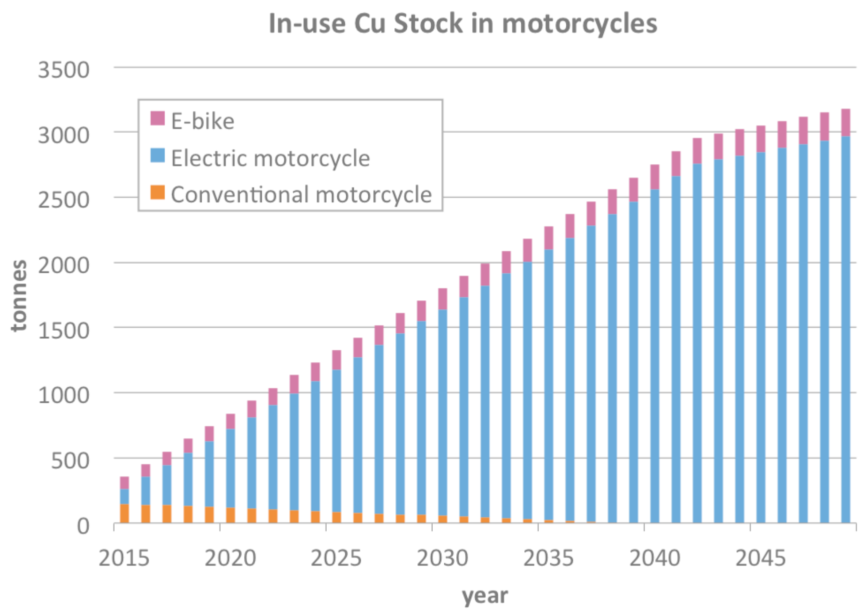

Figure 45. In-use Cu stock in motorcycles (tonnes)

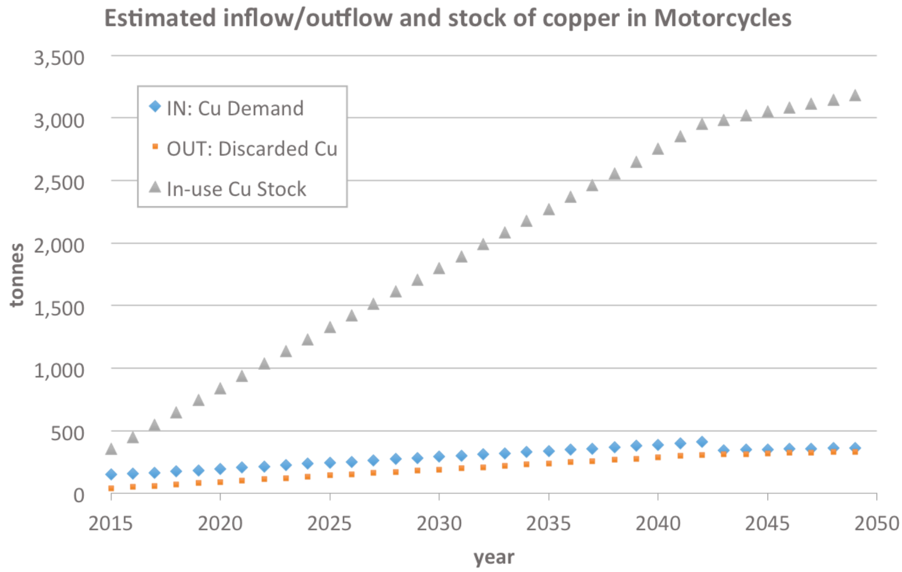

Figure 46. Inflow, outflow and stock of copper in motorcycles (tonnes)

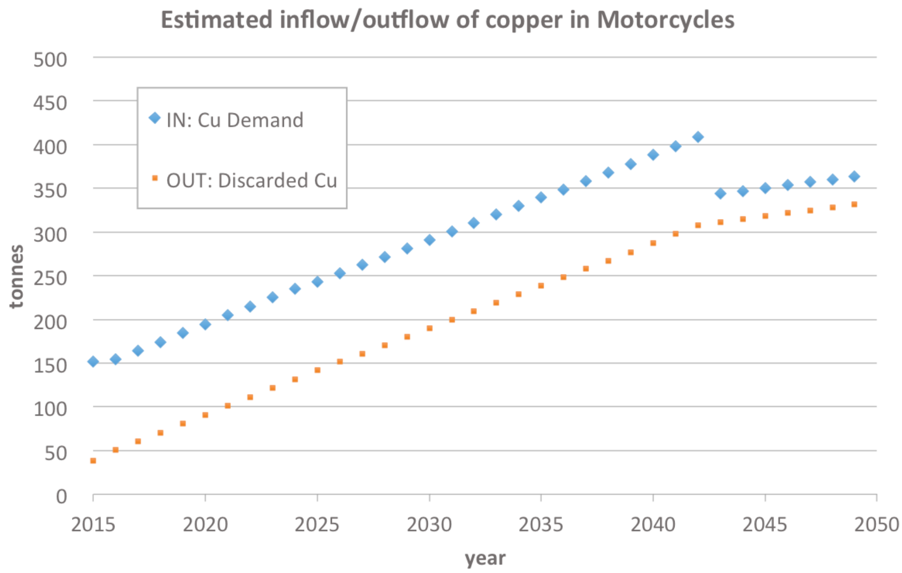

Figure 47. Inflow and outflow of copper in motorcycles (tonnes)

- **Bus**

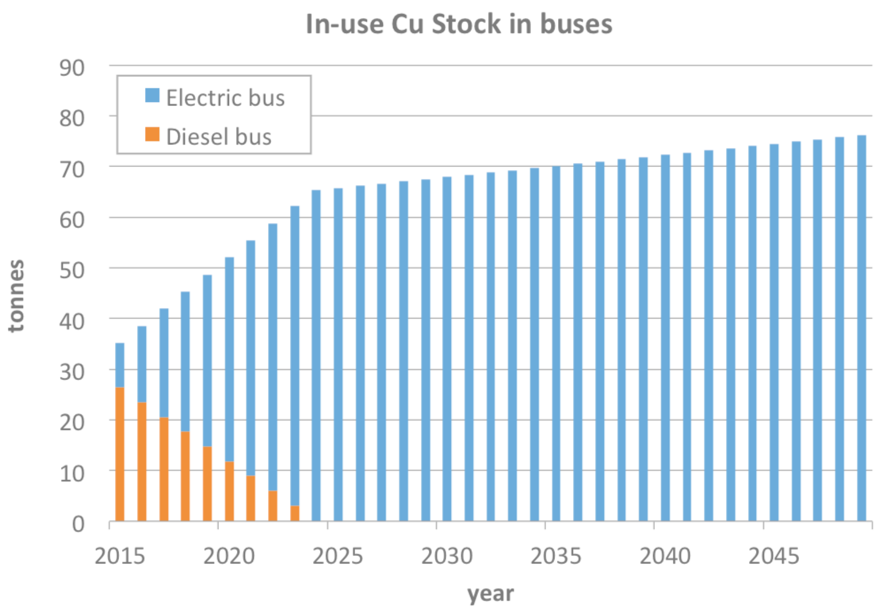

Figure 48. In-use Cu stock in buses

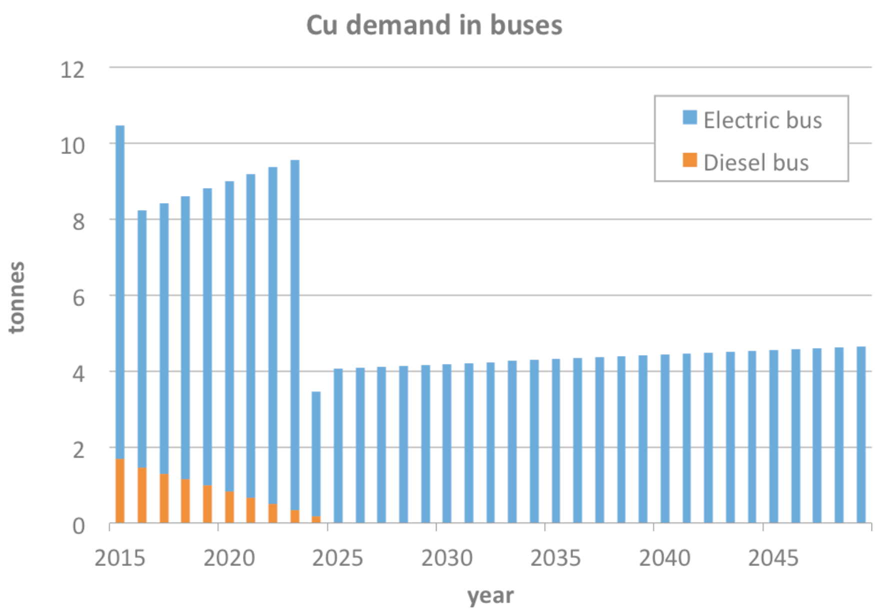

Figure 49. Cu demand in buses (tonnes)

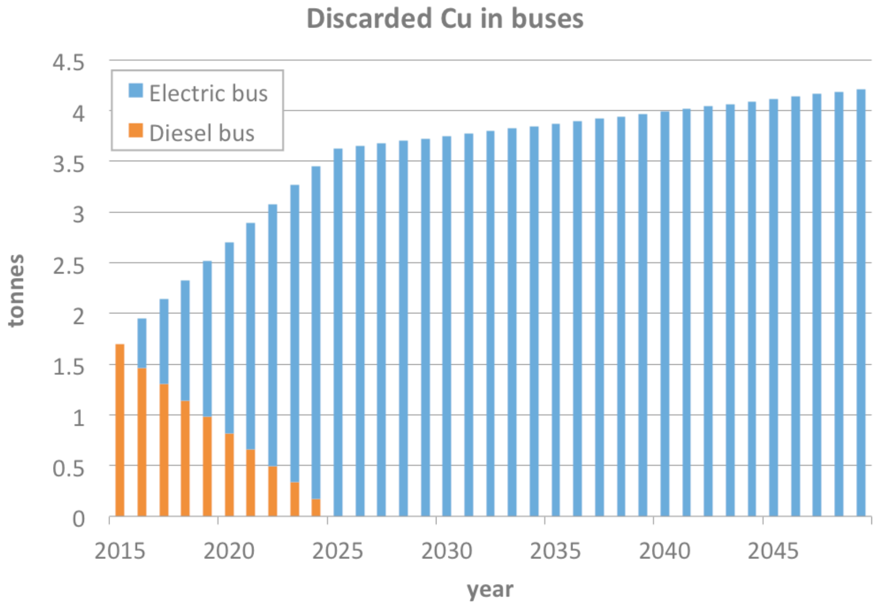

Figure 50. Discarded Cu in buses (tonnes)

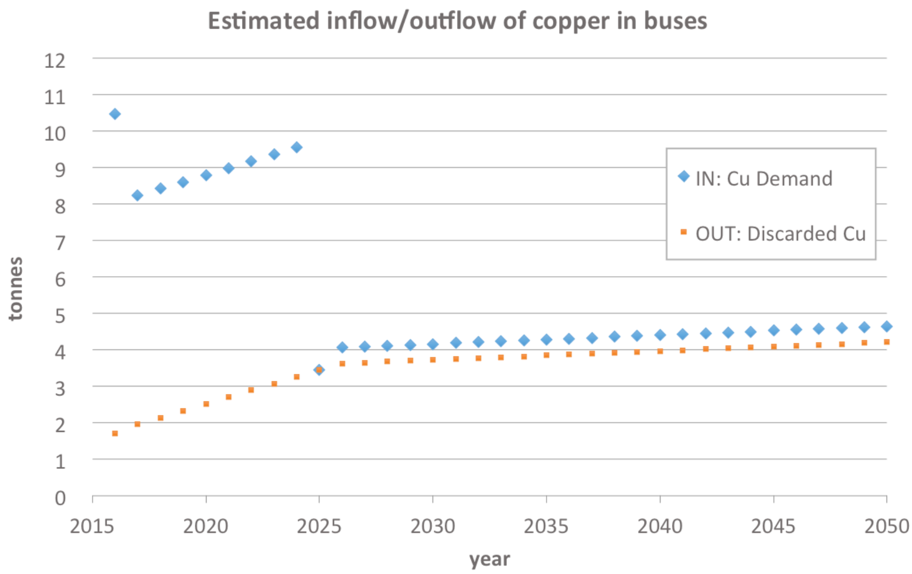

Figure 51. Inflow and outflow of copper in buses (tonnes)

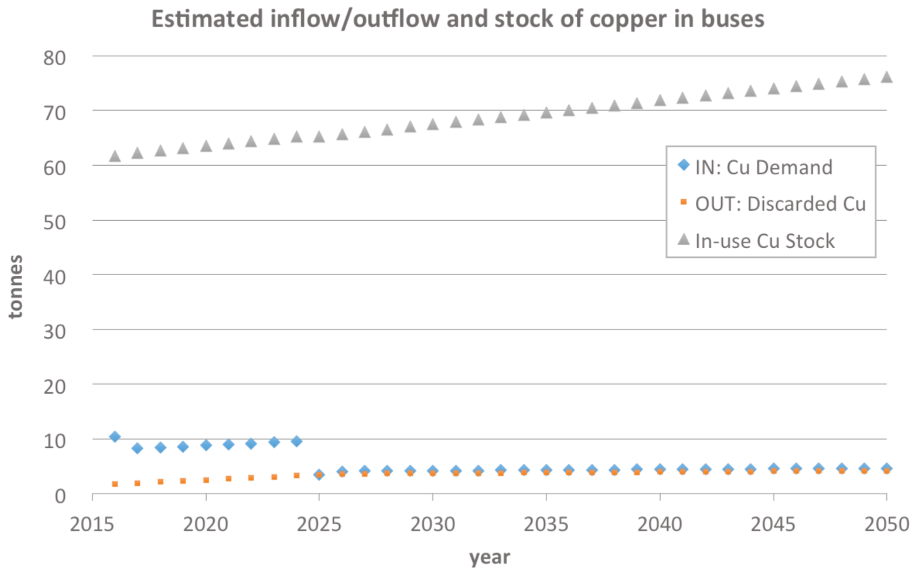

Figure 52. Inflow/outflow and in-use stock of copper in buses (tonnes)

- **Railcar**

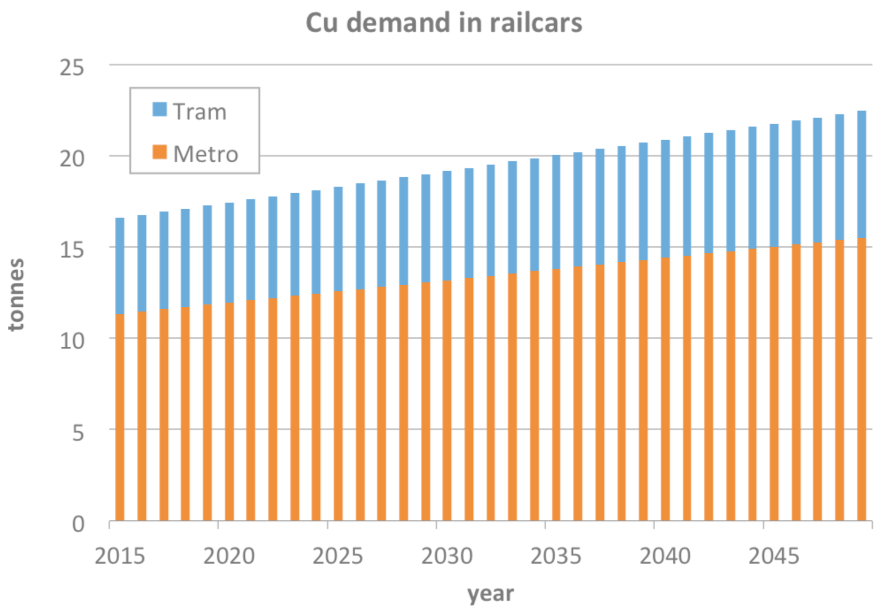

Figure 53. Cu demand in railcars (tonnes)

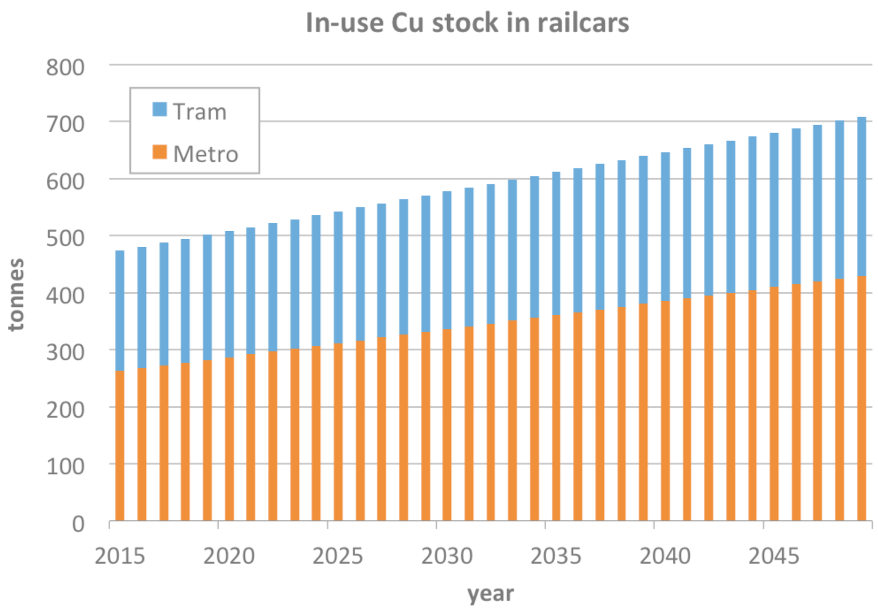

Figure 54. In-use Cu stock in railcars

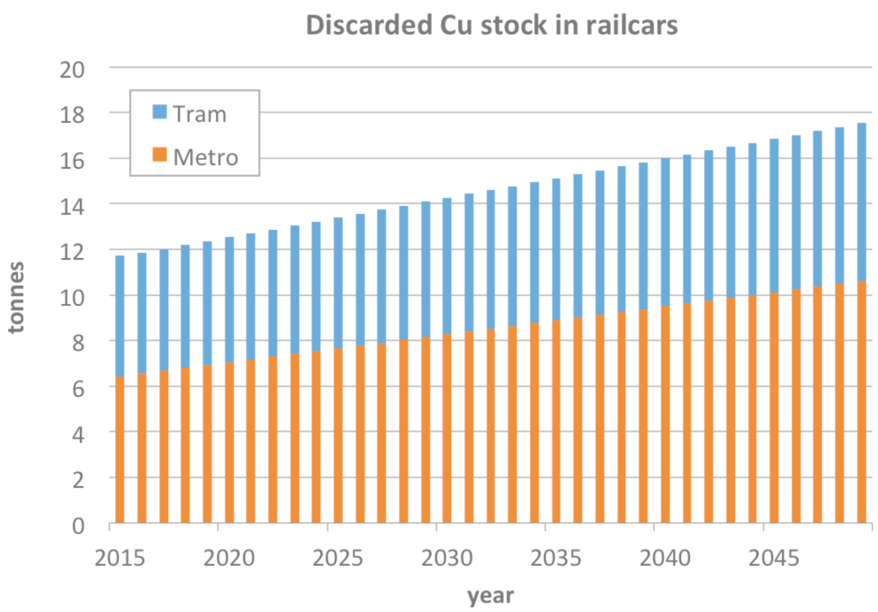

Figure 55. Discarded Cu in railcars (tonnes)

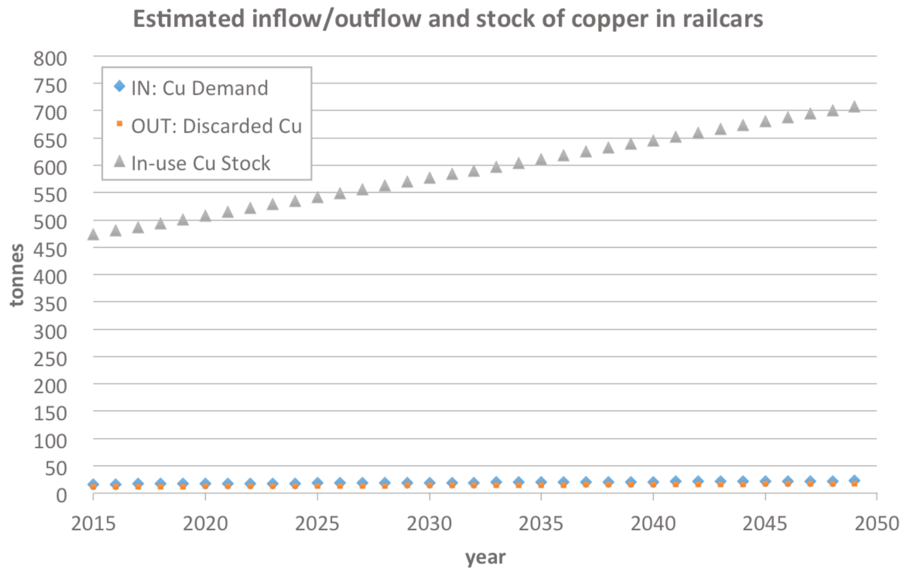

Figure 56. Inflow/outflow and in-use stock of copper in railcars (tonnes)

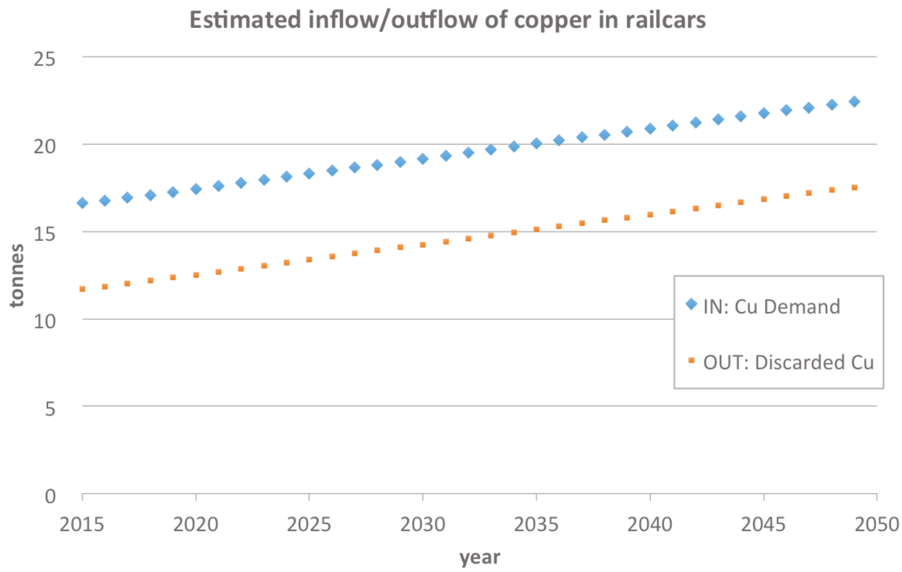

Figure 57. Inflow and outflow of copper in railcars (tonnes)

4. CONSUMER DURABLES

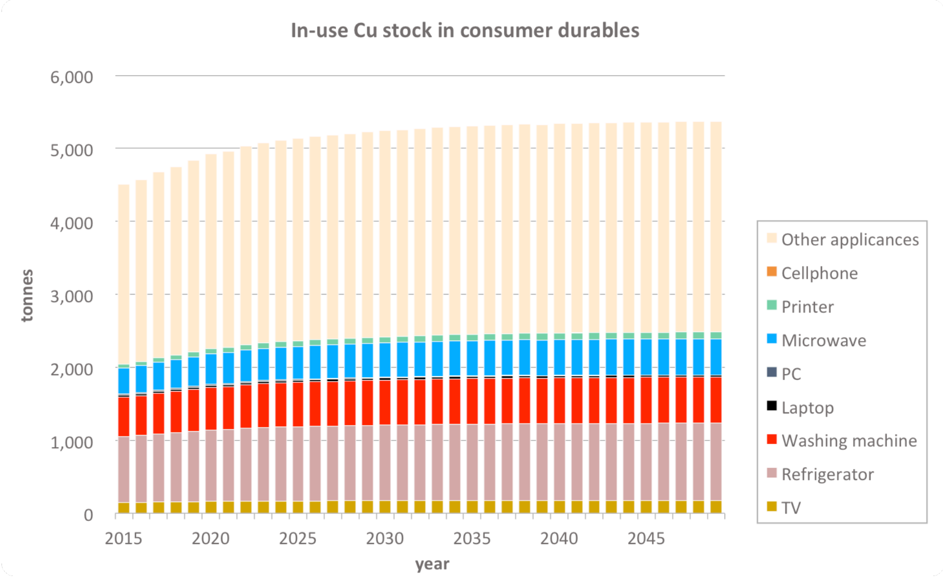

Figure 58. In-use Cu stock in consumer durables

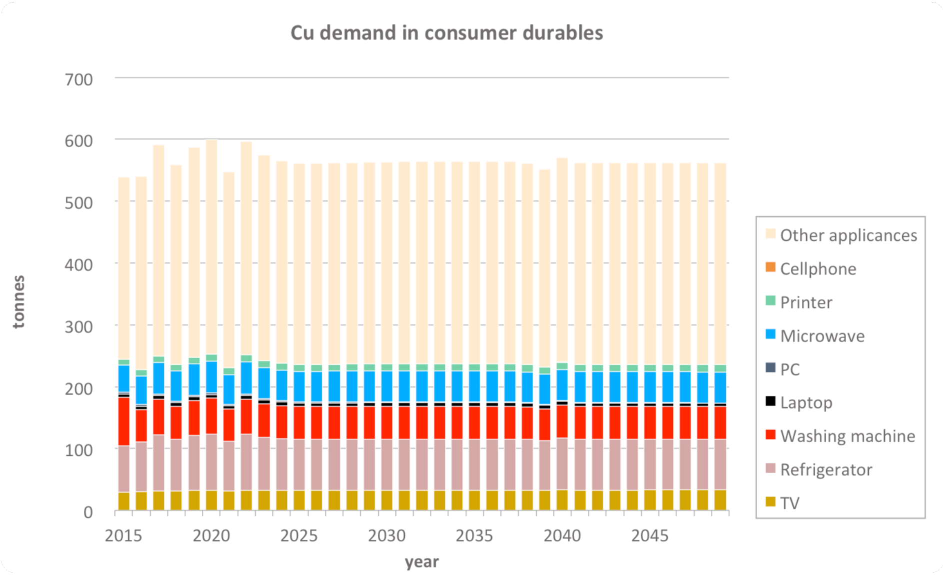

Figure 59. Cu demand in consumer durables

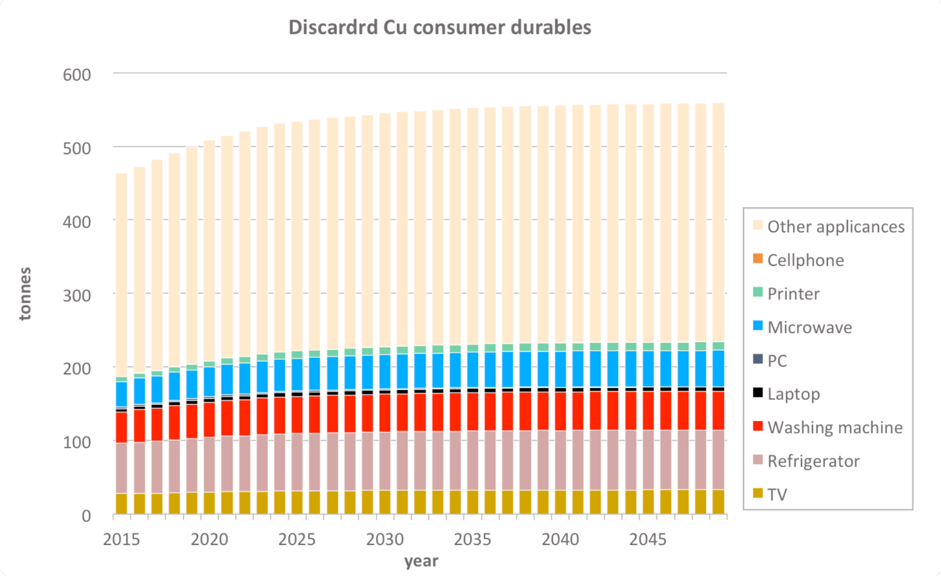

Figure 60. Discarded Cu in consumer durables

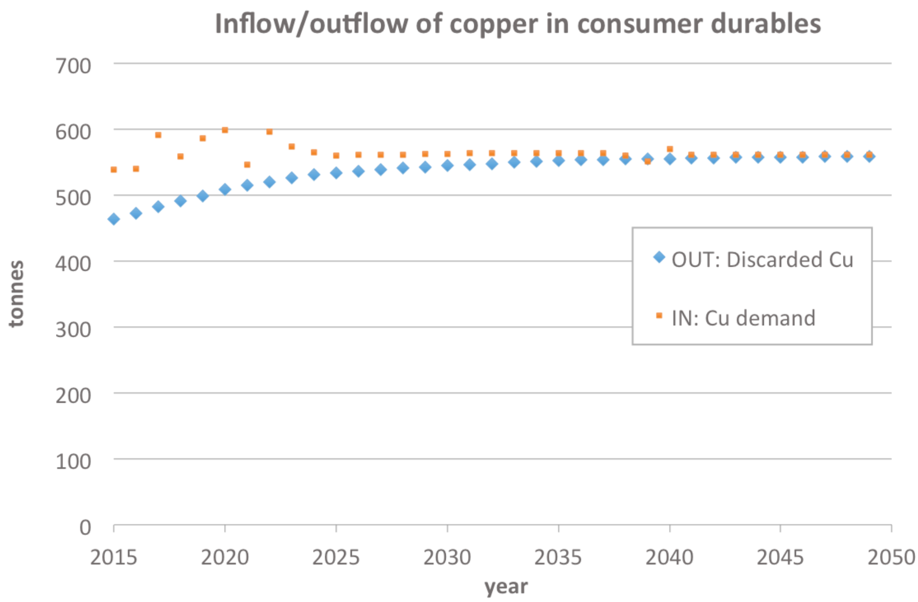

Figure 61. Inflow and outflow of copper in consumer durables (tonnes)

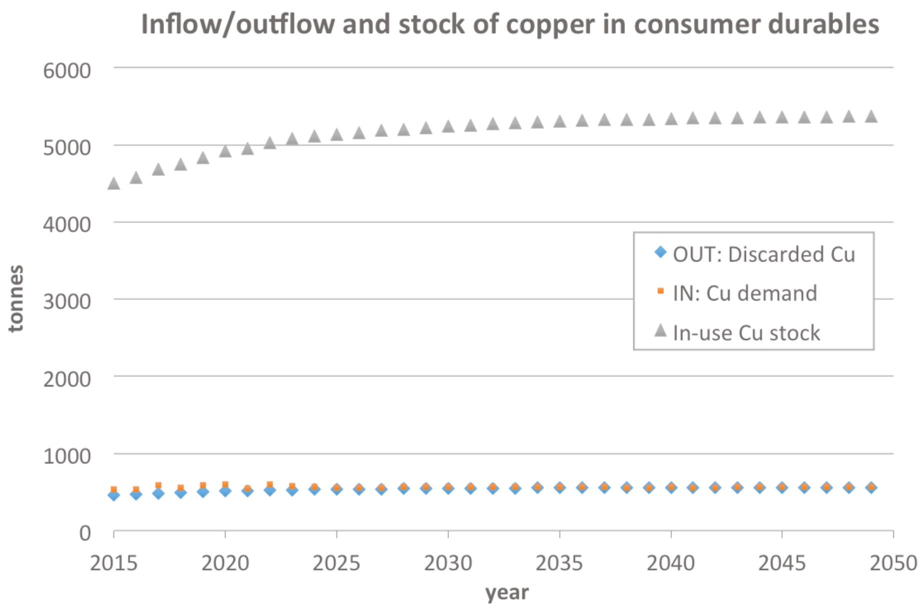

Figure 62. Inflow, outflow and in-use stock of copper in consumer durables (tonnes)

5. INDUSTRIAL DURABLES

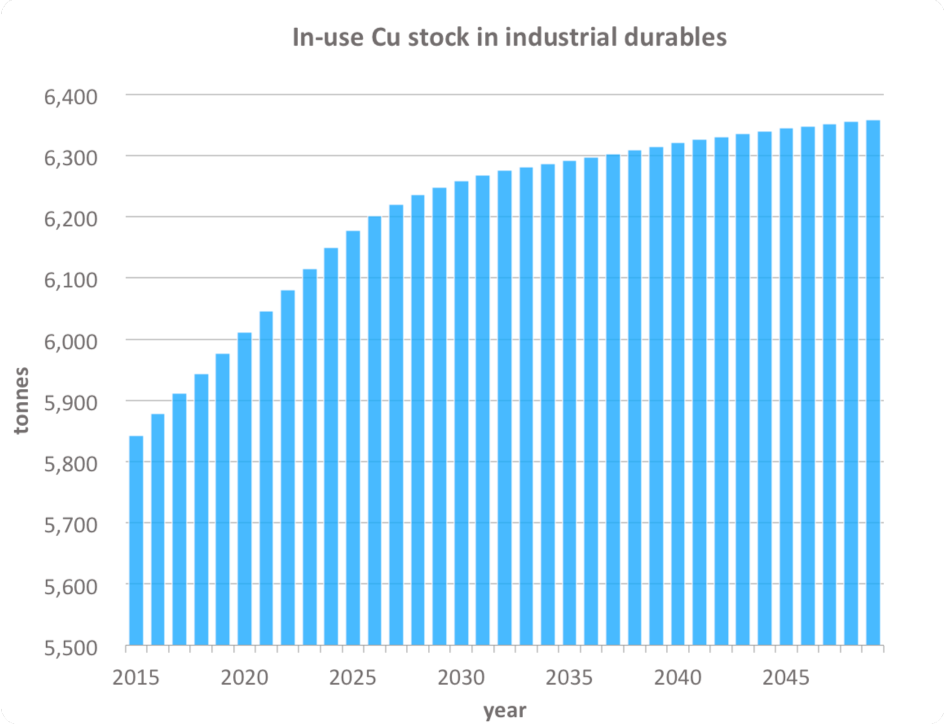

Figure 63. In-use Cu stock in industrial durables

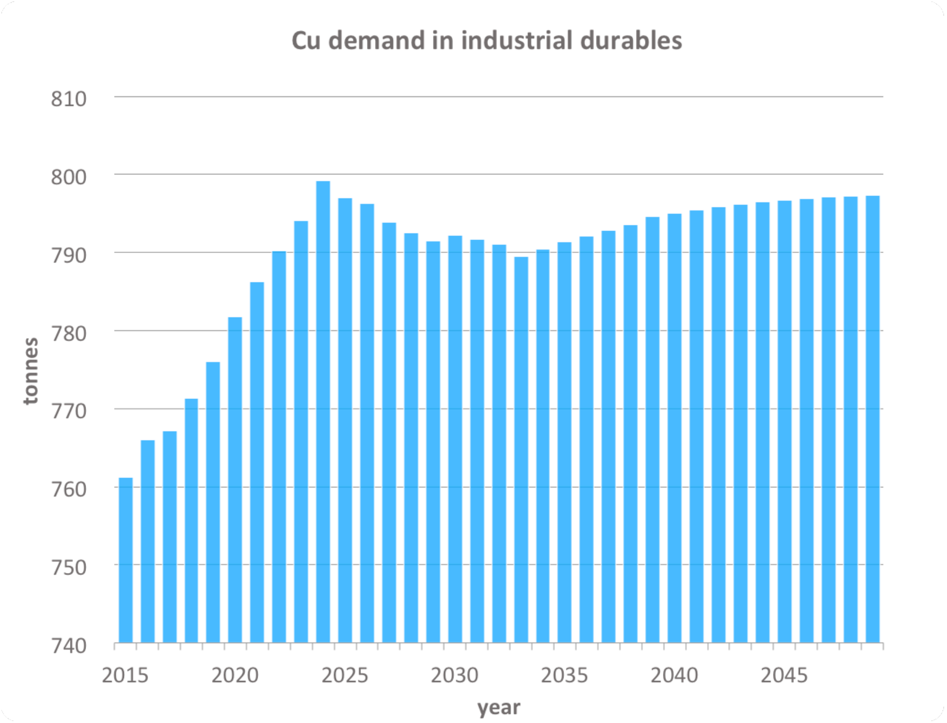

Figure 64. Cu demand in industrial durables

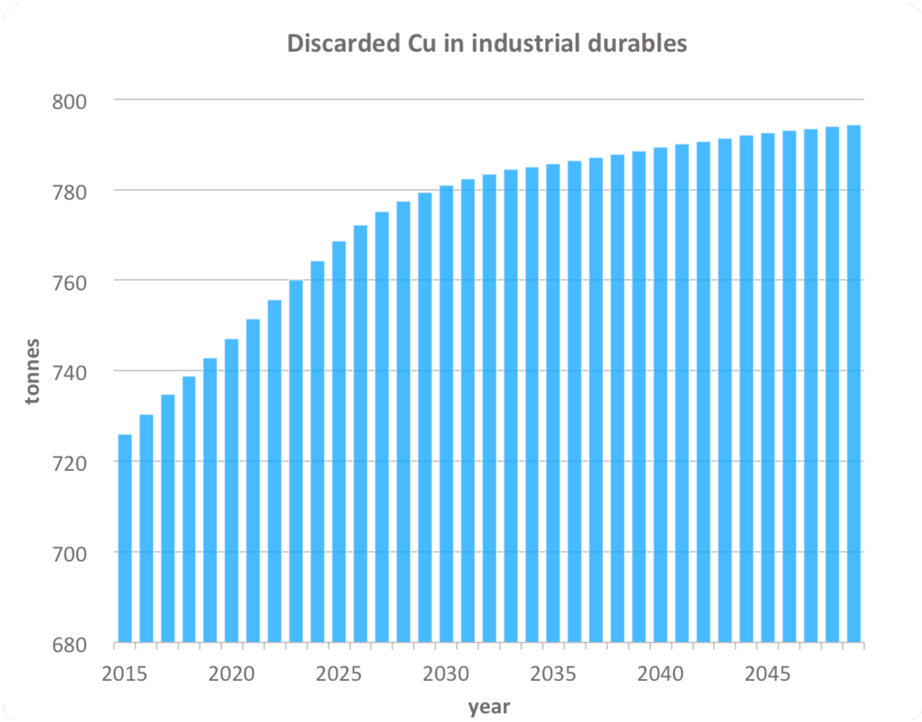

Figure 65. Discarded Cu in industrial durables

6. CORPORATE DURABLES

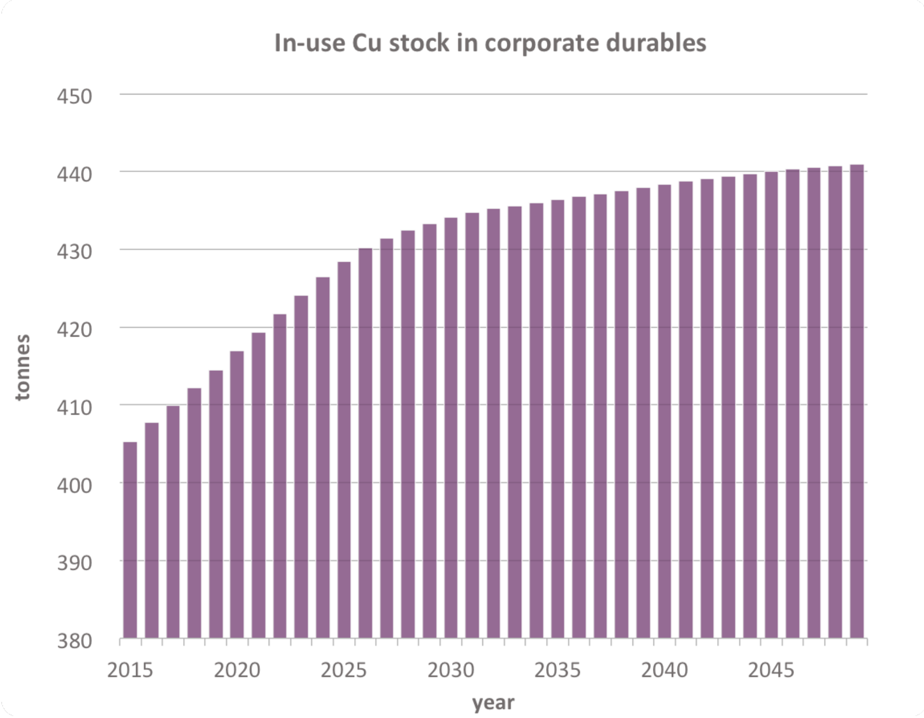

Figure 66. In-use Cu stock in corporate durables

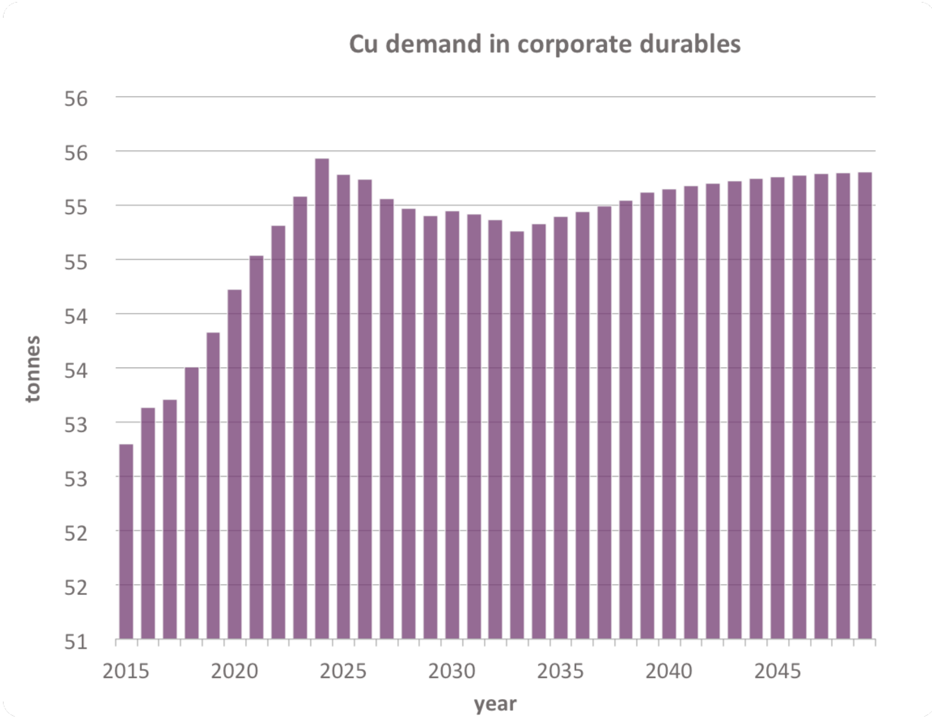

Figure 67. Cu demand in corporate durables

Figure 68. Discarded Cu in corporate durables

APPENDIX 3: PUMA Blog Article

[Note: This article was written in April 2016 for the PUMA Project commissioner AMS to publish on its project Blog as a social outreach]

I am a Masters student studying Industrial Ecology under the Joint Program of TU Delft and Leiden University. My thesis explores how mineable is the City of Amsterdam going to be in 2050 for copper. Wait a second, did you just say that you want to mine the city? Is there a mine in Amsterdam? Well, yes, and you're sitting right in it! I am treating the city as an artificial mine, an urban mine. The valuable metals are lying in your cellphone, in the heater, or in the tram car that you just hopped on. With a different scope but connected with PUMA, my thesis emphasizes on evaluating the city's potential of urban mining to fulfill the copper demand in 2050.

Let's hop on the time machine built by Dr. Emmett Brown in "Back to the future". Now, imagine yourself arriving in Amsterdam in 2050 and taking a picture of the city. What do you see? How many electric vehicles do you see running on the street? And what happens after the electric vehicles reach the end of their lives? Would we be able to reuse these metals that make our daily products such as cars, trams, and buildings in a smart and systematic way? Cities in the Netherlands are enthusiastically racing towards a circular economy with rising renewable energy systems and smart grids installations. But if we put on the "ambition-check" glasses, with the long term vision proposed by current policy, would we be ready to run the city without the help of fresh copper? What still needs to be improved to take us towards a more circular Amsterdam for copper? These are the questions I hope to explore in my thesis.

I am now in the first phase of the research, quantification. I am using a bottom-up method, which means I need to first make a list of where copper is used in the city. Then find out the copper content of all the applications, and their quantities. Of course, no one knows what happens in the future. So I will be constructing a scenario that is in line with the current policy.

The biggest challenge I've had so far is language barrier. Being a foreigner that speaks only a handful of Dutch phrases, I struggle to find my way in information that are only available in Dutch. I am teaming up with colleagues in my program that are also associated with PUMA to facilitate the work. With this research I hope to provide some reality check for the current sustainability ambitions, and use some examples to show where could the copper gone if they are missing in the cycle.