HOW BIG IS THE CHALLENGE?

An exploratory research on modeling an estimation of the costs of a transition towards a circular economy in the metropolitan area of Amsterdam

Erwin Fijt

How big is the challenge?

An exploratory research on the estimation of the transition costs of the metropolitan area of Amsterdam towards a circular economy

by

Erwin Fijt

In partial fulfillment of the requirements for the degree of

Master of Science

Industrial Ecology

First supervisor	:	Dr. Ir. I. Nikolic
Second supervisor	:	Prof. Dr. R. Künneke
Student number TU Delft	:	4525612
Student number Leiden University	:	s1740008

SUMMARY

Nowadays, it seems widely recognized that economies and societies experience various pressures, such as climate change and reaching the boundaries of resource extraction, due to the design of the economy according to linear principles. The largest source of pressures are urban areas, where 75 percent of the global resources and 80 percent of the global energy is consumed. The recognition of the necessity for change led to the signing of the Paris Agreement in which 195 countries agreed on not letting the global temperature rise with more than 2 degrees Celsius. It is often claimed that transforming the design of the economy to one that is based on principles of the circular economy offers a solution to these pressures.

However, the endorsed necessity for this transition is currently not leading to significant systemic changes that enable the transition towards a circular economy. In order to comply with the Paris Agreement, the transition needs to be kickstarted. The finance sector can have an important enabling function in kickstarting the transition towards a circular economy by investing in projects that accelerate the transition towards a circular economy. However, these investments are lagging behind, due to the reduced connection between the financial sector and the real economy.

To get an idea of the order of magnitude of the investments needed, the costs of a transition towards a circular economy should be estimated. As an estimation of the order of magnitude of the costs for a transition towards a circular economy has not been performed yet, a clear methodology on how to estimate these costs is lacking. The lacking methodology represents a knowledge gap. Modeling a well-founded estimation of the costs of a transition towards a circular economy could fill this knowledge gap. While estimating these costs on a global scale is not achievable, the focus lies on metropolitan areas. The main research question of this master thesis is therefore '*How to model a well-founded estimation of the costs of transition towards a circular economy for a metropolitan area?'*. The focus of this master thesis is on the Amsterdam metropolitan area (AMA).

In order to start modeling, the concepts of a metropolitan area and a circular economy were clearly delineated. The delineation of these concepts has been performed by means of a literature review. This literature review showed that when assessing a circular economy in a metropolitan area, the following sectors should be included: Food/agriculture, energy supply, transport, built environment/construction, water and industry.

The next step was to operationalize the concept of a circular economy. Based on Fermi approximation, the most important variables and their relations were determined per sector, which resulted in a conceptual model that visualizes the current design of a metropolitan area. Considering the current design, the limitations of the current design were uncovered to identify which variables under performed in terms of circularity. Applying the principles of the circular economy to the conceptual model of the current situation allowed constructing a general vision for a circular metropolitan area.

Based on literature and the use of Fermi approximation, the conceptual model was specified for the AMA. Variables were decomposed to smaller parts, which made them more suitable for estimating their value. Estimating the values of the variables resulted in a baseline scenario that represented the current design of the AMA. The circularity performances of this baseline scenario were measured according to key performance indicators (KPIs) that resulted from a literature review. The used KPIs were: energy demand, water demand, self-sufficiency of the construction sector, self-sufficiency of the food sector.

The model showed that currently none of the key performance indicators is close to being circular. Only in terms of some food groups, the AMA can be theoretically self-sufficient.

As the baseline scenario was constructed, the following step was to determine what a circular economy would look like in the AMA. The key goal of this step is to identify the changes in the values of variables and new relations between variables. The identification of these changes is performed on the basis of literature research. The construction and quantifying of a vision for a circular AMA resulted in two different scenarios: a minimum scenario and a maximum scenario. The outcome of the model showed that a circular AMA is not possible within the set boundaries of the metropolitan area. One of the key findings of the research is that a fully circular metropolitan area is rather an ambition that gives direction towards a desired situation, than an achievable end goal.

It was not possible to further model the case of the AMA, due to time constraints. However, when time would have allowed it, the quantified vision of a circular AMA would form the basis for identifying the most important resources, processes and technologies that enable the transition towards a circular economy. This identification would be performed by combining life cycle inventory (LCI) databases with the constructed model of the circular metropolitan area. This combination should give insight in how much material and energy is required per function that needs to be fulfilled in a circular economy. Besides the material and energy requirements, the link to an LCI can also help to assess the environmental impacts of a circular AMA.

Based on the mapped resources and impacts, the translation to expressing these in a monetary value is required to estimate the costs of a transition towards a circular economy. Research should focus on willingness to pay studies that quantify environmental externalities and pricing them.

Preface

Since the beginning of my studies, I have been interested in the big challenges we face as a society. Especially the effect of the malfunctioning of financial markets on sustainability ambitions. My belief is that the financial market bears a huge potential to reach our sustainability ambitions. As I reckon that the financial market does not live up to its potential, the belief is translated in a frustration. In the search for a supervisor I spoke to Igor about this frustration. Since he shared my vision, we started to think about a topic that could address this problem. Before we reached a proper thesis topic, some time had already passed. Despite the fact that this thesis does not come up with a redesign of the financial sector, I believe that it does make a positive contribution to finding a solution.

Before one starts reading this thesis, I would like to thank a few people that have had an important role during this process. First, I would like thank my two supervisors, Igor and Rolf, for their guidance throughout the course of this research. They have supported and challenged me to translate a theme of a very large order of magnitude in a manageable research topic. Second, I would like to thank Marijn, with whom I spent lots of hours studying. And last, but definitely not least, I would like to thank my parents for their unconditional love and support during this process.

Erwin Fijt, June 2018

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

LIST OF FIGURES

LIST OF TABLES

1. Introduction

1.1 Problem description

1.1.1 Need for transition

In December 2015 the Paris agreement was signed, in which 195 countries agreed on not letting the global temperature rise with more than 2 degrees Celsius, in order to protect the world against a rising sea level, an increased number of droughts and floods, a decreasing biodiversity, and many other negative consequences resulting from climate change (Winans et al., 2017). Besides the threat of global climate change, several resources are close to their natural or economic boundaries regarding to extraction of these resources (Brown et al., 2014). The pressures resulting from climate change and reaching the boundaries of resource extraction are often mentioned in the same breath with the linear economy and a transition towards a more circular economy.

A linear economy is described as an economy that is based on the 'cradle-to-grave' concept, which translates to resource consumption that follows a 'take-make-dispose' pattern. When resources and products are used and discarded, the value of those resources and products is lost (Ellen MacArthur Foundation, 2012). In combination with the large dependence on fossil fuels and current demographic trends (global population numbers are expected to reach 10 billion by the year 2050 (Roser & Ortiz-Ospina, 2017)), these pressures are often claimed to be responsible for climate change and resource scarcity.

Lots of pressures on societies and the environment are related to the linear economy originate from urban areas. As currently more than 50% of the global population lives in urban areas, this is not very surprising. This number is still rising (Seto et al., 2012). 75 percent of global resources and 80 percent of the global energy supply are consumed in cities (Prendeville et al., 2017). Cities and urban areas are seen as centers of production, consumption and waste disposal. For that reason urban areas are responsible for high environmental impacts, and they represent big challenges for sustainability (Mat et al., 2016; Pomponi & Moncaster, 2017). Furthermore, the threats of climate change could affect urban areas. It could lead to floods, droughts and storms, which can be disastrous for urban areas (Prendeville et al., 2017).

In response to the linear economy, the concept of a circular economy was developed. This started in the 1970s and was further developed in the years that followed (Geissdoerfer et al., 2017; Kobza & Schuster, 2016). Currently, the most widely used definition is the definition developed by the Ellen MacArthur Foundation (2012): *"A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models"*.

1.1.2. Transition towards a circular economy

As the current trajectory of the economy is mostly built upon principles of the linear economy, changes are required in order to shift towards a trajectory that is based upon principles of the circular economy. The focus of the Ellen MacArthur Foundation (2012) is mainly on designing products in a more modular way to create more favorable conditions for efficient and effective take-back systems. It is emphasized that business models should change and have a larger focus on the reuse, refurbishment, and redistribution of products. Furthermore, it is stated that a circular system should run on renewable energy. Based on Bouton et al. (2016), supplemented with insights from other literature, one can distinguish four steps that need to be taken in order to get to a circular economy.

1. One needs to shift towards the use of renewable energy and materials. This step is mentioned by the Ellen MacArthur Foundation, but also emphasized in other literature. This is a very important step, since the IEA expects the global energy consumption to grow with 50% by 2030 (under business-as-usual scenarios)(Ellen MacArthur Foundation, 2012; Preston, 2012).
2. Utilization of products should be maximized by sharing and reusing. This entails changes in business models. Business models should be built around open-loop and closed-loop supply chains (Genovese et al., 2015). On an industrial level, this means that waste streams have to be integrated in the processes in order reuse them (Preston, 2012).
3. Improvement of the performance and efficiency of products and technologies. Despite the focus on working with waste streams, efficiency remains of importance. The Ellen MacArthur Foundation (2012) emphasizes that this should not be the focus, but it should be addressed.
4. Replacing old technologies and materials with new ones. The development of new technologies must be accompanied by the replacement of old technologies to accelerate the transition.

1.1.3. Current status of the transition

The question that arises is *'Has the transition towards are more circular economy already started?'.* As this topic is high on the international agenda, one expects a rapidly changing design of the economy. Regarding this expectation, it could be argued that a transition towards a more circular economy has already started as all the components of a circular economy stated above are increasingly implemented.

Concerning the shift to renewable energy, the share of renewables relative to fossil fuels is nowadays 19,2 percent relative to 78,3 percent of fossil fuels (and 2,5 percent provided by nuclear energy). 8,9 percent of the 19,2 percent renewable energy is attributable to traditional biomass that is mainly used for cooking and heating in developing countries. The remaining 10,3 percent comes from modern renewables (biomass/geothermal/solar heat, hydro, wind/solar energy). However, while the use of renewable energy is increasing, the ratio of renewables to fossil fuels remains equal. This is mainly due to developed countries that are locked-in in an economy based on fossils (Sawin et al., 2016; Wüstenhagen & Menichetti, 2012). Path-dependency plays an important role, as the economy has been built around fossil fuels. Over the years, the vast majority of the infrastructure is based on fossil fuels, which means that switching to a renewable energy based system is considered to be very expensive and time-consuming (Aghion et al., 2014; Sawin et al., 2016).

Another reason that the share of renewables is not increasing is that the institutional environment is fairly rigid as it comes to stimulating renewable energy with subsidies or discouraging the use of fossil fuels by using excises. Numbers of the International Energy Agency show that worldwide fossil fuel subsidies were estimated at USD 493 billion dollars in 2014 (International Energy Agency, 2015). This is way more than the subsidies that exist for stimulating renewable energy. These subsidies account for USD 135 billion (Sawin et al., 2016). One could say that subsidies for fossil fuels undermine the efforts to mitigate climate change, because it has an effect on investments directed towards renewable energy technologies. High subsidies for fossil fuels create an environment in which the rate of return on investment for fossil fuels tends to be higher, compared to the return on investment for renewable energy. Which in turn has an impact on the allocation of resources across industries, including long-term capital investments (OECD, 2015b). This strengthens the earlier described path-dependency.

According to Wüstenhagen & Menichetti (2012), from the year 2009 to 2020, 400-500 USD of investments in clean technologies were needed annually in order to be consistent with the 2 degrees Celsius temperature increase. For the European Union, it was stated that a total investment capital of 1.1 – 1.3 trillion euros was needed to reach the EU targets of 2020. However, investment levels are not high enough to reach these targets. The investment should be directed towards energy supply, transmission networks and storage, and distribution networks (Jacobsson & Jacobsson, 2012).

As stated above, another theme within the transition towards a more circular economy is closing loops and using waste as a resource for new products. Some materials have quite high recycling rates already and are occasionally referred to as success stories in the transition. In OECD countries, this is the case for e.g. steel, glass, aluminum, paper and plastics (mainly PET), as some of these materials reach levels over 80% recycling (Bouton et al., 2016; OECD, 2015a).

To conclude, one could say that the transition has already taken off. However, the transition is not taking happening at a sufficient rate (Haas et al., 2016).

1.1.4. Investment challenge

Changing the leading paradigm to a circular one houses several important challenges. One of these challenges is to overcome the considerably high transition costs. These costs include research and development, subsidies, new business models, waste management, digital infrastructure, and way more (Bourguignon, 2016). A transition towards a circular economy therefore requires lots of investments.

It is often stated that finance has to function as a catalyst in the transition towards a circular economy, since the large amounts of money invested through finance (Sustainable Finance Lab, 2015). Over the past 40 years, the financial sector and its accompanying financial flows have grown enormously. However, the investments in the real economy that are needed for a transition towards a circular economy, such as investments in machinery, buildings, technology and so on, were virtually stagnant over the last 40 years. At the same time, investments in the so-called FIRE-sector (FIRE: Finance, Insurance, Real Estate) have exploded (Bodouroglou et al., 2010). The economy made a shift towards a market-based situation (Hardie & Howarth, 2013). A market-based financial system banks often works with short-term funding that focuses on securitization[1] and selling these securities to investors that are often related to the FIRE-sector (Jacobsson & Jacobsson, 2012; UNEP, 2015). According to Hardie & Howarth (2013), this has led to a situation in which 'patient capital', which is required in the transition towards a circular economy, is reduced and the connection with the real economy gets weaker. Short-term funding carries the upper hand, which has a negative influence on the transition (Jacobsson & Jacobsson, 2012; Martin et al., 2014; Soons, 2016).

[1] Securitization entails creating tradable financial instruments (securities) that represent a monetary value. This can e.g. be based on mortgages

1.1.5. ESTIMATING COSTS

In a context of lagging investments in the real economy, it remains unknown how much investments are required to kickstart the transition towards a circular economy. Considering the complexity and size of the challenge to find out the costs of such a transition, linking an exact number to this challenge is assumed not to be a viable option. Instead, estimating the costs to get a feeling for the order of magnitude of the challenge seems more logical.

As an estimation of the order of magnitude of the costs for a transition towards a circular economy has not been performed yet, a clear methodology on how to estimate these costs is still lacking. The lacking methodology represents a knowledge gap. Modeling a well-founded estimation of the costs of a transition towards a circular economy could fill this knowledge gap. As modeling an estimation of the costs is an ambitious and rather unexplored theme, the challenge lies in the process of how one comes to a model that is capable of estimating the costs.

1.2 RESEARCH QUESTIONS

As economies and populations are nowadays jeopardized by climate change and resource scarcity, speeding up the transition towards a circular economy is becoming an urgent matter (Ghisellini et al., 2016). Despite the growing urgency, the order of magnitude of the challenge in terms of costs of a transition towards a circular economy, remains unknown. As a clear methodology does not exist, the question is how to model these costs. In order to model this, it should be clear what modeling the estimation of the costs of a transition towards a circular economy entails.

Since modeling this for a global transition towards a circular economy as a scope is too big for a master thesis, the goal needs to be delineated. As mentioned, most of the pressures on societies and the environment come from metropolitan areas, so the focus on metropolitan areas narrows the scope, but grasps the largest share of the impact.

In this master thesis, the focus will be on the metropolitan area of Amsterdam, since the Amsterdam Metropolitan Area (AMA) has outspoken the ambition to become a circular metropolitan area. As they are actively involved with the transition, it is likely to find proper data on this topic.

Therefore, the following research question is posed:

"How to model a well-founded estimation of the costs of a transition towards a circular economy for a metropolitan area?"

In order to answer the above stated main research question, several sub-questions have been composed that help to answer the question. The sub-questions are:

1. How to conceptualize and delineate a circular economy in metropolitan areas?
2. How to operationalize a circular economy in a metropolitan area?
3. What would a circular economy in the Amsterdam metropolitan area look like?
4. What are the most important resources for a transition towards a circular economy?
5. What costs have to be considered related to the transition towards a circular economy?

Elaborating on how the costs could be estimated should function as a first step in creating a reliable model to approach questions that map transitions of this order of magnitude.

It should be stated in advance that this research is explorative in nature. Despite the delineation to the Amsterdam metropolitan area, answering the posed questions is very ambitious and a huge task to complete. The ambition is to answer this question, but besides the clear goal of answering the question, one of the goals of this research is to explore how questions of such nature should be dealt with in future research. Progressive insight will learn to extent this question is achievable, considering the restrictions in time.

1.3 RELEVANCE FOR INDUSTRIAL ECOLOGY

This research is very relevant for the field of Industrial Ecology. The most well-known concept that originates from the field of Industrial Ecology, the concept of a circular economy, is nowadays a very hot topic within society. The idea of getting rid of linear structures within the economy and design the economy in circular patterns is very closely related to the basic idea of Industrial Ecology, which is based upon a straightforward analogy with natural ecological systems. Where systems operate through a web of connections and nothing that contains available energy or useful material will be lost (Frosch, 1992). Getting to know what belongs to a circular economy, and what are the most important resources for a circular economy is therefore very relevant.

As a transition towards a circular economy is not something that happens overnight. Such a transition requires lots of time and money. Therefore, it is fundamental to get an idea of how much money it will cost to reach a circular economy (apart from the fact that it also brings lots of benefits, but this is not in the scope of this research).

2. Approach

This section provides a general outline on how to get a proper answer on the posed research question. The outline consists of five steps that are focused on answering the sub-questions. These sub-questions give direction in getting to an answer on the main research question.

Step 1: Conceptual model

The first step is to get a clear vision on what a metropolitan area and a circular economy are. Besides a clear understanding of the concepts, the concepts are delineated. This part of the first step gives an answer on the first sub-question *'How to conceptualize and delineate a circular economy in metropolitan areas?'*.

In order to answer this sub-question, a literature review is conducted. This literature review focuses on scientific literature and grey literature, i.e. reports and databases that elaborate on visions on a circular economy in metropolitan areas. During the literature review, the most important sectors of a metropolitan area, in terms of impact, are determined. These sectors form the basis for modeling a circular AMA.

As the sectors are determined, the follow-up is to create a measurable conceptual model of a circular economy in a metropolitan area. This part of the first step gives an answer on the second sub-question *'How to operationalize a circular economy in a metropolitan area?'*.

The operationalization is executed by constructing a conceptual model of how the sectors should be designed in a circular economy. In order to reach this goal, an overview of how the sectors are currently designed forms the baseline. This overview is created on the basis of scientific literature and grey literature. The result is an overview that includes the most important components, flows, and the relations between these within each sector. Creating this overview simplifies identifying the weaknesses of the system, and related to that, the opportunities for a circular economy.

Having conceptualized the current design of the sectors within a metropolitan area, including the identification of weaknesses and opportunities in terms of circularity, a general conceptual model for a circular economy within a metropolitan area is constructed. As geographic, environmental, economic and social factors influence the specification of a metropolitan area, e.g. geographic factors can be the hours of sunlight per day and naturally occurring falling water, the conceptual model is constructed in general terms.

The model is set up in simple equations, in order to perform some calculations at a later stage.

Step 2: Circular Amsterdam

The first step results in a conceptual model of a general circular economy in a metropolitan area. The second step focuses on what a circular economy means for the AMA. It gives an answer to the third sub question *'What would a circular economy in the Amsterdam metropolitan area look like?'*.

This sub question is answered on the basis of the created conceptual model. The corresponding equations are specified for the case of the AMA. First, the conceptual model is used to create a baseline scenario by specifying the model for the current situation. Data for the model quantification is, as much as possible, based on literature and data. The specific data is acquired by performing a desk research.

Subsequently, the conceptual model is quantified for the situation of circular economy in the AMA. This is based on lots of assumptions. As it concerns a scenario on a future situation, data can be qualified as uncertain. To deal with uncertainty, uncertain quantitative data is presented in a range (i.e. an upper and lower limit).

When quantitative data on the circular economy is lacking, quantitative data is estimated on the basis of Fermi approximation. It is very likely that this will result in lots of different assumptions. Each of these assumptions is noted, as full transparency pursued. This transparency is of great importance due to probability of uncertainty in this research.

Step 3: Resources

Having created a model applied to the situation of a circular AMA, there is a clear image of what a circular economy in the AMA looks like. From that point on, the fourth sub question *'What are the most important resources for a transition towards a circular economy?'* is answered. For this question, the most important resources that enable a transition towards a circular AMA are identified.

In this case, the term 'resources' has a very broad meaning. Resources can be abiotic resources, such as minerals and water, human resources, such as skills and labor hours, and biotic resources, such as wood and food. This information will be obtained by doing a desk research, with a focus on material flow analyses (MFA), substance flow analyses (SFA) and input-output analyses.

MFA and SFA studies can be very relevant for this study, while these tools have the ability to indicate what are the biggest material flows within an economy, sector or any well-defined system. For instance, these tools could reveal the most important material flows that are concerned with the production of many renewable energy technologies. Furthermore, studies based on input-output analyses could be of use, since an input-output analysis show the imports and sales of the various sectors or industries within an economy. The data that is being used in input-output analyses can support answering the sub question

The goal of this step is to create an overview that clarifies what and how much resources are needed in a circular economy in the AMA. The collected data will be processed by creating a simple Python computer model. This computer model will contain lots of parameters that are based on the found data and made assumptions. Python is preferred over Microsoft Excel, because of the possibility to perform uncertainty analyses (based on e.g. Monte Carlo, EMA) more easily. As a consequence of the, in all likelihood, large number of assumptions, this might be very useful for further research.

It is important to mention that, since cost estimations for this kind of research, to my knowledge, is not yet performed, the chosen methodology is not fixed. There is a possibility that during the research, other methodologies seem to be more appropriate than the described method. So, due to the uncertainty of how to perform such studies, the chosen methodology could be altered on the basis of newly found information on how to perform such studies. This shows the exploratory nature of this research. This master thesis also aims to contribute to the knowledge on how to perform studies that have a focus on estimations of a big order.

Step 4: Costs

The fourth step concerns determining what costs need to be taken into account when estimating the monetary value of the resources that have been identified in the previous step. The sub-question that will be answered is '*What costs have to be considered related to the transition towards a circular economy'.*

The procedure of finding costs for the several resources will be based on desk research. Scientific literature, grey literature and databases, such as Global Economic Monitor Commodities database of the World Bank. These databases offer information on commodity prices. The found data will be added to the created computer model. By adding the costs of the resources to the computer model, it is possible to start calculating the costs of a transition to a circular economy. While obtaining this data, the scarcity of resources will be taken into account as much as possible, as this could result in a sharp increase of resource costs.

In order to determine the costs that need to be taken into account when estimating the costs of a transition towards a circular economy, the impacts of the proposed system changes that enable the transition should be mapped. Depending on the impact of the proposed alterations, the type of costs that should be included in the total costs change. When the impacts of the proposed changes are mapped, they can be monetized.

Step 5: Reflect

Having determined the costs that need to be considered in modeling a transition towards a circular economy for the AMA, the method of estimating the transition costs of metropolitan areas towards a circular economy will be evaluated and reviewed. Finally, this will give an answer to the main research question *'How to model a well-founded estimation of the costs of a transition towards a circular economy for a metropolitan area?'*

As the method focuses on the AMA, it is interesting to reflect on the applicability of the created framework and method on other metropolitan areas around the globe. It should be possible to say something about using the created method for similar cases on national, international and a global level.

3. THEORY

This chapter discusses various theoretical concepts that are of importance for this research. Section 3.1 focuses on the concept of metropolitan areas, whereas section 3.2 focuses on the concept of circular economy. Both are important concepts for constructing the conceptual model. This is done in order to delineate the concepts in a way that they are easily applicable and usable in this research. Section 3.3 goes deeper into the concept of costs.

3.1 METROPOLITAN AREAS

A metropolitan area is considered to be an area that consists of a nucleus that houses a large number of people, and some contiguous communities that are strongly integrated in an economic and social way (Census, 1994). The concept of a metropolitan area is intertwined with the concepts of a city and an urban region. Therefore, these concepts are sometimes used as substitutes of each other. Common features are that they consider urbanized areas that lack clear boundaries (Levelt & Janssen-Jansen, 2013).

According to BBSR (2011), a metropolitan area is an area which bears a large variety of metropolitan functions. These functions are 'politics', 'economy', 'science', 'transport', and 'culture'. Each of these functions contains indicators to determine if an area can be considered a metropolitan area. Amsterdam is considered a metropolitan area since each of these functions is fulfilled.

In order to delineate the concept of metropolitan areas for this research, a literature review on circular economy concepts in metropolitan areas is conducted. On the basis of this review, the most important sectors in terms of potential impact are appointed. These sectors then form the basis for the conceptualization of a circular economy in metropolitan areas.

3.1.1 CIRCULAR ECONOMY IN METROPOLITAN AREAS

The literature review is focused on MFAs of urban areas, urban metabolism, circular economy practices in urban areas, and reports and articles on cities that ambition transitioning towards a circular economy.

Barrett et al. (2002) used the sectors energy, transport, food, water, waste and the built environment for their material flow analysis (MFA) on the city of York. Each of these sectors is taken into account in an attempt to calculate the ecological footprint of the city. Inés et al. (2014) consider water, energy, food and construction materials as the inputs for the constructed MFA. Waste is an outflow. In comparison with Inés et al. (2014), Shafie et al. (2016) uses one inflow less for their MFA on Malaysian cities. Construction materials are not part of the MFAs executed in Malaysian cities. So, the MFA studies all take into account energy, food, and waste. Furthermore, transport, construction/built environment, and water incorporated. Based on the flows that are frequently present in MFA studies, the energy, food, waste, transport, and construction sector are considered.

In the article by van Timmeren (2014), the concept of urban metabolism is quite extensively explained. The sectors that are considered to be relevant are water supply, wastewater treatment, solid waste management, energy supply, food supply, and transportation. These flows can be merged to water, waste, energy, food and transport. Leach et al. (2014) give an overview of the flows that are often taken into account. Most flows are in accordance with the sectors that van Timmeren (2014) emphasized. The overview shows that water, waste, transport, energy and food are used frequently, of which transport is only present in a small amount of studies. Davis et al. (2016) only cover the energy, waste and food flows. Thus, the considered urban metabolism studies all embody waste, energy, and food, just as the MFA studies. Besides these flows, water and transport flows occur. Based on the urban metabolism, one can conclude that the waste, water, energy, food, and transport sector are important to take into account.

Furthermore, some reports and papers have been written on urban areas that have the ambition to become a circular urban area. In these reports and papers, some sectors have been highlighted, since they have to be changed in order to make a leap forward in getting circular.

One of the cities for which such a paper has been written is Paris. This paper is created by ADEME (2015). A group of 240 participants, that represented 120 organizations, created a white paper on the transition towards a circular Paris. This white paper consists of proposals to kick-start the transition towards a circular economy. It proposes 65 initiatives that can serve as unifying work strategies in connection with metropolitan planning. In creating these proposals, there were 7 different working groups, covering the following themes: Food, construction, new economies, short-life products, medium to long-life products, recoverable energy, and industrial and regional ecology.

In London the ambition of moving towards a circular economy is also strengthened by a created Circular Roadmap. Their proposed actions are divided in five different categories: Built environment, food, textiles, electricals and plastics (LWARB, 2017).

Amsterdam has also developed a vision and action plan for reaching a circular economy. It identifies in which areas circular business models can be applied. The selected chains were the construction chain and the organic residual chain (Circle Economy, 2016). Furthermore, the Amsterdam Economic Board has developed two programs. These are the 'energy transition', which is focused on accelerating the transition to sustainable energy supply, and the 'raw materials transition', which is focused on keeping material flows and products in circulation as effectively as possible to avoid waste. In practice, this comes down to encouraging reducing, reusing and recycling practices (Amsterdam Economic Board, 2016; Cramer, 2017).

Jonkhoff & van der Kooij (2013) wrote a report that portrays the current and desirable future cycles for food, phosphate, waste, water, and energy (electricity and heat) in Amsterdam.

Prendeville et al. (2017) mapped several regions that are currently facing the transition from a linear to a circular city. In the case of Barcelona, the focus is on local production, especially in the energy and food sector. Another city that is described is Glasgow. Here, the energy and the construction sector are mentioned. Also, the importance of data and technology is emphasized. Three regions in the Netherlands are described. The first one is Rotterdam. The focus of the transition in Rotterdam is mainly on the large port area, in combination with bio-based projects. This area houses lots of energy-intensive industry. A region in the Netherlands that is also interesting because of its industry is the region of Haarlemmermeer. In this region, the large airport Schiphol is a main driver for the regional and national economy. The final region that is mapped by Prendeville et al. (2017) is the city of Amsterdam. The energy, food and transport sector are mentioned. Besides mentioning these sectors, it is also emphasized that knowledge is very important for the transition for such a region. Universities are seen as very important institutes. So, the article of Prendeville et al. (2017) several regions are mapped, and the sectors that are considered in the regions are energy supply, food, transport, waste, construction, and larger industries.

The earlier mentioned book of van Bueren et al. (2012) covers topics such as energy, construction, water, transport, and food. These topics are considered important for sustainable cities.

Based on the performed literature research, several sectors we often highlighted as it comes to transitions towards a circular economy in urban regions. The sectors that will be taken into account are: Energy supply, food/agriculture, transport, water, waste, construction/built environment, and larger industries.

Table 1: Overview of the literature per sector

Sectors	Authors
Energy supply	(ADEME, 2015; Amsterdam Economic Board, 2016; Barrett et al., 2002; Circle Economy, 2016; Davis et al., 2016; Inés et al., 2014; Jonkhoff & van der Kooij, 2013; Leach et al., 2014; Prendeville et al., 2017; Shafie et al., 2016; van Bueren et al., 2012; van Timmeren, 2014)
Food/agriculture	(ADEME, 2015; Amsterdam Economic Board, 2016; Barrett et al., 2002; Circle Economy, 2016; Davis et al., 2016; Inés et al., 2014; Jonkhoff & van der Kooij, 2013; Leach et al., 2014; LWARB, 2017; Prendeville et al., 2017; Shafie et al., 2016; van Bueren et al., 2012; van Timmeren, 2014)
Transport	(Barrett et al., 2002; Circle Economy, 2016; Leach et al., 2014; Prendeville et al., 2017; van Bueren et al., 2012; van Timmeren, 2014)
Water	(Inés et al., 2014; Jonkhoff & van der Kooij, 2013; Leach et al., 2014; Shafie et al., 2016; van Bueren et al., 2012; van Timmeren, 2014)
Waste	(Amsterdam Economic Board, 2016; Barrett et al., 2002; Circle Economy, 2016; Davis et al., 2016; Inés et al., 2014; Jonkhoff & van der Kooij, 2013; Leach et al., 2014; LWARB, 2017; Prendeville et al., 2017; Shafie et al., 2016; van Timmeren, 2014)
Construction/ built environment	(ADEME, 2015; Circle Economy, 2016; Inés et al., 2014; LWARB, 2017; Prendeville et al., 2017; van Bueren et al., 2012)
Industry	(Circle Economy, 2016; Prendeville et al., 2017)

As shown table 1, there are seven sectors that have a large potential as it comes to implementing circular economy principles in metropolitan areas. All these sectors will be taken into account when conceptualizing a circular economy in metropolitan areas. For the sake of practicality, there is not chosen to apply the life cycle approach, but to use the boundaries of the metropolitan area, as the boundaries for this research.

Furthermore, as waste is considered as an integral component of each sector, this will not be treated separately. So, each sector will have waste incorporated. The sectors taken into account are energy supply, food/agriculture, transport, water, construction/built environment and industries.

3.2 CIRCULAR ECONOMY

The foundation, upon which research on circular economy is built, has already been described in the late 1970s. The main focus then was on the linearity of the economy (Geissdoerfer et al., 2017). Research of Stahel & Reday (1976) introduced the concept of closing loops in an industrial economy, which is the most important principle of the circular economy. However, nowadays the most well-known and influential research on the circular economy comes from the Ellen MacArthur Foundation. The Ellen MacArthur Foundation (2012) describes a circular economy as "*an industrial system that is restorative or regenerative by intention and design*". This holds that the end-of-life notion is replaced. In a circular economy, two types of material flows are considered. The first type considers biological nutrients, and the second type considers technical nutrients. Systems should be designed in a way that both types of material flows can circulate at high quality through the economy.

The circular economy, as it is explained by the Ellen MacArthur Foundation (2012), is based on a five principles. The principles that give direction to the concept are:

1. **Design out waste**: Products and systems should be designed in a way that waste is minimized. Biological nutrients should be non-toxic and designed in a way that they are easily composted. Whereas technical nutrients should be designed for using minimal energy and to be retained after its service lifetime is over.
2. **Build resilience through diversity**: This is mainly about modularity, versatility, and adaptivity. These characteristics of products and systems are highly-valued, as societies and economies can evolve radically over time.
3. **Rely on energy from renewable sources**: As economies are currently largely fueled by fossils, a shift should be made towards economies that run on renewable sources.
4. **Think in systems**: Considering systems as a whole, instead of only parts of the system. When thinking in systems, one can more easily determine weak spots within a system, and opportunities to strengthen these weaknesses from within. This can be done by e.g. implementing several loops.
5. **Waste is food**: The role of waste within a circular economy is emphasized. Waste flows often still contain lots of value that is currently wasted but offer possibilities to be recovered.

These principles form the basis for reaching a circular economy. In practice, this means that new ways of value creation should be utilized. The opportunities for value creation lie in circulation of material flows, as visualized in figure 1. The tighter the circle, the less value is lost in terms of materials, energy, capital and externalities. Furthermore, the more often materials go through cycles, the higher the level sustainability.

Besides publications of the Ellen MacArthur Foundation, lots of other literature is written on the circular economy. Most of this literature confirms and endorses the principles outlined by the Ellen MacArthur Foundation. The majority of the conducted research is about implementation of (one of) these principles in an industrial setting, e.g. eco-industrial parks (Geng & Doberstein, 2008). Despite the difference in scale with this research (i.e. industrial parks and metropolitan areas), the approach is very similar. Both approaches are systemic and require high-level integration and collaboration between various stakeholders.

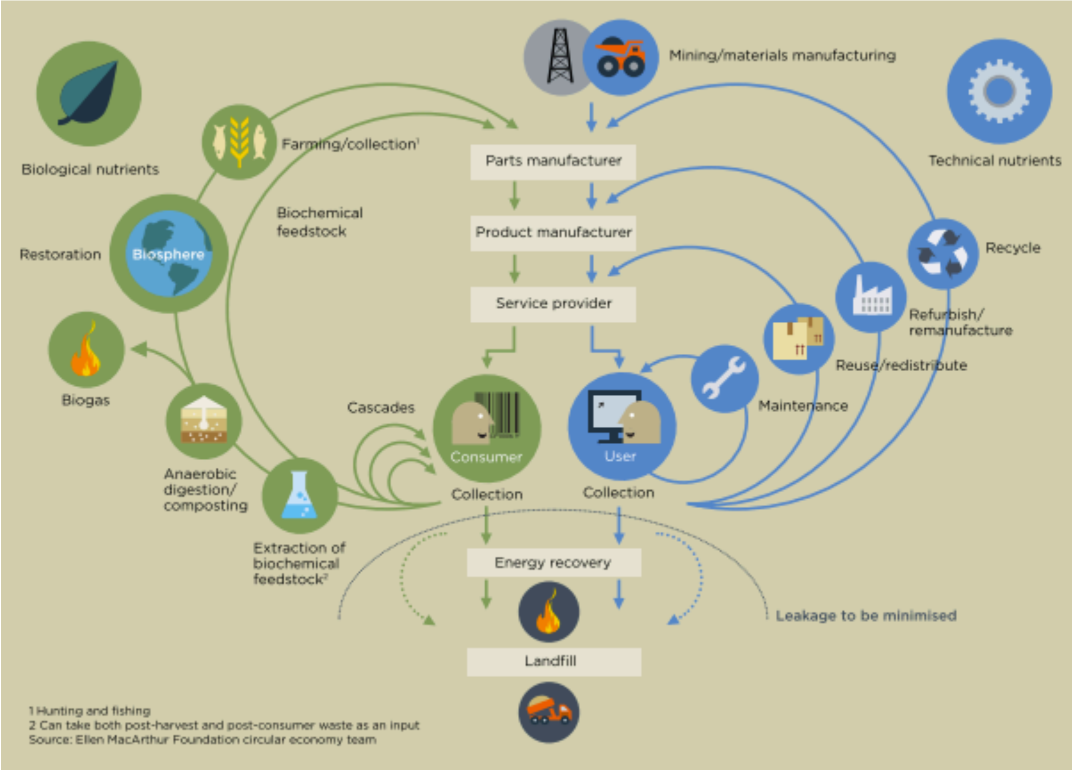

Figure 1: Circular economy

Based on the principles of the circular economy, literature shows three general results of implementing these principles. The clearest result within literature is the shift towards a system that is based on energy from renewable energy technologies. This obviously linked to the third principle of the circular economy.

Of some innovations and technologies that on first sight seem to improve circularity and sustainability of the economy in terms of energy, it is quite debatable if they do contribute to increased circularity. Haas et al. (2015) appoint two different technologies that are often framed as sustainable, but deserve more attention, since their sustainability is often subject to lots of debate. It concerns the use of carbon capture and storage (CCS) and the use of biomass. CCS is often seen as an end-of-pipe solution that does not tackle the core of the problem, the use of fossil fuels. One could argue that the use of CCS even reinforces the economy's linearity, by creating 'demand' for CO2 and standing in the way of kick-starting the development of energy technologies such as solar, wind, geothermal and tidal energy.

The use of biomass is often referred to as being carbon neutral, and therefore a good substitution for fossil fuels to produce energy. Carbon is released during the combustion of biomass, but taken up by photosynthesis by vegetation growth processes (Heinimo & Junginger, 2009). According to this view, biomass does not contribute to increased emissions of greenhouse gases and counts as a good solution for the international concern about climate change (Stupak et al., 2007). However, the described situation does not include aspects of the production process of biomass which can have negative sustainability results. Due to sustainability policies, there is a growing demand for biomass, which means that trade in biomass increases and biomass has to be transported over longer distances, thereby contributing to additional greenhouse gas emissions (Heinimo & Junginger, 2009). The growth in demand for biomass does not only lead to greenhouse gas emissions during transport, but it can also affect land use practices. The land use can change with a loss of biodiversity as result, or can compete with land that is used for food production (Evans et al., 2010). Therefore, when it comes to the use of biomass, it is great importance to keep in mind what kind of biomass is being used. In this research, CCS is not considered an option in a circular economy. The use of biomass to replace fossil fuels is taken into account, but only for small amounts.

The second result that is recognized within literature is closing material loops. This means that the resources are captured and reused. However, this is not as easy as it may sound. Preston (2012) describes that, when it concerns finite resources, such as metals and minerals, the resource loop should be closed. This is also endorsed by Haas et al. (2015), but they also emphasize that this becomes increasingly difficult as mankind is using almost the entire spectrum of available metals. Often in very small quantities or in complex alloys. Recycling technologies still face some major challenges, and should be further developed in order to cope with these difficulties. Haas et al. (2015) also state that non-metallic minerals are the largest fraction of global material extraction, and consumption is still increasing rapidly. This commonality is related to the first, fourth, and fifth principle of the circular economy.

One of the problems that is related to the above-mentioned difficulties, is the current way of designing. The best example concerns the construction sector. In general, each type of construction material can be recycled, however, recycling does not always seem to be the most sustainable solution, because the current stock of buildings is not designed for recycling. Therefore, the most important strategy in increasing circularity would be to reduce the size of stocks and extend service lifetime of existing structures (Schut et al., 2015). This is related to the second principle of the circular economy.

A third result that is derived from literature is the use of digital technologies to enable circular economy practices (Bouton et al., 2016; Ellen MacArthur Foundation, 2015b; Hobson & Lynch, 2016). In terms of mobility this could have an impact on car sharing, autonomous driving, electric vehicles and better materials. In terms of the agricultural production, traditional agriculture could transform into precision agriculture, which improves efficiency of water and fertilizer use by 20 to 30 percent and reduces the need for machinery and input costs. In terms of building construction, passive housing and modular processes could contribute significantly to the circular economy.

The three practical results of implementing circular economy principles that derived from literature are in this research to conduct the conceptual model.

3.3 COSTS

In order to answer the fifth sub-question, *'What costs have to be considered related to the transition towards a circular economy'*, it should be clear what is meant by costs and how this is operationalized. For the defining and operationalizing costs, the article of Correljé & Groenewegen (2009) is used. In their article, Correljé & Groenewegen (2009) elaborate on the concept of costs and values in the light of sustainability from the perspective of various economic schools.

Mainstream economics is based on the objective to minimize costs and it is assumed that the economy represents an ideal market in which private actors exchange goods and services. However, it is acknowledged that markets do not always function in an ideal way. An example of this is that some transactions within the economy have consequences for actors that are not involved in these transactions. Experiencing consequences of actions in which an actor is not involved is called an externality, which can be both positive or negative (Correljé & Groenewegen, 2009). A well-known example of a negative externality is a person experiencing air pollution, due to actions in which it is not involved. On the other side, a well-known positive example of an externality is due to the introduction of electricity in developing countries. By introducing electricity, less time is needed to gather fuels to produce energy. This time can now be used for better education.

Currently, these externalities are rarely incorporated in the price that is paid, despite the fact that they do have influence on costs and benefits of several actors. In total, costs may be therefore higher than the paid price. However, within mainstream economics it is assumed that prices reflect the costs for operation and management, the capital charges and the opportunity costs for the producers, and the price consumers are willing to pay for the value they attach to a product (Correljé & Groenewegen, 2009). This is showed in figure 2.

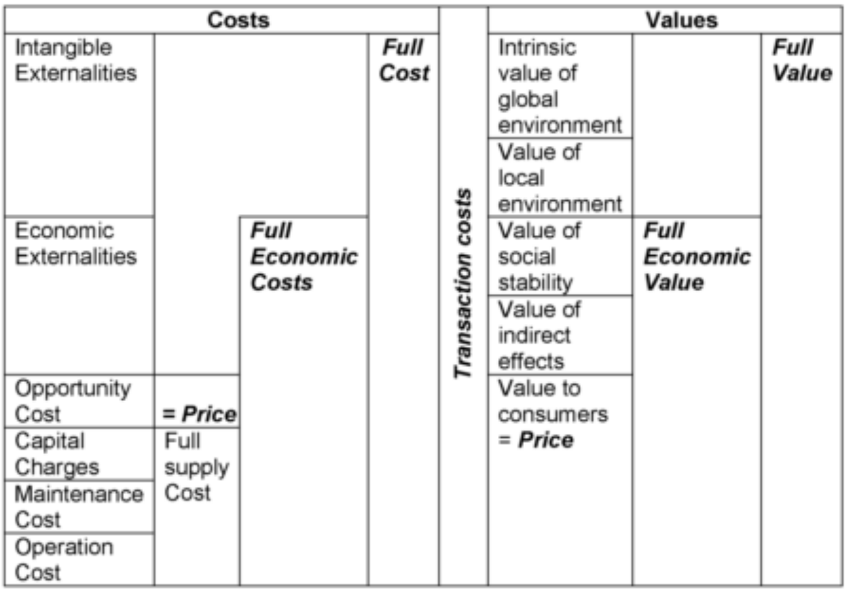

Figure 2: Components of costs and values (Correljé & Groenewegen, 2009)

As stated, externalities are often not taken into account when it comes to determining the market price. According to the Correljé & Groenewegen (2009), externalities come in two types: Economic externalities and intangible externalities. Economic externalities are the externalities that influence the costs and benefits of actors. These externalities represent the value of social stability and indirect effects. An example for this research could be a switch towards a renewable energy system could reduce the dependency on energy imports from other countries with volatile prices, or air pollution as a consequence of transporting food over long distances (Correljé & Groenewegen, 2009). Intangible externalities are considered to be externalities that involve individual and societal costs that are not easily integrated in a cost-benefit analysis. Values that intangible externalities reflect can also be related to the quality of local and the global environment. Several of these values can be converted into economic and social costs, such as the costs associated with the restoration of nature. An example of intangible externalities with respect to e.g. oil and gas, may involve the costs of military interventions to secure production in failing states, civil wars on resource control, the strategic oil stocks to maintain security of supply, strategic pipelines to avoid hold- up problems, etc. (Correljé & Groenewegen, 2009).

As the goal of this research is to create a model that allows it to estimate the costs of a transition towards a circular economy, the question arises which values the costs should reflect. Keeping in the mind the definition of a circular economy, developed by the Ellen MacArthur Foundation (2012), a circular economy refers to a system that is restorative and regenerative by intention and design. The principles of the circular economy translate into a need for new ways of value creation that are based on the circulation of resource flows. The better resources circulate through the economy, the less value is lost in terms of materials, energy and capital. This should result in less negative externalities (Ellen MacArthur Foundation, 2012).

Within a circular economy one attempts to retrieve value that otherwise would have been lost if the standard linear economic paradigm was followed. This could be e.g. the utilization of waste heat or the reuse of a material. Besides retrieving the direct value of a resource, the process of recovering value also affects other processes. When the value of a certain resource is recovered, this also means that the resource that would otherwise have been used to represent a value does not have to be used. This is a way of value creation in which the value of the resource is maintained and also positively affects the environment as a new process resource extraction is averted. On a larger scale, some of the environmental gains that results from a transition towards a circular economy may translate in a social or economic gain, as stocks of certain resources are kept at a stable level, which sustains economic and social stability. The same applies the other way around when the value is not recovered but lost. A transition towards a circular economy therefore touches upon all the values stated in figure 2.

Furthermore, one of the principles of the circular economy is to think in systems. One of the goals of thinking in systems is to oversee as much impacts of a certain process as possible. Therefore, operationalizing circularity for this research would require including externalities to make sure that prices paid take into account the impacts on the environment, and subsequently the society. In order to include these externalities, it is required to have a clear vision on the impacts of the actions that need to be undertaken in the attempt to reach a circular metropolitan area.

Besides mapping the impacts of the actions that need to be undertaken in the attempt to reach a circular metropolitan area, it is necessary to quantify these actions in monetary terms. Lan et al. (2016) discuss various ways of quantifying environmental externalities with a view to internalizing them in the price of products, using different monetization models. They suggest performing a life cycle assessment (LCA) in order to obtain an overview of the impacts related to the reaching the desired design of a metropolitan area. For the monetization of the impacts, three different methods are compared. These are the EPS 2000, the Stepwise 2006, and the Ecotax. Using these methods to perform the monetization requires decent research into lots in willingness to pay studies on various topics (Lan et al., 2016). For this thesis the data requirements will depend on the future vision that will be constructed during the course of this research.

In the attempt to operationalize circularity for this research, in order to make it applicable to the AMA, this effort is judged to be an ambition too big to be achievable considering the constraints in time for this thesis research. Fulfilling this ambition requires huge amounts of data collection and would go into too much detail compared to other identified problems within this research.

4. METHODS AND TOOLS

This chapter discusses the methods and tools that are used to operationalize the theoretical concepts that are introduced and elaborated on in chapter 3. The tools and methods that are discussed are Fermi approximation, mass and substance flow analyses, input-output analyses and key performance indicators to measure circular economy performances.

4.1 FERMI APPROXIMATION

The estimation technique that forms the basis of this research is Fermi approximation[2]. Fermi approximation is used to answer so-called Fermi problems, or estimation problems. These problems are often questions that are characterized by unknown numbers and are, at first sight, too big to answer. Usually, the goal of a Fermi approximation is to stay within the boundaries of a factor 10 of the real answer (Morrison, 1963; Weinstein, 2012).

Putting Fermi approximation into practice requires several steps. First, as the number that is strived for is probably too large to estimate at once, the problem has to be decomposed. This holds that the problem needs to be broken down into different parts that are more suitable for a well-founded estimate. The key is to identify the variables that will have an influence on the final answer. A more complete identification will lead to a more accurate estimation (Pickard, 2010; Weinstein, 2012). Second, estimate the low and high boundaries of the smaller parts. These boundaries need to be written in a scientific notation. This means that e.g. 2 is written as 2×10^0 and 400 is written as 4×10^2. Third, after setting the low and high boundary, the approximate geometric mean (AGM) needs to be calculated. This means you take the average of the coefficients and the average of the exponents. Continuing with the previous numbers (2×10^0 and 4×10^2), this would give 3×10^1 (Weinstein, 2012).

Ishida & Chiba (2015) divide a Fermi approximation in three different categories:

1. Target data
2. Related data
3. Relations

The target data refers to the number that answers the final question. In the upcoming example, the target number refers to the number of piano tuners in Chicago. Related data refers to numbers that are easy to calculate or are accessible through use of e.g. scientific literature. Relations refer to the links that exist and on which the target number can be estimated from the related numbers (Ishida & Chiba, 2015).

The core of making a Fermi calculation lies in figuring out which variables are important, how they will influence the answer, and then quickly estimating both of them and the answer to an accuracy better than a factor of two or three (Pickard, 2010). To clarify the process of Fermi approximation, an example is given below.

[2] Fermi approximation is named after the American-Italian physicist Enrico Fermi, famous for his contribution to the nuclear power development.

Box 2: Example of Fermi approximation (Wikipedia, 2017b)

<u>Fermi approximation example</u>

The most famous example of Fermi approximation is estimating the number of piano tuners in Chicago. When making well-founded assumptions, a good estimate of the number of piano tuners in Chicago, the target data, can be given. Presume the following assumptions for the related data:

- *There live ± 9 million people in Chicago.*
- *In Chicago, a household consists of ± 2 persons.*
- *1 in 20 households have a piano that is frequently tuned.*
- *Frequently tuned pianos are tuned once every year.*
- *It takes 2,5 hours to tune a piano.*
- *A piano tuner works 8 hours a day, 5 days in a week and 50 weeks a year.*

With the given assumptions, one can estimate the number of piano tuners in Chicago.

(9.000.000 people in Chicago) / (2 persons per household) x (1 piano per 20 households) x (1 piano tuning per piano per year) = 225.000 piano tunings per year in Chicago.

(50 weeks a year) x (5 days a week) x (8 hours a day) / (2 hours to tune a piano) = 1000 piano tunings per piano tuner per year

*(225.000 piano tunings per year) / (1000 piano tunings per piano tuner per year) = **225 piano tuners in Chicago***

*The exact number of piano tuners in Chicago is about **290**, so the Fermi approximation allowed it to estimate the number of piano tuners in Chicago within the boundaries of a factor 10*

The goal of this research is to model an estimation of the costs of a transition towards a circular economy for a metropolitan area. This estimate of the costs functions as the target data. In order to get the target data, variables that influence the target data need to be identified. Variables that influence the costs of a transition are selected within the identified sectors of a metropolitan area, based on how sectors are currently designed and how they should be designed in a circular economy. These variables form the related data.

After decomposing the estimation problem, the circular vision on a circular metropolitan area is projected on the AMA. Since it concerns a vision on a possible future scenario, the factor of uncertainty is incorporated by determining a lower and upper boundary, between which the correct value lies.

4.2 MFA/SFA

The decomposition of the estimation problem requires lots of data collection in order to create a conceptual model and to quantify this for the AMA. Important sources of information are material flow analyses (MFA). A material flow analysis is a systemic assessment of the flows and stocks of materials within a system defined in space and time. A MFA delivers a complete and consistent set of information about all flows and stocks of particular materials within a system. Through balancing inputs and outputs, the flows of wastes and environmental loadings become visible, and their sources can be identified. In a MFA, materials are substances and goods. A system in a MFA comprises a set of material flows, stocks, and processes within defined boundaries. In this research such systems concern metropolitan areas, urban areas or specific sectors. MFAs are often mentioned as an important tool to study the circular economy, as they are suitable for recognizing of problems such as future environmental loadings and resource depletions. So the tool can evaluate existing systems, but is also used to evaluate systems for their ability to support new and more efficient systems (Brunner & Rechberger, 2005). For this research specifically, MFAs can be used in two different ways. The first way is that it helps to identify important activities (variables), and the relations between them, in a metropolitan area (EASAC, 2016). And second, at a later stage MFAs help to identify the most important resources for a transition towards a circular economy, as MFAs show what the largest flows are within a system. At this stage another type of MFA is of use. This type of MFA is a Bulk-MFA. Bulk-MFAs consider a broad range of aggregated materials, such as metals, fossil fuels, etc.

Closely related to a MFA, is the substance flow analysis (SFA). Similar to MFAs, SFAs can be used at a later stage in order to identify the most important resources that enable the transition towards a circular economy. Where a MFA seeks to analyze the material flows through a system, SFAs seek to analyze the flow of one substance through a system. As indicated above, materials in a MFA have a very wide scope as they can concern substances and goods. However, substances in a SFA often refer to chemical substances.

4.3 INPUT/OUTPUT ANALYSIS

Input-output tables describe the sales and purchase relationships between different producers and consumers in an economy, which is given in an analytical framework. The economy is viewed as a table with each industry listed across the top as a consuming sector and down the side as a supplying sector. With an input-output analysis, one can find and describe connections between production and some economic phenomena by performing a macro-economic calculation method (United Nations, 1999).

Economic input-output modelling has been used for environmental systems analysis, with a primary benefit having the capability to estimate direct and indirect economic and environmental impacts across the entire supply chain of production in an economy (Hawkins et al., 2007). It is possible to combine physical and monetary units in an input-output table, especially with respect to energy and mineral products. This can e.g. be combined with MFAs that traditionally have been used to track the production, use, and consumption of materials. Combining MFA and input-output analysis creates a mixed-unit input-output model, which is able to better track economic transactions and material flows throughout the economy associated with changes in production. The combined model can track materials through entire supply chains in response to any monetary or material demand (Hawkins et al., 2007).

4.4 KEY PERFORMANCE INDICATORS

After constructing the conceptual model, the model needs to be specified for the AMA as it functions currently and for the AMA in a circular economy. In order to make statements about the adoption rate of the circular economy principles in the AMA, the term 'circular economy' has to be measurable. This term becomes measurable when one links it to key performance indicators (KPIs) that are specified for a circular economy. With these KPIs it is possible to analyze the current performances of the AMA when it comes to adopting the circular economy principles, and it enables comparing it with a future vision on a circular AMA.

The Ellen MacArthur Foundation (2015a) developed several KPIs that measure the degree of circularity. Despite the fact that these KPIs are developed on a product-level and a company-level, these KPIs are discussed in order to determine the applicability for this research. The KPIs that are developed by the Ellen MacArthur Foundation (2015a) can be divided in one main indicator and several complementary indicators. The main indicator is called the Material Circularity Indicator and it measures the extent to which linear flows concerning a product have been minimized, restorative flows are maximized and how long and intensively products are used compared to a similar industry-average product. This indicator uses the same approach on a company level. Three different product characteristics determine the degree of circularity. These are:

- The use of virgin raw material;
- The mass of unrecoverable waste;
- The length and intensity of a product its use.

The key idea of the Material Circularity Indicator is that the products and companies get decoupled from external inputs by decreasing the dependence on virgin raw materials and increasing the use of restorative flows.

The complementary indicators can be divided in 'impact indicators' and 'risk indicators'. Examples of the risk indicators are 'material price variation', 'material scarcity' and 'toxicity'. Once the most important resources for the transition towards a circular economy are determined, the themes that are covered by the risk indicators on materials are of importance. The impact indicators cover 'energy use', 'CO_2 emissions' and 'water'.

Besides the developed KPIs on a product-level and company-level, the Ellen MacArthur Foundation (2015) also developed KPIs to measure circularity on a national ambition level. The developed KPIs cover four different themes:

- Resource productivity;
- Circular activities;
- Waste generation;
- Energy and greenhouse gas emissions.

Resource productivity refers to the amount of GDP produced per ton of material consumption. The circular activities theme is about a set of indicators that measures the adoption of e.g. sharing and remanufacturing activities. Waste generation refers to the waste production per capita and the waste generated per GDP. Energy and greenhouse gases emissions are the most straightforward theme, as it concerns the share of renewables and greenhouse gas emissions per GDP.

The KPIs developed by the Ellen MacArthur Foundation for a product/company level show some similarities with the KPIs for a national level. First, the clearest similarity in that energy use and greenhouse gas emissions are taken into account. Second, the strong focus on the reduction of waste and input of virgin raw materials.

As the KPIs developed by the Ellen MacArthur Foundation do not address the level of a metropolitan area or a city, the KPIs cannot be copied. Based on the delineation of metropolitan areas in sectors and the theory on circular economy, the KPIs for metropolitan areas are constructed towards this delineation. Considering the theory on circular economy and the earlier mentioned KPIs, the energy demand of the metropolitan area is the first KPI. This KPI measures the energy demand of the metropolitan area and shows what fraction comes from renewable resources. As MacKay (2009) shows, energy mainly comes in the form of electricity and heat. Therefore, the KPI is divided in heat demand and electricity demand. The second KPI shows the water footprint, i.e. how much water is used within a metropolitan area. The importance of this indicator is endorsed by the Ellen MacArthur Foundation (2015a). The third KPI is focused on the reduction of waste and the reduction of input of virgin raw materials in the construction sector. In order to grasp both reduction ambitions, the KPI measures the self-sufficiency of the sector. The fourth KPI is focused on the food sector in a metropolitan area. This KPI is also based on the reduction of waste and the reduction of input of virgin raw materials, but in more general terms, it is measured in terms of potential degree of self-sufficiency. It is measured if a metropolitan area produces enough food within the area itself to be self-sufficient. The fifth, and last, KPI is meant to judge whether a circular economy is achievable within a metropolitan area and to get an idea of how much extra land it requires to become a circular metropolitan area. This gives the following key performance indicators:

1. Energy demand
    a. Heat demand
    b. Electricity demand
2. Water demand
3. Self-sufficiency of the construction sector
4. Self-sufficiency of the food sector
5. Land use

A KPI that would be good to include in future research is a KPI on greenhouse gas emissions (CO_2-equivalents). This is not taken into account for this research, because it is outside the scope. Including greenhouse gas emissions on the scale of a metropolitan area does not capture the whole problem, since greenhouse gas emissions are often found upstream supply chains. Creating a KPI on greenhouse gas emissions would create a KPI that is most probably out of proportion compared to the total greenhouse gas emissions that are related. Despite the absence of a KPI for greenhouse gas emissions, greenhouse gas emissions are mentioned in constructing the conceptual model due to their importance.

5. CONCEPTUAL MODEL

The focus of this chapter lies on creating a conceptual model of a metropolitan area. In order to construct a conceptual model, the sectors that have been selected in chapter 3 are decomposed based on Fermi approximation. This decomposition leads to the identification of different variables and relations between them that are of importance for a circular economy in a metropolitan area. This results in a clear overview of how the sectors are currently designed. Subsequently, for each of the sectors it is determined which variables do not fit within a circular economy in their current form. This is followed by a general outline of how the sectors can be designed according to the principles of the circular economy.

5.1 FOOD/AGRICULTURE

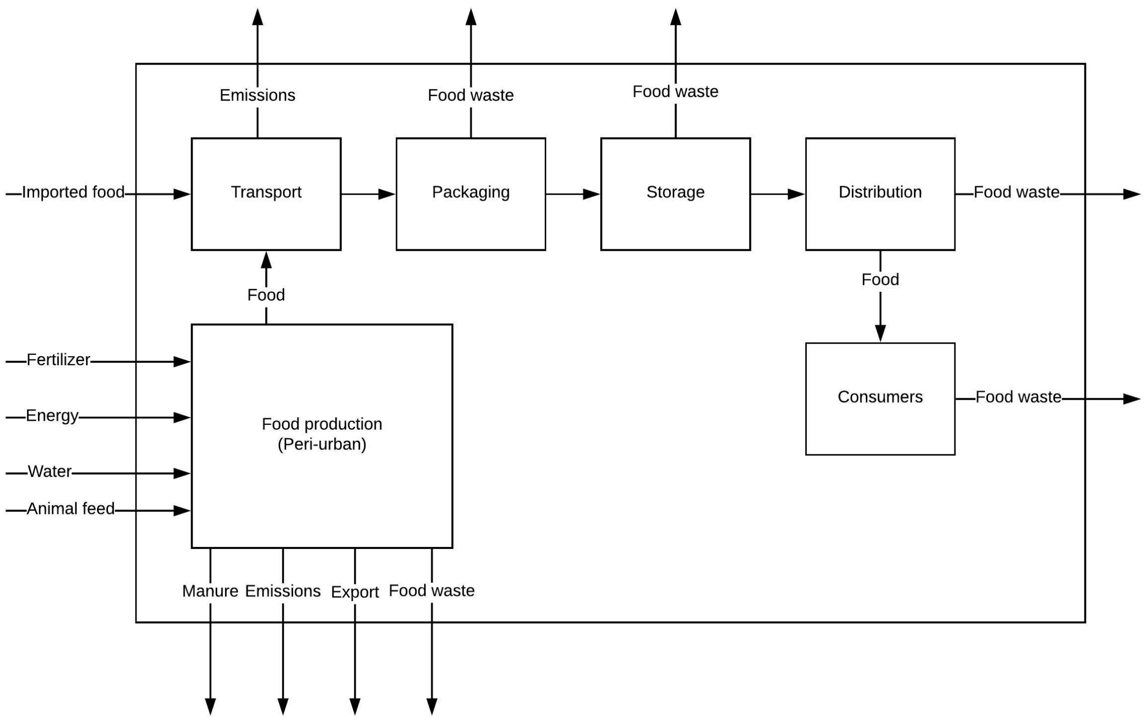

Figure 3: The food sector in a metropolitan area

The food and agriculture sector within a metropolitan are intertwined to a certain extent. Therefore, the two sectors are considered as one sector in this research.

Food within a metropolitan area comes from two sources. These are food that is produced within the metropolitan area itself and food that is imported from outside the area, which can be anywhere in the world (Jonkhoff & van der Kooij, 2013; Jurgilevich et al., 2016). Within food production, one could make a distinction between crop production and livestock. Both of these require inputs to sustain production. The main inputs for crop production are fertilizer, water and energy (Ellen MacArthur Foundation, 2015b). Different than crop production, livestock does not make use of fertilizers, but does require animal feed. Food production generally has five different outflows. These are food, food waste, exported food, manure, and emissions (Ellen MacArthur Foundation, 2015b; Jonkhoff & van der Kooij, 2013; Ward et al., 2016). Produced food goes in three different directions. First, food is produced for the internal market. Second, food is produced to export to other regions, elsewhere in the world. Third, a percentage of the produced food is wasted already at the production facilities (Ellen MacArthur Foundation, 2015b; Jonkhoff & van der Kooij, 2013). The two other outflows are manure and emissions. Manure is a by-product of keeping animals for livestock. Emissions are a consequence of using machinery at farms and keeping animals that exhaust greenhouse gasses (Ellen MacArthur Foundation, 2015b; Ward et al., 2016).

The imported food and the food that is produced in the metropolitan area both go on transport to packaging facility (Jonkhoff & van der Kooij, 2013). After the packaging process, the food gets transported to distribution facilities. From these distribution facilities food goes to supermarkets, where the food gets to the consumers (Jonkhoff & van der Kooij, 2013). Each time the food gets transported, this contributes to total amount of exhausted greenhouse gas emissions (EEA, 2016; Schneider Electric, n.d.). Furthermore, in each distinguished phase of the food sector within metropolitan areas a fraction of the food is wasted.

Limitations

The current food system can be described as wasteful and quite inefficient. A large share of the produced food does not reach the consumer, of which estimations are that at least one-third of the food is wasted in the current system (Ellen MacArthur Foundation, 2015b; Jurgilevich et al., 2016; Ward et al., 2016).

Agriculture in Western economies relies heavily on fossil inputs as it became more resource-intensive over the past half century. The fossil inputs flow into the agricultural and food sector in the form of synthetic nitrogen and phosphorus fertilizers, agrochemicals, and fossil fuels for machinery (Miccoli et al., 2016; Ward et al., 2016).

Furthermore, a significant share of the resources used for growing crops is not used for its purpose, as crops absorb 35 percent of the water and fertilizer applied to the field (Ellen MacArthur Foundation, 2015b). The remaining percentage of the resources goes to waste. Also, lots of products considered as waste, still contain valuable nutrients, which are not recovered. This goes for food waste, and sewage and waste water (Ellen MacArthur Foundation, 2015b).

Another problem that is associated with the current food system is the concept called 'food miles'. Food miles stand for the distance that is covered by food from the location where it is produced to the place where it is consumed (Satterthwaite, 2011). The transport from the one place to the other is often associated with the combustion of fossil fuels.

A point of interest in the transition towards a circular food system is the consumption pattern of people living in Western countries. Currently, from an environmental point of view, the largest concern is the high share of industrially-produced meat in the Western diet. This causes a high demand for nutrients and is responsible for emitting large amounts of greenhouse gas emissions (Jurgilevich et al., 2016).

CIRCULAR

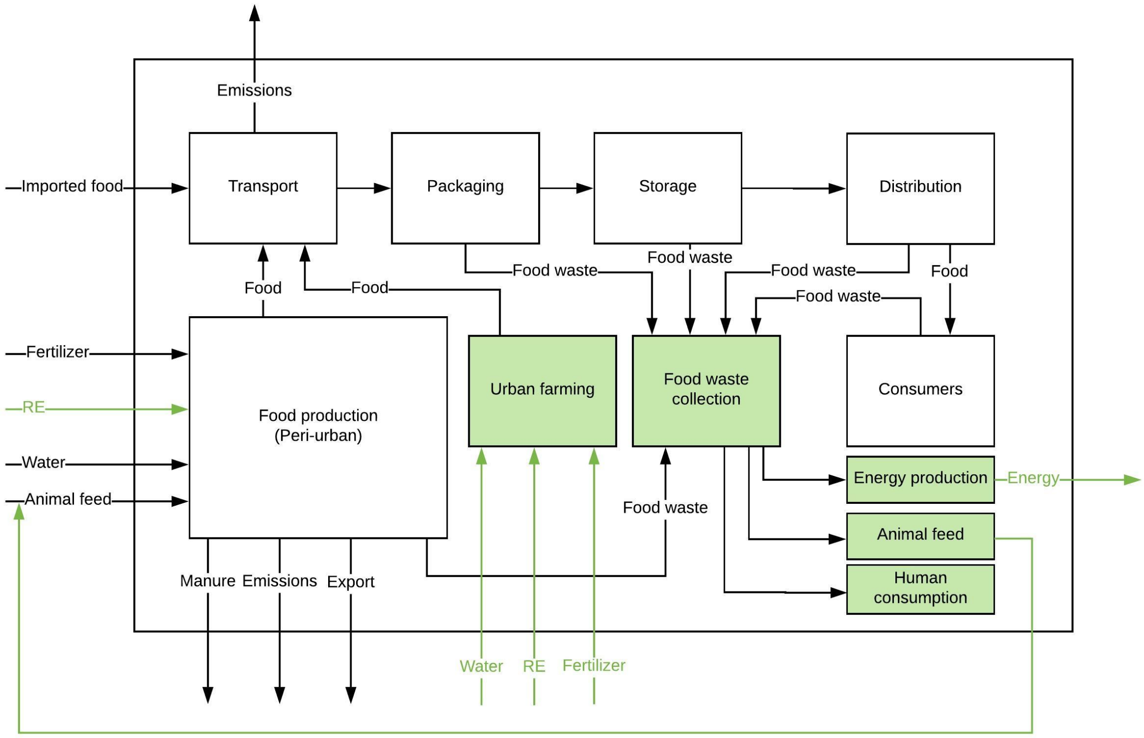

Figure 4: Circular food sector

According to Ellen MacArthur Foundation (2015), a circular food system is characterized by being non-wasteful, close to the consumer, organic, and having reconnected nutrient loops that would encourage the rehabilitation of degraded land.

Being non-wasteful and efficient are very closely related principles, as inefficiency causes e.g. nutrients to go to waste. In terms of food waste, the most important strategies are prevention and reuse (Jurgilevich et al., 2016). Prevention results from designing the food system in a more efficient way, and as it comes to reuse there are different ways of reusing. According to the principle of cascading, the form of reuse with the highest value is preferred (Rood et al., 2017). This can be e.g. reuse by distributing the non-used food to people that affected by food poverty, reusing the food as animal feed, or waste-to-energy reuse (Jurgilevich et al., 2016). Putting food waste to a better use would require a system to collect the food waste from each phase and redistribute it to its optimal cascading level.

A development that increases efficiency of agriculture is the development of precision farming. Precision farming is based on an increase in the use of IT in farming practices. With the use of IT systems, big data, remote sensing and satellite positioning data, inputs for agricultural systems can be optimized. The most important result of precision farming is that the amount of resources that are used as inputs for agriculture can be minimized (Ellen MacArthur Foundation, 2015b; Ward et al., 2016). According to the Ellen MacArthur Foundation (2015), this is already commercially viable. It is stated that irrigation is 20-30 percent more efficient with precision farming, and for fertilizer use the efficiency has been improved by 10-20 percent.

For the food system to become more locally oriented, in order to reduce food miles and shorten the supply chain length, it requires a shift towards increased use of peri-urban and urban farming, as most people nowadays live in cities (Dieleman, 2017; Ellen MacArthur Foundation, 2015b). According to the FAO (1997), urban farming refers to small areas within a city for growing crops and sometimes raising small livestock, and peri-urban farming considers farm units close to a city which operates semi-commercial or fully commercial. Urbanized regions are often characterized by a lack of space. Hence urban farming needs to be more creative in terms of their location. A rather new development is that urban farming takes place on rooftops or in so-called vertical gardens (Dieleman, 2017). In these farms, crops grow in a controlled environment, which allows it to achieve an optimal yield. Furthermore, there is no agricultural runoff, it enables year-round crop production, and it operates more efficiently than traditional agriculture (Despommier, 2013; Ellen MacArthur Foundation, 2015b). A shift towards peri-urban and urban farming reduces the number of food miles drastically. However, transport would still be of significant importance for the food system. The transport should therefore make the shift away from fossil fuels, and rely on more sustainable options, such as electric vehicles or hydrogen-based vehicles.

The outflow of manure from livestock is sometimes seen as waste (Ward et al., 2016). However, animal manure contains lots of valuable nutrients, which can be used as a substitute for mineral fertilizer (Jurgilevich et al., 2016; Ward et al., 2016). If the soil is already saturated with nutrients, the nutrients can be recovered and transported to other areas (Jurgilevich et al., 2016).

As stated earlier, the meat-intensive diet of people living in Western countries causes the biggest impact in the food system. In a circular economy, the diet of people would be more plant-based, instead of strongly based on industrially-produced meat consumption (Jurgilevich et al., 2016). However, changing this is not just a matter of implementing a new technology, but it has to do with behavior of consumers. Options to alter the behavior of the consumer are e.g. education or awareness campaigns. Jurgilevich et al. (2016) state that these actions would definitely contribute to this transition, but that this is not enough to reach an entire population.

5.2 ENERGY SUPPLY

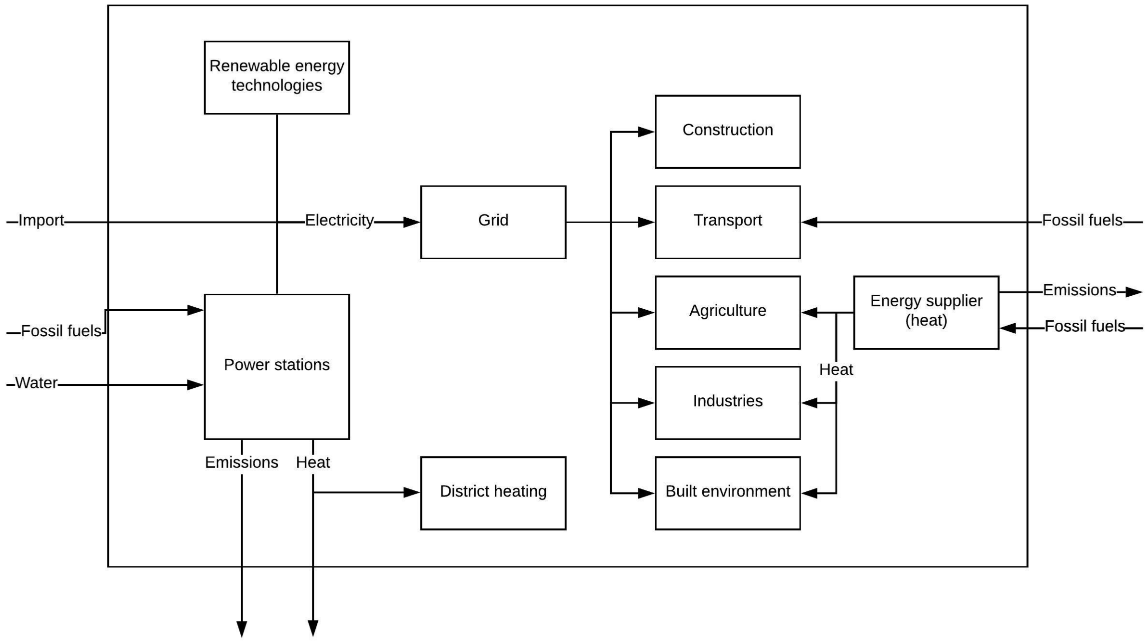

Figure 5: The energy supply sector in a metropolitan area

Equal to the food sector, the energy supply sector consists of a flow of energy that is produced within the boundaries of the metropolitan area, and a flow of energy that is imported from outside the metropolitan area.

Power stations produce two different types of energy that are useful. These are electricity and heat, which are both required within metropolitan areas. The main energy source of these products are fossil fuels, such as coal, natural gas, and oil (IEA, 2012; Jonkhoff & van der Kooij, 2013). In order to run, power stations burn these fossil fuels to create heat, which heats up water to create steam that drives turbines. These turbines in turn produce electricity. The heat that is produced at power stations is often going to waste, but in some cases this heat is still being used by district heating. The residual heat goes to an underground network of pipes that heats houses (Jonkhoff & van der Kooij, 2013). In order to cool the steam that is used for electricity production and make it water in a liquid form again, cold water flows into the power station. Besides the outflows electricity and heat, the power station also produces by-products. These are greenhouse gas emissions that result from burning fossil fuels.

Nowadays, electricity is not only produced by burning fossil fuels. Another source of electricity production is electricity generated by renewable energy technologies. The technologies that already penetrated the market and are commercially viable are wind energy (both on-shore and off-shore) and solar energy (mostly photovoltaics) (MacKay, 2009).

The electricity that is produced within the boundaries of the metropolitan area and the electricity that is imported from outside the region are added to the grid. From that moment, the electricity needs a destination. The largest consumers of electricity within a metropolitan area are generally industries, transport, the built environment, construction and agriculture (IEA, 2012, 2014; Jonkhoff & van der Kooij, 2013).

Besides the need for electricity in metropolitan areas, there is also demand for heat, which can partly come from power stations, via district heating systems. However, this is not enough to meet the total demand for heat. Hence, energy suppliers often sell natural gas, which is transported to its destination through a network of pipes. The natural gas is burned at its destination to produce heat (Jonkhoff & van der Kooij, 2013).

Limitations

The energy system can be divided into broadly three different components, which are energy sources, energy conversion and distribution, and energy services (IEA, 2012).

Clearly, energy sources should shift from fossil fuels to renewable sources. As said, nowadays the energy supply mainly comes from fossil fuels. This goes for both the production of electricity and heat. The main sources of energy are coal, gas and petroleum (European Commission, 2017; IEA, 2012, 2014). Using these energy sources results in emitting greenhouse gasses and contributes to the strengthened greenhouse effect (IEA, 2012; Jonkhoff & van der Kooij, 2013).

As it comes to energy conversion and distribution, the energy system is largely centralized and depending on generation of heat and electricity via the combustion of fossil fuels (IEA, 2012). Network operators are responsible for getting the electricity and the heat from the producers to the consumers (Jonkhoff & van der Kooij, 2013). An important characteristic of fossil fuels is that the energy in fossil fuels is already stored. This allows it to control the amount of energy produced and to transport it easily (IEA, 2012). In the current situation (in the Netherlands), the grid operator forecasts the energy demand one day ahead to determine which energy supplier should produce energy at what time, and this forecast can be changed up to fifteen minutes before it is used (Galiana & Conejo, 2008).

Energy services imply the main sectors using energy. The largest consuming sectors are generally power supply, industry, transport, and buildings (IEA, 2012).

CIRCULAR

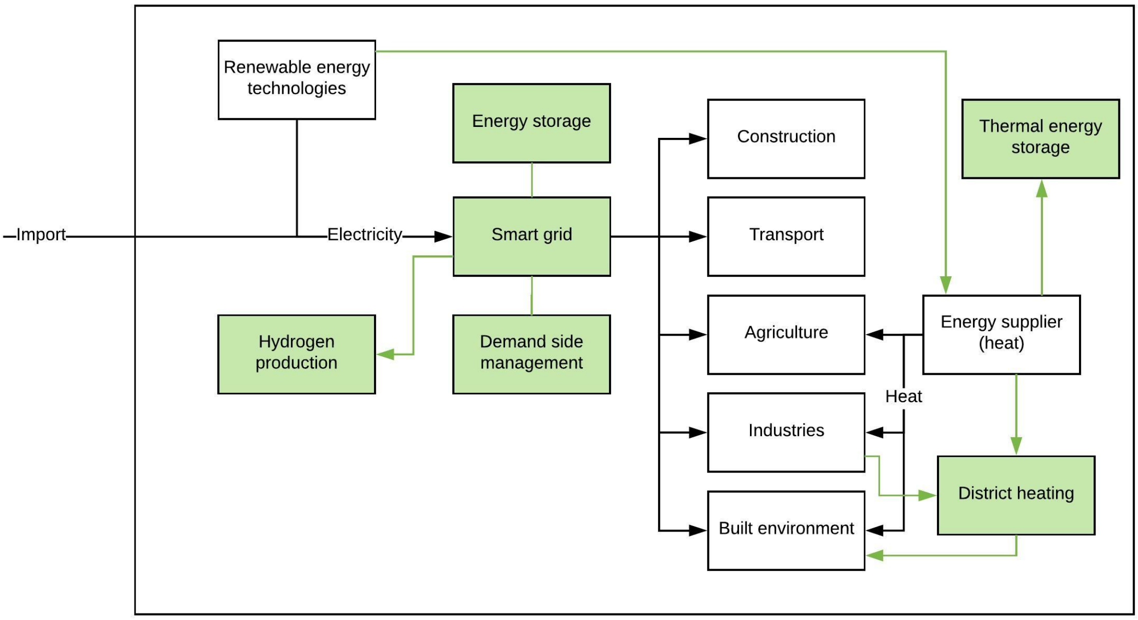

Figure 6: Circular energy supply sector

In the first publication of the Ellen MacArthur Foundation, they give an outline of a circular economy. One of the main principles discussed in this publication is to '*rely on energy from renewable sources, and ultimately all systems should run on renewable sources*' (Ellen MacArthur Foundation, 2012). Besides this sentence, it is not outlined how this would look like in a circular society.

As said, nowadays the energy supply mainly comes from fossil fuels. In a perfect circular setting, all activities shift towards the use of energy from renewable resources. Currently there are many renewable energy technologies present that use of renewable energy sources, of which some are already proven concepts and some are still operating in niche markets. The most well-known, and already proven, energy technologies are solar, wind, hydro, biomass and geothermal energy. Furthermore, wave, tidal and ocean thermal energy are upcoming (MacKay, 2009).

As it comes to energy conversion and distribution, different than in the current centralized system, a circular economy would imply a mix of a decentralized and a centralized system. This is mainly due to the role of energy consumers and the intermittency of renewable energy technologies (IRENA, 2016; Kleijn, 2012). One of the characteristics of using renewable energy is that consumers can also be producers. In an economy based on renewable energy, this means that lots of different producers exist (IRENA, 2016). However, renewable energy is not the same as fossil energy. An important characteristic of the production of electricity by some renewable energy technologies (wind and solar) is that it is intermittent. This means that it is not fully controllable when the renewable energy technologies produce electricity, as electricity production depends on e.g. sun hours and availability of wind (an example of an intermittency problem is shown in figure 6)(Kleijn, 2012). And when electricity is produced, it has to be consumed directly in order to prevent it from going to waste, which leads to economic failure (Yekini et al., 2014). Balancing renewable energy supply and demand requires a smarter and more flexible grid (IRENA, 2016). A circular economy would probably have a large penetration of electric vehicles into the market, which could be of significant importance when it comes to balancing electricity supply and demand. As electric vehicles have batteries to store energy, they can be connected to the grid and charge on peak-loads, and discharge when there is a shortage of electricity supply (IRENA, 2016)

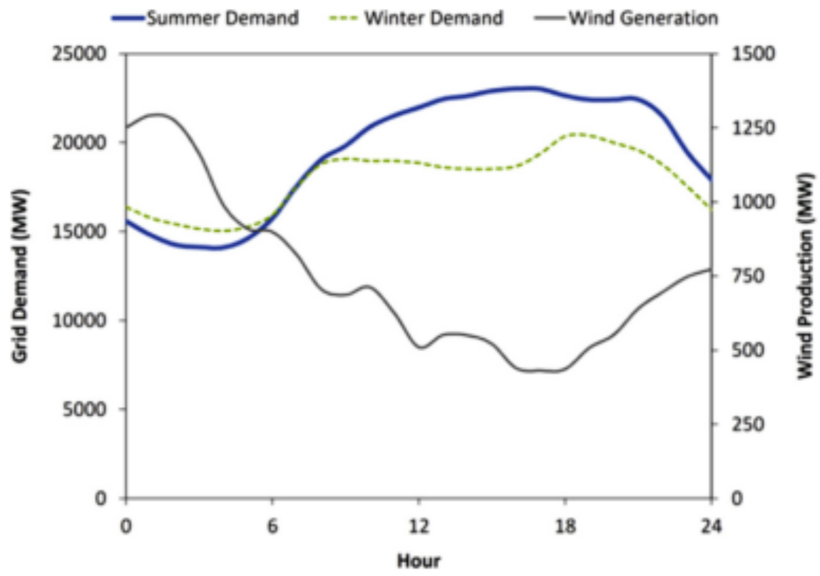

Figure 7: Example of an intermittency problem (Yekini et al., 2014)

In order to deal with the problem of intermittency and having to consume electricity immediately, it is necessary to have electrical energy storage systems that charge when demand is low and discharge when demand is high (Yekini et al., 2014). There are currently several technologies to store electrical energy. These technologies are mechanically by pumping water or compressing air or increasing rotational speed of electromagnetic flywheels; chemically by producing or converting components in chemical systems such as batteries of flow batteries; and by modifying electrical or magnetic fields in capacitors or superconducting magnets (Kousksou et al., 2014).

Another option to store energy is to produce hydrogen with excess electricity. In turn, this hydrogen can be used to support sustainable transport. Options for the application of hydrogen in transport are to use it directly as a fuel for hydrogen cars that work with combustion motors, or to fuel cell cars, which convert the hydrogen into electricity to power electric motors (IEA, 2012; IRENA, 2016; Kleijn, 2012).

Besides energy storage, demand side management (DSM) will play a crucial role in the energy system. Well-functioning DSM requires the use of IT to synchronize demand and supply. IT will especially be useful to upgrade the existing grid in order to make it smarter. These upgrades are e.g. two-way digital communication devices. Eventually, a smart grid increases the degree of controllability (IRENA, 2016).

Despite the fact that the energy system will become more decentralized than it currently is, more centralized will still play a role within the energy system. Energy suppliers will produce renewable energy, which is still distributed to consumers. This will still be dealt with centrally. Another centralized option is to implement district heating networks based on renewable energy (IRENA, 2016; Jonkhoff & van der Kooij, 2013). Such a network consists of a network of underground, insulated pipes that pump hot or cold water to multiple buildings in a district or city (IRENA, 2016). There are a few options to produce heat with electricity. These are electric boilers and heat pumps. The heat that is produced, using these technologies, can then be used immediately by letting it feeding it to the grid, or it can be stored in hot water tanks (IEA, 2012; IRENA, 2017).

5.3 TRANSPORT

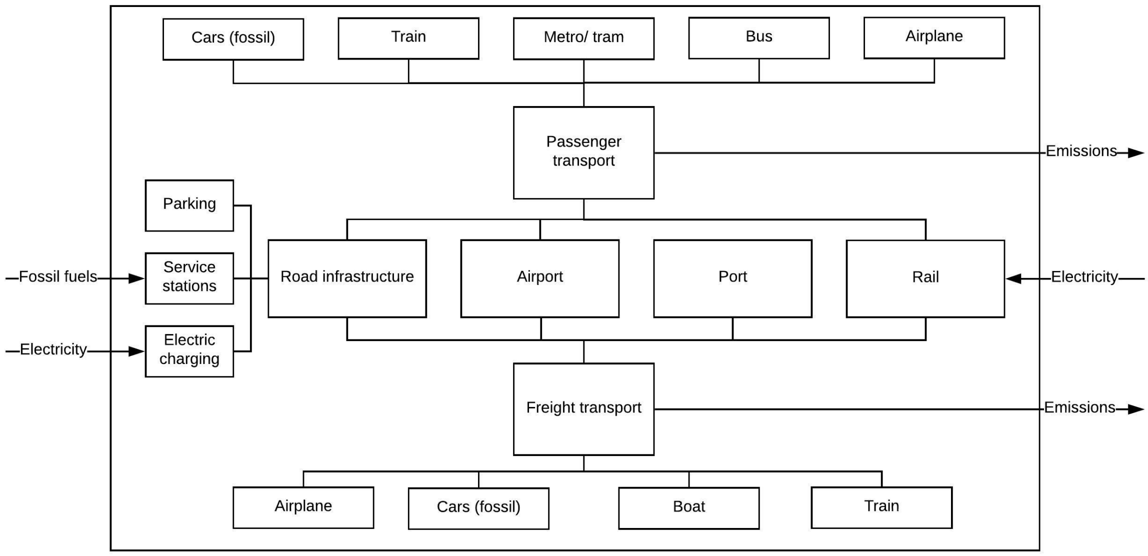

Figure 8: Transport sector in a metropolitan area

Transport within a metropolitan area can be divided in two different categories; passenger transport and freight transport (Barrett et al., 2002; MacKay, 2009). Passenger transport can be subdivided in transport by car, bus, train, metro/tram and airplane. Freight transport can be subdivided in transport by road, sea, rail and air (Barrett et al., 2002).

Each way of transport within a metropolitan area uses the infrastructure that is present. The infrastructures can be categorized in four different categories: Road, rail, airport and port infrastructure. Both road and rail infrastructure are abundantly present in cities, whereas airport and port infrastructure are present in metropolitan areas, but not in cities.

Some of the main elements of road infrastructure are roads, service stations, parking lots, and electric charging stations. The road infrastructure is used by cars, busses, and freight transport (i.e. trucks). The majority of these vehicles are based on fossil fuel combustion engines, which means that their energy sources are mainly petroleum and natural gas. These fossil fuels are distributed by service stations. A minority of vehicles is fully, or partially, based on electric motors. These vehicles need electrical charging infrastructure. This can be at home or somewhere along the road. Furthermore, an important aspect of the road infrastructure is the required possibility for vehicles to park. The importance is emphasized by the percentage that cars are parked on average, which lies around 90% (European Commission, 2016).

Rail infrastructure mainly consists of tracks and overhead lines. This infrastructure is used by trains (for both passenger and freight transport), metros and trams. Trams and metros are only used within cities, whereas trains are used for transport over longer distances. All of these transport modes run on electricity. The overhead lines are used to power the trains, metros and trams.

Airports in metropolitan areas are used for passenger transport and freight transport. When it comes to airports, it is important to have a clear determination of what is taken into account. One could argue that only the physical airports, without taking its activities into account, are a part of the transport sector of a metropolitan area. However, the largest impact of the aviation sector, self-evidently, comes from the flights and not from the airport itself. On a global scale, only 5 percent of the impact of aviation comes from activities at airports (Huffington Post, 2016). However, since the core of the aviation business is not likely to shift away from fossils, aviation is out of scope for this research. This means that bunker fuels are not taken into account, which is in line with the energy report on the AMA of the Ministry of Infrastructure and Environment (2017). Thermodynamics currently do not allow a transition to another mode of transport within aviation, because of the energy density that is required for aviation. Apart from the discussion on the energy source of aviation, the frequency of flights due to a transition towards a circular economy is within scope of the research.

The same discussion is applicable to the seaports. Again, here the major impact comes from the transport itself, not necessarily from the seaport. For seaports, there is chosen for the same delineation as for airports.

Limitations

The transport sector is considered as one of the sectors that has the largest impact on the sustainability performances of nowadays' society. This is largely due to the fact that the prevailing energy source on which vehicles in this sector run are fossil fuels, and mainly petroleum (Ellen MacArthur Foundation, 2015b; IRENA, 2016). However, for the general passenger car, this is very inefficient. This is mainly due to the weight of the car and the Carnot cycle. The heavier the car is, the more energy it uses to move the car. Furthermore, the Carnot cycle, which is applicable on each fossil fuel engine, does not allow 100 percent efficiency, since not all energy is converted into work. Besides these thermodynamic inefficiencies, another reason for the inefficiency is the undercapacity of most vehicles. European cars have on average 5 available seats in a car, of which on 1,5 is generally used per trip (Ellen MacArthur Foundation, 2015b).

Besides the inefficiency of fossil fuel combustion engines, the cars are currently parked for 92 percent of the time. The time vehicles are parked, they are just occupying land that could be used for other purposes as well (Ellen MacArthur Foundation, 2015b).

One of the new technologies seems to be slowly penetrating the market are electric vehicles. However, the adoption rate of vehicles using this technology is fairly low. One of the reasons for this is the lack of good charging infrastructure (IRENA, 2016).

CIRCULAR

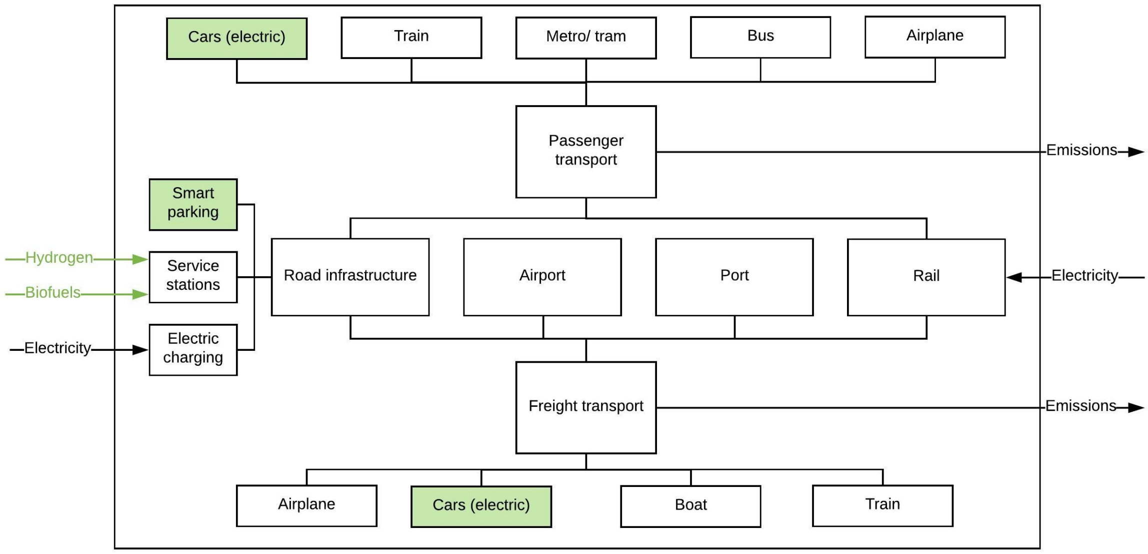

Figure 9: Circular transport sector

As the largest impact in the transport sector is linked to the energy source for vehicles, it seems clear that the source of energy on which transport is based needs to change. A shift from fossil fuels to more sustainable alternatives is required. Possible alternatives would be electricity from renewable energy technologies, hydrogen and biofuels.

The road infrastructure would change on the basis of the changing car fleet. Cars based on fossil fuel combustion engines would represent a very small fraction of the car fleet, as most of these cars are replaced by electric vehicles, and some cars by hydrogen-fueled cars. The number of service stations can be reduced significantly, as there will be a small demand for fossil fuels. The remaining service stations could supply biofuels and hydrogen. On the other side of the balance, the charging infrastructure for electric vehicles needs to be expanded significantly. An expanded charging infrastructure for electric vehicles offers the possibility to balance supply and demand of electricity, as stated earlier. With this technique could the wastefulness of parking be addressed (EEA, 2016; IRENA, 2016). Cars fueled by hydrogen would be an option in a circular transport system if the hydrogen is produced with renewable energy. A possibility is to use excess renewable electricity to produce hydrogen. This could be a technique to store energy produced with renewable energy technologies (IRENA, 2016; MRDH, 2016).

Another promising technology is autonomous driving. Autonomous driving could offer advantages over controlled driving in terms of optimization. Autonomous vehicles can have optimized car performances as they accelerate and decelerate at an optimum level. Besides efficiency increases for the car itself, autonomous driving can also contribute to an increase in efficiency in a systemic way, as it could reduce congestion. All these effects improve the energy efficiency of the transport sector (Ellen MacArthur Foundation, 2015b).

Besides the electrification of transport, a circular transport system makes use of sharing, in order to tackle the problem of undercapacity in cars. This can be car-sharing or ride-sharing. Sharing in transport requires a system that links supply and demand, which can be done with the use of digital technologies (EEA, 2016; Ellen MacArthur Foundation, 2015b).

Within a circular transport sector, the public transport sector is almost fully based on rail infrastructure, since these transport systems run on electricity and already form a sustainable option when electricity is generated by renewable energy technologies (IRENA, 2016). Furthermore, public transport is responsible for a larger share of the total traveled kilometers in a circular economy (Ellen MacArthur Foundation, 2015b)

As it comes to aviation, there is currently only one alternative for using kerosene and that is using advanced biofuels. This is the only option since electrification is not yet an option, as stated before (EEA, 2016). Equal to the use of biomass for energy supply, using biofuels is something that requires extra attention. Biofuels come in a variety of types. Currently, there are first-generation and second-generation biofuels. The generation depends on the feedstock that is being used. First-generation biofuels are based on agricultural crop. Second-generation, advanced, biofuels are based on non-edible feedstocks, which is inherently more sustainable than first-generation fossil fuels. Still it is the question if production of these feedstocks competes with land that could be used for other purposes (IRENA, 2016). This is especially the question if this will be considered as a sustainable fuel and the demand for this product rises significantly. If cars, planes, industry, and energy supply all run on biofuels, this cannot be sustainable.

5.4 BUILT ENVIRONMENT/ CONSTRUCTION

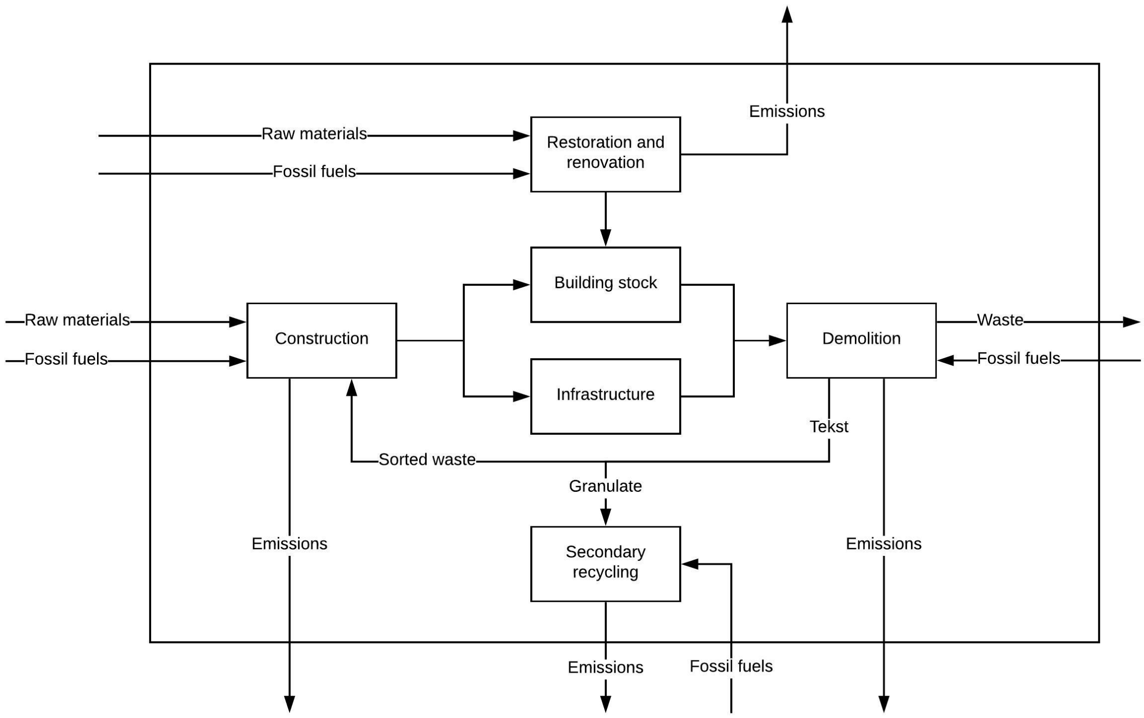

Figure 10: Built environment/ construction sector in a metropolitan area

The built environment can be considered as a stock of buildings and infrastructure. On the one side, the construction sector is adding to this building stock by building new houses, offices, infrastructure, etc. (Pomponi & Moncaster, 2017; van Bueren et al., 2012). On the other side, buildings and infrastructure are being demolished (Circle Economy, 2015; Schut et al., 2015). At the same time, existing buildings are being restored and renovated, which expands the life time of buildings.

The construction sector is largely based on fossil fuels, which causes the exhaust of greenhouse gasses. Furthermore, the sector is very dependent on the import of raw materials, such as iron, aluminum, copper, sand, clay, limestone, and wood. Within the construction sector, concrete counts as the material that is responsible for the largest impact on the environment (Circle Economy, 2015).

Demolition activities, just as activities in the construction sector, mainly run on fossil fuels. Demolishing buildings and infrastructure results in a flow of demolition waste that can have various destinations. The first option is that the waste flow gets dumped, by which each form of value is destroyed. The second option is that the waste flow can be used in recycling projects that are considered as 'downcycling'. This refers to the recycling of a flow in less high-quality state. The third option is that the waste gets recycled in a way that it can substitute high-quality raw materials.

Due to the long lifespan of buildings, buildings can undergo changes during their lifetime. This allows it to apply restoration/renovation and retrofitting to existing buildings. Retrofitting holds that new technologies are added to existing buildings. This often concerns technologies that improve the energy efficiency of the buildings. Restoration and renovation is about fixing structures that are up to change.

Limitations

The construction sector is often mentioned as one of the most polluting sectors around. This is mostly due to the energy and material intensiveness. However, the largest impact does not occur within metropolitan areas. The extraction of raw materials more upstream in the supply chain is related to large amounts of greenhouse gas emissions. (Circle Economy, 2015; Schut et al., 2015). These are often very energy-intensive processes that are based on the use of fossil fuels (Circle Economy, 2015; Nasir et al., 2016; Pomponi & Moncaster, 2017; Schut et al., 2015). As stated earlier, the sector is largely depending on the import of raw materials, which contributes considerably to resource depletion (Nasir et al., 2016; Schut et al., 2015; World Economic Forum, 2016).

Another impact related to the construction sector are the large amounts of waste it produces (Circle Economy, 2015; Nasir et al., 2016; Schut et al., 2015). Currently, if demolition waste is being recycled, it is often being recycled in a suboptimal way. The demolition waste is often stone rubble, which is being reused in e.g. new roads (Circle Economy, 2015). One of the major causes of this suboptimal recycling is that the buildings that already have been built are not constructed with the idea of recycling at the end-of-life stage and are constructed with the focus on a long lifespan. This has been stimulated by the fact that producers are not responsible for the demolition, which causes a conflict of interests (Pomponi & Moncaster, 2017; Schut et al., 2015). The long lifespan of the buildings makes it that it is expected that, in the northern hemisphere, 75-90 percent of the current building stock still exists in 2050 (Pomponi & Moncaster, 2017). As the building stock is expected to stand for many more years, this also leads to another problem. This concerns the difference in supply and demand as it comes to recycled material. As more buildings and infrastructure is being built, less than being demolished, there is a shortfall of recycled material (Circle Economy, 2015). All in all, the building stock in the built environment embodies a potentially huge supply of materials that is not expected to be released on a short term (Schut et al., 2015).

CIRCULAR

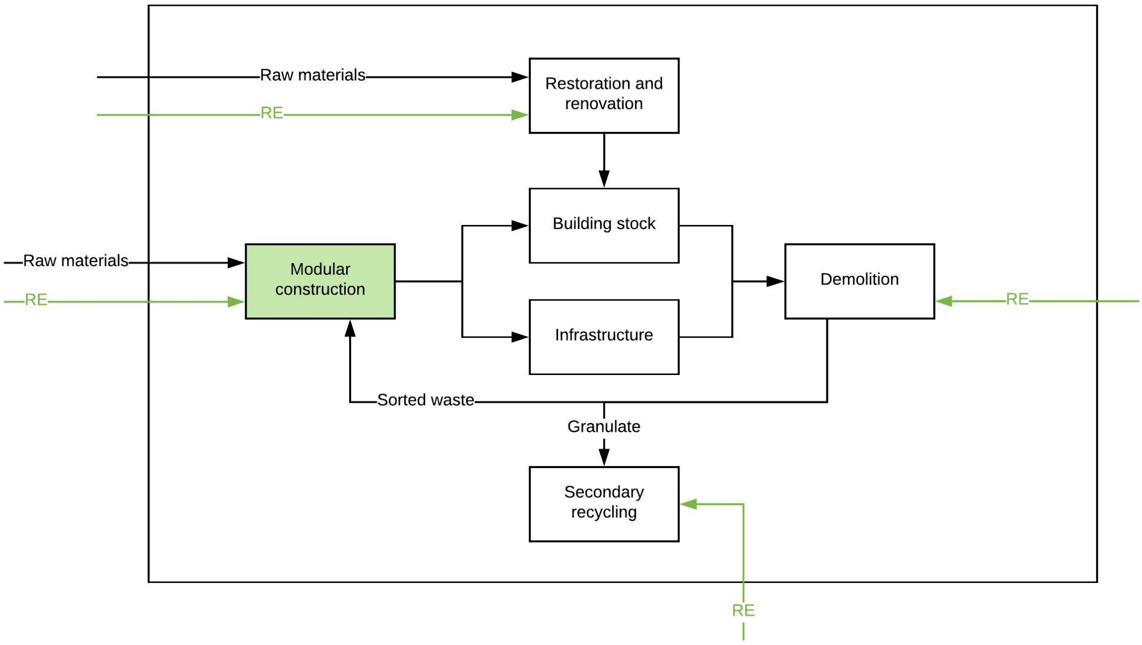

Figure 11: Circular built environment/ construction sector

In a circular economy, the construction sector manages and recycles its material streams efficiently, runs completely on renewable energy and does not have a negative impact on human life or the ecosystem (Circle Economy, 2015). In a circular construction sector, buildings are designed in a modular and flexible way, which allows it to make maximize the lifespan of materials through reuse and repurposing (Circle Economy, 2016).

Managing and recycling material streams efficiently is the biggest challenge in this sector. As stated earlier, materials and structures are not designed in a way that they are easy to reuse. This results in a situation where materials are not easily sorted when buildings or infrastructure are demolished (Schut et al., 2015). This means that it is extremely difficult to fully recycle the demolition waste that comes from the existing building stock. However, new buildings that are being built should be built in a modular way, in order to ease the process of recycling afterwards and to make it easier to adjust buildings to meet demands of various residents (Circle Economy, 2016). This situation can be improved by using Building Information Modelling (BIM). This technology creates a material passport, which contains lots of information on the materials that are used during the building process. It should present the characteristics of materials, in order to determine their usefulness as it comes to value recovery and reuse (Circle Economy, 2015; Schut et al., 2015).

Furthermore, the waste flows in a circular economy should be reused for high-quality purposes. The way that waste flows are currently being used is not circular. Recycling of waste flows resulting from demolition are often used as secondary building material, such as gravel for the construction of roads. Since this considers a one-time cycle, this cannot be described as fully circular (Schut et al., 2015)

Since it is expected that current building stocks will last for lots of years, improving the sustainability performances of existing buildings will one of the best options for cities that do have a building stock that is not growing that much anymore. This is often referred to as retrofitting, i.e. applying new, sustainable, technologies on old buildings or products. According to the Ellen MacArthur Foundation (2015), retrofitting could reduce the energy consumption of buildings with 20-40 percent. Adjustments that fall under retrofitting are e.g. better insulation, solar roofs, heat pumps, double glazing, and making homes 'smart' (smart meters and thermostats) (Ellen MacArthur Foundation, 2015b; IRENA, 2016). In this way, the skeleton of the building can stay intact (Schut et al., 2015).

5.5 WATER

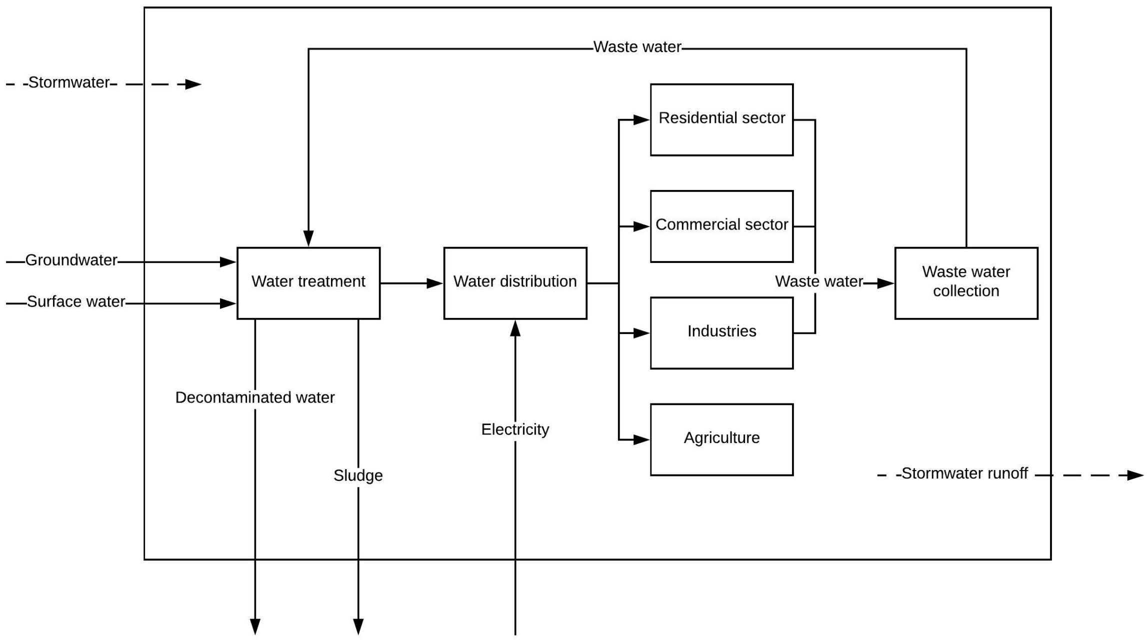

Figure 12: Water sector in a metropolitan area

Depending on the location of the metropolitan area, the water that flows into the urban area is extracted within the metropolitan area, otherwise it is imported from another place. The water is often extracted from groundwater. Via pipes this water is transported to a water treatment, where the water gets treated to make it of a quality that is high enough to meet the current leading standards. In these treatment processes the water gets purified, the taste and color get improved and it is decalcified (Jonkhoff & van der Kooij, 2013; van Bueren et al., 2012).

When the water is treated, the quality is high enough to transport it to the users. This transportation goes via a large system of mains that runs on electricity (Jonkhoff & van der Kooij, 2013). The most important sectors to which the treated water flows are the building environment, industries and the agricultural sector. The building environment can be divided into a residential sector and a commercial sector (IWA, 2016; van Bueren et al., 2012). In the residential sector, most water is used for drinking water, toilet flushing, showering, cleaning, and washing. Within the commercial sector there is a less clear image of what uses the most water, due to the larger variety of activities within this sector. Components of the commercial sector are offices, hospitals, SMEs, catering, etc. For industries, there exists a clearer view. The largest flows are used for heating and cooling. Here, energy supply is considered a part of industries. In the agricultural sector, water is mainly used for growing crops (Lisa Scholten, personal communication, 2016

The used water from the residential sector, the commercial sector and industries is called wastewater. Wastewater is collected and transported via sewers to the wastewater treatment plant. At the plant, the wastewater is decontaminated and often released to the environment, such as the sea. A by-product of the decontamination process is sludge.

Besides the water that is used in the sectors that are described above, another large inflow of water is rainwater. Currently, it is considered as stormwater runoff that is not being put to use.

LIMITATIONS

Water systems that are currently installed can be described as inefficient, as water is lost, polluted, wasted and misused. Several water flows that are not, or not fully, used to its potential. These flows are rainwater, grey water and decontaminated water (IWA, 2016).

Furthermore, it is mentioned that wastewater contains lots of nutrients and materials that could be of use, while they are now going to waste. It mainly considers bio-solids in sludge, such as nitrogen and phosphate (IWA, 2016; Jonkhoff & van der Kooij, 2013).

Wastewater does not only contain nutrients and materials that could be used, but it is also often heated. This is done for e.g. showering, washing, etc. Currently, this energy in the form of heat is lost (IWA, 2016; Jonkhoff & van der Kooij, 2013)

CIRCULAR

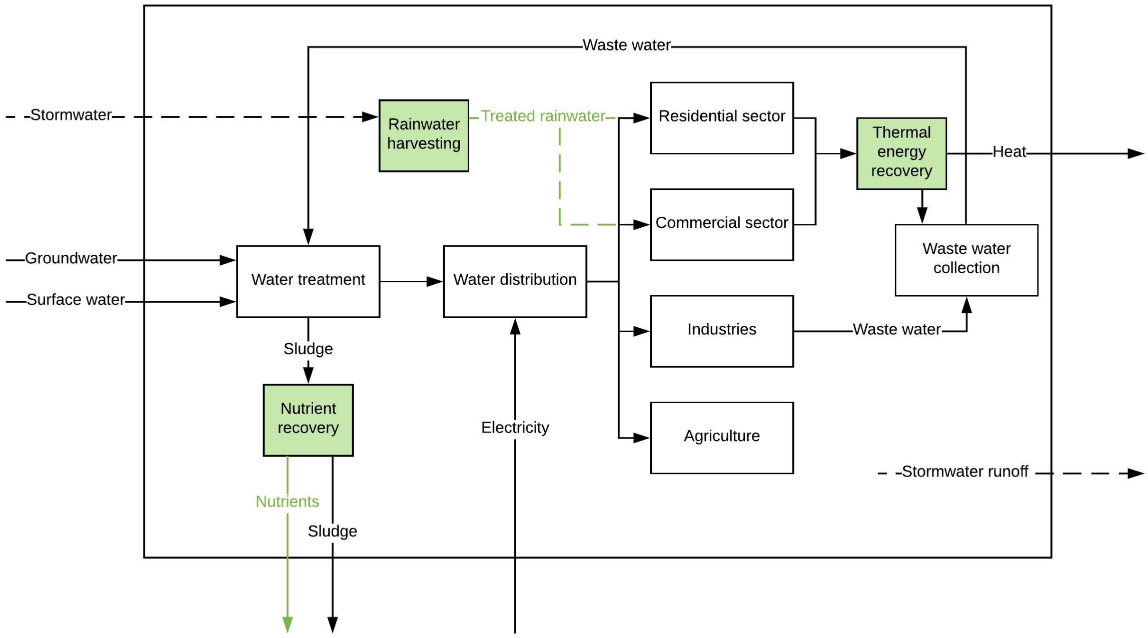

Figure 13: Circular water sector

Circularity in the water sector can be applied on three different themes. These are water, materials and energy. The water theme mainly focuses on water flows that are currently present in the sector, but do not live up to their potential. The focus of the material theme is on nutrient recovery from water flows. The last theme, energy, focuses on energy consumption related to the water sector.

As it comes to water, there are several flows that are hardly used. One of these flows is rainwater. Currently, rainwater comes into the system and directly goes into the sewers and eventually it ends up in the environment. However, in a circular economy this rainwater gets harvested locally and subsequently it gets a small treatment, or it can be used directly for e.g. toilet flushing, irrigation, washing, or even drinking water (IWA, 2016). Harvesting this rainwater can be done by using roofs and terraces. Green roofs can be applied with a linked storage tank (Ellen MacArthur Foundation, 2015b). Besides circulating the water, harvesting rainwater also reduces flood risks and the load on sewer systems (Goyal, 2015).

Furthermore, households and offices produce grey water, which is wastewater that comes from the houses, except for wastewater that comes from toilets, which is called black water (containing urine and feces). Grey water may come from showers, washing machines, sinks, etc. If this water is collected and treated, it can be used for the same activities as rainwater (IWA, 2016; Jonkhoff & van der Kooij, 2013).

The water that is decontaminated at the wastewater treatment is now drained to the environment, while this water could be of use for industries that need e.g. cooling water. This water does not need to meet the high quality standards of drinking water, so it should be possible to use it for industrial processes (IWA, 2016)

In terms of materials, existing water flows contain materials and nutrients that are currently wasted, but if they are recovered, they could serve several purposes. One of the products of the water sector is sludge, which comes from treating water at the wastewater treatment. This sludge is rich in nutrients, such as nitrogen and phosphorus. When these nutrients are stripped from the sludge it can be used for non-agricultural uses. Using it for agricultural uses is not yet possible, due to strict regulation (IWA, 2016; Jonkhoff & van der Kooij, 2013).

In terms of energy, lots of heat is being lost in the water sector. Buildings often have a large demand for heat, which is used to heat up water. This is done for e.g. showering, washing, etc. In the current situation, the heated water is wasted. In a circular economy, this heat should be recovered. One of the possibilities to make this possible is by installing heat exchangers in showers (IWA, 2016; Jonkhoff & van der Kooij, 2013). The same applies for sewers, which are one largest leaks of heat in buildings (IWA, 2016).

6. AMSTERDAM METROPOLITAN AREA

Based on the conceptual model that has been constructed in general terms, the model requires specification for the case of the AMA. The focus of this chapter is on specifying the conceptual model for the case of the AMA. This implies that the conceptual model is translated in equations that enable modeling the AMA.

6.1 GEOGRAPHICAL AREA

The Amsterdam Metropolitan Area embodies 2 provinces (North-Holland and Flevoland), 32 different municipalities, and the Amsterdam City Region (CITIES, 2011; PlanAmsterdam, 2016). It stretches from IJmuiden to Lelystad and from Purmerend to Haarlemmermeer (Amsterdam Economic Board, 2017). The region is visualized in figure 14. The Amsterdam Metropolitan Area houses 2.4 million people, which equals about 14 percent of the Netherlands (Amsterdam Economic Board, 2017; PlanAmsterdam, 2016).

The total metropolitan area accounts for 2580 square kilometers (Wikipedia, 2017a). According to the Ministry of Infrastructure and Environment (2017), the spatial division of the AMA is:

- 9,2% Residential area 237,4 km^2
- 38,1% Water 983 km^2
- 26,6% Agriculture and horticulture 686,3 km^2
- 3,4% Infrastructure 88 km^2
- 3,3% Business parks 85 km^2
- 1,6% Trade, service and government 41,3 km^2
- 17,7% Miscellaneous 456,7 km^2

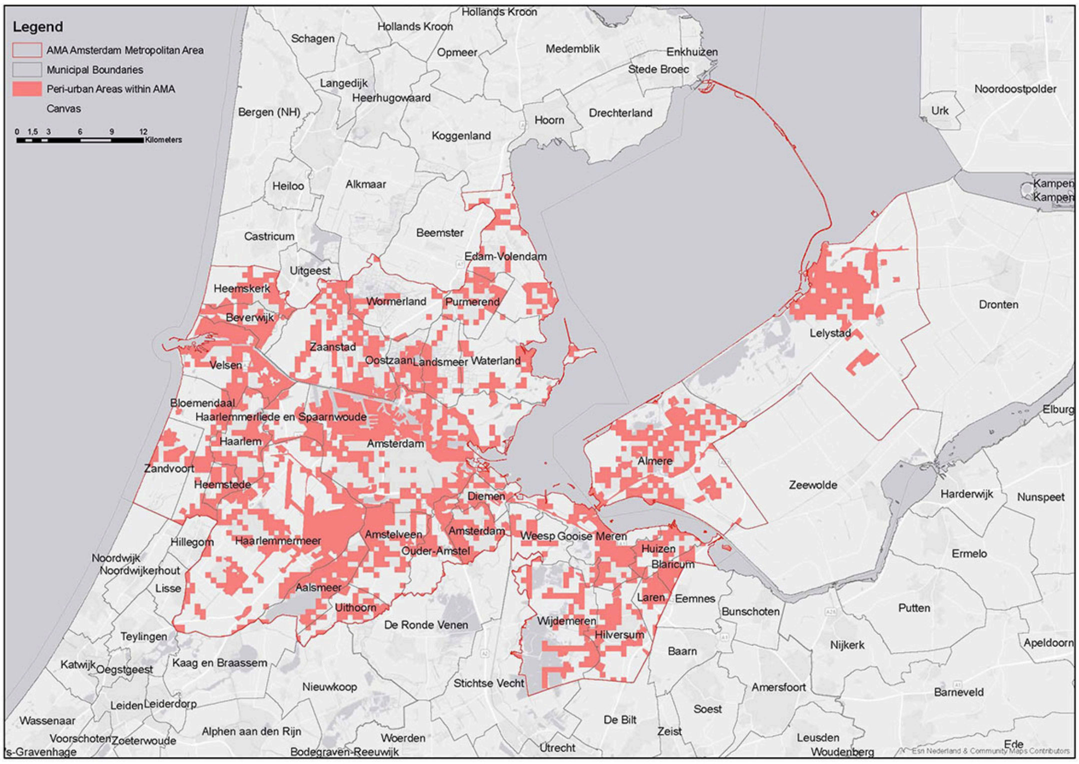

Figure 14: Amsterdam Metropolitan Area (REPAiR, 2017)

6.2 MODELING THE AMSTERDAM METROPOLITAN AREA

Specifying the model for the AMA requires decomposing the identified variables and relations of the conceptual model to a larger extent. This specified model forms the baseline scenario, which can be quantified based on well-informed estimates. The baseline scenario forms the basis of modeling a circular AMA. An overview of all equations can be found in Appendix A and a table with the quantified model parameters can be found in Appendix B.

FOOD SECTOR

In the conceptual model, the food sector is roughly divided in four different components: 'food production', 'food consumption', 'food waste', and 'energy and resources'.

The first variable of interest is food production. The food that is being produced in the AMA mostly comes from peri-urban areas, since urban agriculture is not yet developed. Although there is an increasing amount of projects on urban agriculture that is being started (CITIES, 2011). As food consists of several food groups, food production requires decomposition in order to get an idea of what food is produced is the AMA, and if this is enough to provide its own population. Data on quantities of produced food is not available for the AMA, but this data is available for the Netherlands as a whole. In order to estimate the quantities produced in the AMA, extra data is needed. In case of animal protein products or other products coming from animals (beef, pork, poultry, sheep, eggs, milk), there is data on the number of animals for both the Netherlands and the AMA, and in case of other food products, such as cereals, vegetables, fruits, legumes and potatoes, there is data on the size of the area appointed to producing these products for both the Netherlands and the AMA (CBS, 2017a, 2017b, 2017c). With this data, it is possible to make well-founded estimations for food production. The estimations are presented in equations. The quantity of animal protein products is estimated with the following equation:

<u>Beef production</u> = Production NL * (# of animals AMA/ # of animals NL)

This structure of this equation is also used for estimations of poultry, pork, sheep, egg and milk production. The estimations for the remaining food groups, fruits, vegetables, legumes, cereals, potatoes and legumes, are stated in this form:

<u>Fruits greenhouse production</u> = Production NL * (Purpose area AMA / Purpose area NL)

The second important variable is food consumption. Rossum et. al. (2016) have written a report on the composition of the average diet of a Dutch citizen. The report states the number of grams of consumption of a food group per day. These numbers are assumed to be representative for an inhabitant of the AMA. Food consumption is estimated per food group according to the following structure:

<u>Vegetable consumption</u> = Consumption per person per day * Inhabitants AMA * 365

Since Rossum et. al. (2016) do not differentiate between different types of meat, meat consumption needs to be broken down into the same four categories that apply for meat production, since this gives a more complete view on the flows of meat through a metropolitan area. Furthermore, the impact per type of produced meat differs. Ritchie & Roser (2018) give an overview of consumption patterns per country, including the earlier used categories of meat consumption. Besides the four categories of meat consumption, the overview of Ritchie & Roser (2018) also gives another category of meat consumption, this category is named 'Other', which accounts for ten percent of the total meat consumption. For this research, only the categories 'Poultry', 'Beef', 'Pork' and 'Sheep' are taken into account. The category 'Other' is evenly distributed among the three biggest categories (poultry, beef and pork). The estimations have the following structure:

<u>Poultry consumption</u> = Meat consumption * Poultry consumption fraction

As stated in the conceptual model, food production and food consumption are not completely efficient mass flows. To some extent, both of these flows result in food waste, which is the third variable. According to Rood et al. (2017), the total amount of food waste per person per year lies between 109 and 162 kilograms. The assumption for this research is that the total amount of food waste per person per year lies exactly in the middle of this range, at 135,5 kilograms. Different processes within the food sector are related to food waste production, the Ellen MacArthur Foundation (2015) states what stages of the food chain are responsible for which percentage of food waste. Although the total food waste per person per year is the base number here, the quantities of food waste at the different food chain stages will function as the base numbers in modeling the AMA. This allows it to adjust the efficiency per stage of the food chain. The food waste production is estimated according the following equation:

<u>Food waste</u> = Consumer waste + Production waste + Storage waste + Distribution waste + Processing waste

Data on food waste production alone is not useful, since food waste is related to other flows within the AMA. Currently, food waste has three different destinations, 25 percent goes to animal feed and less than 1 percent of the food waste is distributed to food banks. The rest of the food gets incinerated for energy (Rood et al., 2017). Therefore, the following structure for the estimations applies:

<u>Food waste to animal feed</u> = Food waste * Animal feed fraction

The last component of the food sector is 'energy and resources'. Part of this component are animal feed, fertilizer use, manure, energy and water.

The production of animal-based food, which also includes eggs and milk, requires animal feed. Ritchie & Roser (2018) state the amount of animal feed that is needed per kilogram of end-product. The required quantities for animal feed are estimated as stated below. The relation with food waste is incorporated in the estimation of the total animal feed requirements:

<u>Beef animal feed</u> = Animal feed per kg * Beef production

<u>Animal feed</u> = Beef animal feed + Pork animal feed + Poultry animal feed + Eggs animal feed + Sheep animal feed + Beef milk animal feed – Food waste to animal feed

A result of having animals is the production of manure, which is another important variable within the food sector. CBS (2017a) gives the numbers on the total manure production in the AMA, which consists of liquid and solid manure. As this equation is not linked to the number of animals, it is static. To overcome this, data on the number of animals in the AMA is linked with data on manure production per type of livestock from NRCS (2017). However, the result of this calculation comes to approximately 82 percent of the quantity of manure stated by CBS (2017a). Since the quantity of manure stated by CBS (2017a) is assumed to be the correct quantity, this quantity will be combined with the percentage distribution of the calculation with the numbers of NRCS (2017). This calculation can be found in Appendix C.

<u>Manure</u> = Liquid manure + Solid manure

Another variable in the food sector is the fertilizer flow. Fertilizer is used to make agricultural grounds more fertile, which increases the yield of agricultural land. The World Bank (2017) states the fertilizer consumption in kilograms per hectare of arable land for the Netherlands. Since it is assumed that this number is the same for the AMA, this can be used to estimate the total fertilizer use in the AMA. According to the Ministry of Infrastructure and Environment (2017), the agricultural land in the AMA accounts for 686,3 square kilometers. Fertilizer use is estimated as follows:

<u>Fertilizer use</u> = Agricultural land * Fertilizer use per ha

To some extent, each form of food production depends on water. CLO (2016b) states that the average use per agricultural company is 2111 cubic meters per company. Since CBS (2017a) provides data on the number of agricultural companies in the AMA, the water use of the food sector can be estimated. The following structure applies:

<u>Water use agriculture</u> = Average water use per company * # of companies

There are no clear numbers on the import and export flows of the AMA. Therefore, in order to determine the import and export flows of the AMA, it is assumed that the result of the production of a certain product group subtracted with the consumption of this product group is equal to the import or export rate. When the result of this subtraction is a positive number, it means that more food is produced than is consumed, so the remaining number concerns exports. When the result is a negative number, it is considered to be the import rate. This results in the following equation structure:

<u>Vegetable import/export</u> = Vegetable production – Vegetable consumption

Energy sector

The energy sector can be broken down in two main variables, which are 'electricity' and 'heat'. Both categories can be subdivided in 'non-renewable' and 'renewable'.

Following the conceptual model, the major sectors to which electricity is related are 'construction', 'transport', 'agriculture', 'industries' and the 'built environment'. Klimaatmonitor (2017) and a report by the Ministry of Infrastructure and Environment (2017) provide data on the total electricity use of the sectors 'construction', 'built environment' (which consists of household and commercial service), 'industries' and 'agriculture'. However, since data on 'transport' lacks, electricity use of the transport sector needs to be decomposed further. In order to estimate the electricity use of 'transport', it is assumed that transport by train, metro, tram and electric car are responsible for the electricity use of the transport sector. Klimaatmonitor (2017) provides the number of kilometers traveled by these transport modes. However, the data on traveled kilometers by tram and metro is merged with the data on kilometers traveled by bus. It is therefore assumed that metro and tram make up 2/3 of this number. When the data on traveled kilometers is combined with the average electricity use per traveled kilometer, which is provided by the Dutch Railway Company (NS, 2016), it is possible to estimate the electricity use of rail transport. This only covers the rail transport, and not the transport by electric car.

Since there is no exact data on the electricity use of electric vehicles in the AMA, this flow requires further decomposition. Klimaatmonitor (2017) provides data on the number of electric vehicles in the AMA. Two types of electric vehicles are distinguished: Plugin hybrids (PHEVs) and full electric vehicles (FEVs). Klimaatmonitor (2017) also states the total traveled distance by car and the number of plugin hybrids and electric cars in the AMA. As PHEVs account for 2,5 percent and EVs for 0,4 percent of the AMA car fleet, it is assumed that they account for those percentages of the kilometers traveled by car. As the EV Database (2017) and the Consumentenbond (2016) provides data on the average electricity use per kilometer of an electric car (EV) and a PHEV, the electricity use by electric cars be estimated. The total electricity use in the AMA can be estimated by applying the following equation:

<u>Total electricity use</u> = Electricity households + Electricity commercial + Electricity agriculture + Electricity construction + Electricity transport + Electricity industries

In a circular economy, the origin of electricity is crucial, as it is aimed for that all energy comes from renewable resources. The database of Klimaatmonitor (2017) provides data on the amount of gigawatt hours (GWhs) of electricity produced in the AMA, based on renewable energy sources. The same number based on fossil energy sources is missing in the database. However, it is assumed that subtracting the amount of GWhs produced by using renewable energy sources from the total electricity use gives the electricity produced by using fossil energy sources.

As it is known what fraction of the electricity comes from renewable sources and what fraction comes from fossil sources, these flows need to be decomposed in order to get a clear vision on what energy technologies produce the electricity. According to the database of Klimaatmonitor (2017), the renewable sources are wind energy, solar energy, biogas co-fermentation, waste incineration, biogas sewage electricity, decentral biomass and landfill gas. The amount of produced GWh per renewable energy source is given. However, wind and solar energy differ from the other renewable energy sources as they are intermittent by nature. This means that the electricity production depends on external factors, e.g. wind energy depends on the amount of wind (full load hours), and solar energy on the total hours of sunlight. Despite the intermittent nature of the full load hours and the sun hours, both full load hours and hours of sunlight are fixed numbers in the model, based on van Sark & Muizebelt (2016) for the total hours of sunlight and the full load hours generated wind power divided by the installed capacity. Besides wind and solar energy, electricity from waste incineration is responsible for a large amount of renewable electricity. The production of electricity (and heat) by incinerating waste depends on the amount of residual waste that is collected in the AMA. The estimations for the production of renewable electricity are structured as follows:

<u>Wind energy</u> = Installed capacity * Full load hours per year

<u>Renewable electricity</u> = Wind energy + Solar energy + Biogas co-fermentation + Waste incineration electricity + Biogas sewage electricity + Decentral biomass + Landfill gas

The next step is to decompose electricity from fossil energy sources. CBS (2016) provides data on the energy mix for electricity production in the Netherlands. It is assumed that this is the same for the AMA. Given the energy mix of fossil fuels for electricity production, the equations take the following structure:

Coal electricity = Fossil electricity * 0,42

The second important variable in the energy sector is heat. The major sectors that require heat are the 'built environment', 'industries' and agriculture'. The built environment is subdivided in a residential sector and a commercial sector. Data on heat use per sector in the AMA is provided by the Ministry of Infrastructure and Environment (2017). Heat use in the industry sector requires some extra attention. Heat demand for industrial practices has to be divided into two different types of heat demand. First, there is low temperature heat, which is used for practices such as creating steam. Second, there is heat which can be classified as industrial heat, or high temperature heat. This is heat that is required for some chemical processes and steel production located in the AMA. High temperature heat is responsible for approximately 80 percent of the heat demand from industry. The heat demand can be estimated with the following equation:

Total heat demand = Residential heat + Commercial heat + Agriculture heat + Industry heat

As for electricity, the production of heat is divided in heat production based on fossil fuels and renewable heat production. As most of the heat in the Netherlands comes from natural gas, it is assumed that heat from fossil sources is fully allocable to the burning of natural gas (SenterNovem, 2009). Renewable heat comes from various energy sources. These are waste incineration, biogas from sewage treatment, biomass boilers, geothermal energy, wood stoves in houses, charcoal, aquifer thermal energy storage (ATES), landfill gas and decentral burning of biomass (Klimaatmonitor, 2017). Heat production is estimated with the following equation:

Renewable heat = Waste incineration heat + biogas sewage sludge heat + biomass boilers + geothermal + wood stoves + charcoal + ATES + landfill gas + decentral biomass

Transport sector

As shown earlier, the transport sector is connected to the energy sector as the type of transport determines the impact on circularity performances. The amount of energy used for traveling depends on the distance traveled per transport mode. Klimaatmonitor (2017) provides data on the total traveled distance of passenger transport per year. This data is built up from a fraction personal transport by car and a fraction public transport. The total distance traveled per transport mode (personal transport or public transport) is estimated based on the structure of the following equation:

Distance by public transport = Total distance traveled * Public transport percentage

The public transport mode can be decomposed in four different transport options: train, metro, tram and bus. Klimaatmonitor (2017) provides data on the distribution of these options. Furthermore, the main energy source of personal car transport is largely depending on the car fleet. The car fleet is built up of passenger cars and commercial cars, which run on gasoline, diesel, natural gas or electricity (PHEV and FEV)(Klimaatmonitor, 2017). Exact data on the built up of the car fleet is provided by Klimaatmonitor (2017). The structure of the equations below is used to estimate the size of the car fleet:

Passenger fossil cars = Total passenger cars * Passenger fossil percentage

Passenger cars on gasoline = Passenger fossil cars * Passenger gasoline percentage

Whereas fossil fuels can be tanked at service stations, PHEVs and EVs depend on the availability of charging points. The AMA currently houses 6117 (semi-)public charging point and 37 public fast charging points (Klimaatmonitor, 2017).

Freight transport is largely depending on the main ports present in the AMA. As stated in the previous chapter, the main ports are not fully in the scope of the research, as aviation is not likely to shift from using fossil fuels, due to the needed energy density and lack of a technological development prospects. Both the Amsterdam Port and Schiphol Airport are for a large portion based on transits. The Amsterdam Port imports 64 million tons of goods, and exports 27 million tons of goods. 37 million tons of the imports are directly used in the port area. This mainly concerns metal ores for the steel industry, coal for energy production, other fuels, and foods. Exports consist for of 69 percent fuels, 7 percent metals, and 6 percent foods (van den Bosch et al., 2013).

The total transshipment of Schiphol Airport accounts for approximately 1,68 million tons of goods, of which half is import. 61 percent of the freight is transported via special cargo planes, and the other 39 percent of the goods is transported with passenger planes (CBS, 2016c). From the total imports via air, 53 percent of the goods are unloaded in Amsterdam. The rest is exported across the borders (CBS, 2016b). The average weight of freight at these flights are 4 tons per passenger flight, and 40 tons per cargo flight. The goods that are transported by air are often goods that spoil quickly, such as fish, vegetables and fruit (CBS, 2016c).

CONSTRUCTION SECTOR

Despite the often-heard claim that the Dutch construction sector has a very high recycling percentage, it is still largely depending on the import of raw materials. Import variables for this sector are the import of raw materials and the flow of construction and demolition waste (C&D waste). The construction sector in the AMA depends on a yearly input of 1500000 tons of materials (metals, minerals and other materials) (Circle Economy, 2016), this is assumed to be the yearly requirement of raw materials. This number consists of imported raw materials and a fraction of recycled material.

The flow of C&D waste can be decomposed further. As this flow consists of 15 percent of material that is considered to be dangerous and unusable, the usable fraction is 85 percent. The usable fraction consists of a fraction of granulate, which mainly consists of stony rubble, and a percentage of the waste that is sorted. The sorted waste can be used as a substitute for the input of raw materials (Circle Economy, 2015). Therefore, the flow of raw material inputs is related to the percentage of sorted waste. The size of the flows in the construction sector are estimated according the following structure:

<u>Raw material import</u> = Raw material requirements – Sorted waste

<u>Sorted waste</u> = C&D waste * Sorted waste percentage

The available numbers from the flow diagram of Circle Economy (2015) are copied. When flows where not accompanied by numbers, the numbers are estimated on the basis of the relative size of the flow.

Water sector

The most important variable of the water sector is water use. Following the conceptual model, the major sectors that use water are the residential sector, the commercial sector, agriculture and industries. The total water use is estimated with the following equation:

<u>Total water use</u> = Residential water use + Commercial water use + Industrial water use + Agricultural water use

A rather detailed overview of the water use of the residential sector has been provided by Waternet (2017). It states how much water is used per activity per day. Besides the total residential water use, also the quantity of grey water and black water can be retrieved from this overview.

Circle Economy (2016) presents a flow diagram of the AMA. One can read from the diagram that 87 million cubic meters of water is distributed over all sectors, except for the residential sector. It is assumed that the three remaining sectors make up these 87 million cubic meters. Earlier equations enabled us to estimate the water use of agriculture in the AMA. The estimated water use of the agricultural sector in the AMA is 4,6 million cubic meters. Subtracting the agricultural water use from the 87 million cubic meters results in a water use of 82,4 million cubic meters from industries and the commercial sector. The water flow in the flow diagram only shows a total amount (87), but it does not give exact numbers. However, the relative size of the flows suggests that industrial water use accounts for 58,9 million cubic meters and commercial water use for 23,5 million cubic meters. These values are assumed.

Another flow of water that comes into the AMA is rainwater. In 2015 there was 880 mm of rainfall in the whole of the Netherlands (CLO, 2016a). This number is assumed as yearly rainfall. With the surface area of the Netherlands and the surface area of the AMA, the yearly rainfall in the AMA can be estimated. Dividing the surface area of the AMA by the surface area of the Netherlands gives a fraction that represents the AMA as a part of the Netherlands. The surface area of the Netherlands and the AMA are respectively 41543 square kilometers and 2580 k square kilometers (CIA, 2017; Wikipedia, 2017a). The yearly inflow of rainwater in the AMA is 54,65 mm or 141 cubic meters.

7. Circular Amsterdam

This chapter focuses on the changes that will have to take place in order to reach a circular (or as circular as possible) economy in the AMA. Since this chapter is about future scenarios, a relative high degree of uncertainty is associated with the data. For that reason, data is an as large as possible extent based on literature. Uncertain data is presented with a lower and upper limit, between the value is expected to be.

Food sector

As stated in the fifth chapter, one of the characteristics of a circular food system is that it is non-wasteful. According to Ellen MacArthur Foundation (2015), if current trends are to be continued, consumer waste will be reduced by 35-40 percent by the year 2050. All the other food waste could be reduced by 45-50 percent. In a the most optimistic view, food waste could be reduced by 80 percent (Ellen MacArthur Foundation, 2015b). In compliance with the Ellen MacArthur Foundation, Abdel-Magid & Faris (2014) state that 61 percent of the food waste is avoidable if it would have been better managed.

Table 2: Food waste in a circular economy

FOOD WASTE				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Consumer waste	foodwaste_consumer	9.5	30.7	kg/person/year
Processing waste	foodwaste_processing	4.3	10.8	kg/person/year
Distribution waste	foodwaste_distribution	2.4	6	kg/person/year
Production waste	foodwaste_production	7.6	18.9	kg/person/year
Storage waste	foodwaste_storage	3.2	8.1	kg/person/year

Besides reducing the amount of food waste, the food waste of which no value is recovered still represents a potential value. A report by Soethoudt & Timmermans (2013) on food waste in the Netherlands states that, despite unavoidable food waste, some fractions of the food waste are still not recovered. The unrecovered part of food waste can increase the fractions of food waste destinations for food banks and animal feed. The fraction of food waste that can go to the food bank is considered very small is assumed to potentially increase by 0,2 percent. The fraction of food waste suitable for animal waste is assumed to be 5 to 6 percent.

Table 3: Food waste destination fractions in a circular AMA

FOOD WASTE DESTINATION				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Food bank fraction	foodbank_fraction	0.01	0.012	Percentage
Animal feed fraction	animalfeed_fraction	0.25	0.26	Percentage

Furthermore, agriculture can be classified as wasteful, since the application of some resources is not efficient. With the introduction of precision farming, the efficiency of resource application can be increased. Using several technologies, precision farming enables to assure that nutrients and resources are applied at the right time and in the right quantities, for optimal performances (Ministry of Infrastructure and Environment, 2016; Ward et al., 2016). These technologies are often based on IT and automation, and can include big data, remote sensing, satellite positioning data, etc. (Ellen MacArthur

Foundation, 2015b). According to Bouton et al. (2016), both fertilizer and water input can reach an increased efficiency of 20 to 30 percent, whereas the Ellen MacArthur Foundation (2015) only estimates this for water efficiency, but estimates fertilizer efficiency on 10-20 percent. In the most optimistic view, the water efficiency could be increased with 45 percent by the year 2050 (Ellen MacArthur Foundation, 2015b).

Table 4: Nutrient and resource inputs in a circular AMA

NUTRIENT AND RESOURCE INPUTS				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Average water use of agricultural companies	average_water_use	1161	1689	m^3/ company

In a circular economy, the production of food happens as close to the consumer as possible. This premise advocates for as little import of food as possible. So, if possible, food should be produced locally. However, metropolitan areas are often densely built places, that lack space. Therefore, urban agriculture bears some potential for metropolitan areas. Urban farming is often located at vacant lots, community gardens, balconies, rooftop gardens, indoor farms and greenhouses (Game & Primus, 2015; Grewal & Grewal, 2012; Specht et al., 2014). Urban indoor farming offers many advantages over traditional farming, due to the fact that it is not exposed to variable weather conditions, but only to totally controlled conditions. This allows it to reduce the agricultural runoff of an absolute minimum and optimize the yield per square meter (Despommier, 2013). The focus of urban agriculture is almost invariably on crops, and seldomly on animals. The combination of urban agriculture and animals often includes fish, such as tilapia, by means of hydroponics (Specht et al., 2014).

Urban farming, mainly indoor, is not yet developed to an extent to which it is very clear what all the pros and cons of this innovation are. Specht et al. (2014) attempt to cover the potential and the limitations of urban farming for each sustainability dimension, based on 96 articles. In terms of environmental sustainability, urban farming can reduce a significant amount of food miles, which leads to a cut down of transport emissions. Furthermore, the earlier mentioned high efficiency regarding resources of urban farming is often stated as an advantage. The largest potential lies in creating synergies by using e.g. waste heat and waste water from buildings or industries. Despite the large potential, it is not sure if urban can live up to this potential, due to the lack of large scale experiments and lack of experience with some technologies.

In an economical sense, the introduction of urban agriculture to metropolitan areas could result in a new variety of jobs for the local community. However, the most debated economic topic of urban agriculture is the yield (Specht et al., 2014). Despite the fact that potential yields of urban agriculture practices are not yet validated, Specht et al. (2014) argue that it can be assumed that the yield is comparable to existing greenhouse technologies. Caplow (2009) states that the yield of a recirculating hydroponic greenhouse lies between 50 and 100 kg of vegetables per square meter each year. Economic limitations of urban agriculture are the limited range of products that can be produced and the lack of space within urban areas to exploit urban agriculture. The range of producible products for urban agriculture mainly concern leaf and vine crops (Specht et al., 2014). Producing cereals, root vegetables, fruit trees and animal protein are often not viable (Ellingsen & Despommier, 2008). As it concerns the lack of space within urban areas, the AMA houses between 3.5 million and 5 million square meters of fallow areas and the municipality of Amsterdam has 800.000 square meters of vacant officers (Gemeente Amsterdam, 2017; Metropoolregio Amsterdam, 2017).

Besides the contribution to environmental sustainability, urban agriculture could deliver a significant contribution to social sustainability, by fulfilling an educational function. Connecting urban agriculture to educational programs could link consumers to food production. This could be of great importance, since industrialization increased the gap between food production and the consumer. This has led to a situation where consumers got disconnected and alienated from food production (Specht et al., 2014). The educational function of urban agriculture could also play a role in a shift of diet composition. In a circular economy, the diet composition is less based on animal protein and more on vegetable protein. For this transition in source of protein, especially the consumption of legumes should increase relative to the consumption of meat (Rood et al., 2017). As the AMA produces more vegetables than it consumes (surplus of 283 kton), focusing urban agriculture on vegetables is not necessary, since it would only increase the surplus. Considering that legumes potentially play a more import role in future diet compositions, it seems plausible that urban agriculture would focus on the production of legumes. It is therefore assumed that urban agriculture in a circular AMA only produces legumes.

With regard to the composition of the diet, it is assumed that the change meat consumption ranges between two meatless days a week and no change in meat consumption at all. On the other hand, the consumption of legumes is expected to change between a range of no change at all and two days per week of eating legumes instead of meat. According to the Voedingscentrum (2018), the Dutch information office on nutrition, 100 grams of meat can be substituted by 135 grams of legumes. It is assumed that the total amount of urban agriculture production equals the amount of extra legume consumption resulting from the shift towards a diet composition with a smaller share for meat consumption (See Appendix D for the calculation of the equations).

The establishment of urban agriculture in the AMA requires new equations for the model and some new parameters. The follow equations and parameters will be used:

<u>Meat consumption change</u> = Meat consumption per day – Meat consumption per day new

<u>Urban agriculture production</u> = Meat consumption change * 1,16

<u>Legume consumption per day</u> = Urban agriculture production + 4

<u>Urban agriculture land use</u> = Urban agriculture production / Urban agriculture yield

<u>Legume production</u> = Production NL * (Purpose area AMA / Purpose area NL) + Urban agriculture production

Table 5: Urban agriculture in a circular AMA

URBAN AGRICULTURE				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Urban agriculture yield	UA_yield	5×10^{-5}	1×10^{-4}	kton per m^2
Meat consumption per day new	meat_consumption_day_new	$7{,}1 \times 10^{-8}$	$1{,}01 \times 10^{-7}$	kton

Parameter	*Name in model*	*Value*	*Unit*
Urban agriculture production	UA_production	Function	kton
Urban agriculture land use	UA_landuse	Function	m^2

ENERGY SECTOR

Following the conceptual model Ellen MacArthur Foundation (2012), ultimately all systems should run on renewable resources. For the AMA, to comply to this principle of the circular economy, 12337 GWh of electricity and 12895 TJ of heat should all come from renewable resources, when these numbers would stay equal. However, electricity use of each sector is expected to change as a result of the transition towards a circular economy. Electricity use of agriculture will probably increase, due to the need for lighting and pumps. According to Goldstein et al. (2016), the electricity use of a an indoor urban farm per kilogram of production is 0,04 kWh[3]. Since it concerns an uncertain number, the range between 0,01 kWh and 0,07 kWh is assumed. As Klimaatmonitor (2017) provides the total electricity use of agriculture in the AMA (213 GWh), this data can be combined with electricity use of urban agriculture. This results in the following equation:

<u>Electricity urban agriculture</u> = Urban agriculture production * Electricity urban agriculture input

<u>Electricity agriculture</u> = 213 + Electricity urban agriculture

Table 6: Electricity use of urban agriculture in a circular AMA

ELECTRICITY USE URBAN AGRICULTURE				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Electricity urban agriculture input	UA_electricity_input	1×10^{-8}	7×10^{-8}	GWh per kg
Parameter	*Name in model*	*Value*		*Unit*
Electricity urban agriculture	UA_electricity	Function		GWh

As well as electricity use of the agriculture sector, the electricity use of the transport sector is likely to increase. This increase is due to the changing car fleet. According to the Ellen MacArthur Foundation (2015), if current trends persevere 60 percent of the share of total traveled kilometers by car could be traveled by EV in 2050. It is assumed that the 60 percent of the car fleet is EV. In the most advantageous scenario, 90 percent of the share of total traveled kilometers by car could be traveled by EV. It is assumed that the ratio between commercial cars and passenger cars stays the same (10,4 percent commercial cars, 89,6 percent passenger cars). The assumed range of EV share in the car fleet in a circular AMA lies between 60 and 90 percent.

[3] The publication by Goldstein et al. (2016) is based on tomatoes. It is assumed that legumes require the same amount of electricity.

Table 7: EVs in a circular AMA

EV IN THE CAR FLEET				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Passenger cars EV	passenger_cars_ev	678759	1018541	#
Commercial cars EV	commercial_cars_ev	79084	118224	#

Currently, the largest user of electricity in the AMA is the built environment (residential and commercial), as it is responsible for approximately 69 percent of the electricity use. However, levels of energy use within the built environment are expected to change due to the transition towards a circular economy. A report by the Dutch Ministry of Infrastructure and Environment (2017) shows two possible energy futures in an energy transition for the AMA. One scenario assumes moderate changes in energy demand, and the second scenario assumes maximum changers for future energy demand. However, as this report speculates on a future energy demand, also factors that are not considered to be a part of the transition towards a circular economy are taken into account. In Appendix E, the corrected values are calculated.

As said, energy use in the built environment is expected to change. Both the residential and the commercial sector will be subject to more or less the same innovations that will cause changes. First, a common expectation is that devices that are used by households and in the commercial sector will increase their efficiency. This causes a decrease in the electricity use for both sectors.

The second reason that energy use will change is retrofitting of existing buildings. Since existing buildings are not built in a modular and sustainable way, it is complicated to turn them into energy neutral buildings. The maximum achievable is to effectuate efficiency increases (Prendeville et al., 2017). The retrofitting activities that are assumed in the report of the Ministry of Infrastructure and Environment (2017) are isolating existing buildings and replacing heating boilers based on natural gas with heat pumps. Isolating buildings results in a decreased demand for heat, as heat is better conserved in buildings. Heat pumps are an alternative technique to meet the heat demand in buildings. Currently, almost every building in the Netherlands is generating heat by burning natural gas (Jonkhoff & van der Kooij, 2013). Two possible scenarios are assumed. The first scenario considers all houses to have energy label B (moderate energy savings), and the second scenario (maximum energy savings) considers that all houses have energy label A+. In the moderate changes scenario, the electricity demand decreases a little bit. The change is small due to decreased electricity use by devices, but an increased electricity use by the use of heat pumps, instead of central heating boilers. As a result of the isolation and the use of heat pumps, the heat demand decreases to 32000 TJ. The maximum scenario assumes an increased electricity demand, due to the increased use of heat pumps. The electricity demand is set at 3500 GWh, and the heat demand is set at 21800 TJ (Ministry of Infrastructure and Environment, 2017).

On top of the mentioned energy savings, additional energy savings are achievable by using heat exchangers in showers. Currently, heated water used for showering is only used once, despite the fact that the heat in this water bears the potential to be reused. By installing heat exchangers, the total energy demand can be reduced. Deng et al (2016) argue that, based on experiments in the city of Amsterdam, a total of 4 percent of the current energy consumption be recovered. This sets the heat demand in the maximum savings scenario at 19,9 PJ.

Since the electricity demand and the heat demand are related it is necessary to link them to each other for modeling purposes. Therefore, the heat demand for households in a circular AMA is represented with the following equation:

Residential electricity demand change = Electricity demand residential - 2778

Residential heat demand = 32 – (Residential electricity demand change * 0,016759)

The prospects for the commercial sector are a bit different than the prospects for the residential sector, as the electricity demand is stated at 5777 GWh for both the moderate scenario, and the maximum scenario. However, the heat demand ranges from 14,4 PJ in the moderate scenario to 12,9 PJ in the maximum scenario (Ministry of Infrastructure and Environment, 2017).

Table 8: Energy demand households in a circular AMA

ENERGY DEMAND				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Electricity demand residential	electricity_households	2778	3500	GWh
Heat demand commercial	commercial_heat	12,9	14,4	PJ

Energy use for construction and industry is assumed to stay at the same level. However, energy use in industry is not as straightforward as it is in sectors where energy is divisible between electricity and heat. This difference is due to heat requirements in industry, as the demand for heat in industry can be about temperatures that are way higher than in other sectors. This demand for higher temperatures is considered to be industrial heat. Industrial heat is required for e.g. chemical processes or base metal industry. It is assumed that 80 percent of the heat used in industry is industrial high temperature heat. Some of the applications of industrial heat are currently, and in the foreseeable future, not replaceable by renewable alternatives. Replacing fossil fuels for industrial heat generation with a renewable alternative is only possible with biomass. However, as this is not widely available in the AMA, this would require very large imports of biomass, which also causes a significant increase in transport. Using biomass as an alternative for fossil fuels to generate industrial heat is considered not to be an option (Ministry of Infrastructure and Environment, 2017).

RENEWABLE ENERGY TECHNOLOGIES

As stated by the Ellen MacArthur Foundation, all systems should run on renewables. In this section the potential of renewable energy technologies is elaborated on. The included technologies are wind energy, solar energy, geothermal energy and biomass.

The potential of wind energy depends on the several factors. The first factor is the capacity of the turbines. Currently, the turbines are primarily placed on land, and generally have a capacity ranging from 0,9 MW to 3,3 MW. Most newly placed turbines have a capacity of 3,3 MW. The potential capacity mainly depends on restrictions imposed by policy. Within the current policy framework, the maximum potential lies around 1222 GWh. However, when the policy is liberalized, the potential capacity doubles. This illustrates the impact of change in policy. The maximum potential of wind energy within the AMA depends on this liberalization of the policy. The maximum potential of wind energy on land is 2160 MW. When the area on the lake would be in play, the maximum potential on the lake would be 70011 MW.

Both of these numbers can be seen as a theoretical maximum (Ministry of Infrastructure and Environment, 2017). Wind energy is split up in wind on land, and wind on water functions. For land use, a typical 3 MW turbine requires 2000 m^2 of land (Prodeon, 2017). This is assumed for each turbine.

Assuming that each turbine on land has a capacity of 3 MW, the land use per turbine is 2000 m^2.

<u>Wind energy on land land use</u> = (wind_land / 3) * 2000

Table 9: Potential wind capacity in a circular AMA

WIND ENERGY				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Wind energy on land	wind_land	327,6	2160	MW
Wind energy on water	wind_water	0	70011	MW

Solar energy has two potential options. The first option is to cover roofs with solar panels, which is already applied. The second option is to install solar fields on agricultural land.

According to the Ministry of Infrastructure and Environment (2017), the total roof area in the AMA is 101,2 square kilometers. However, the roof area that is accessible for solar panels does not equal the total roof area, as not all roof area is suitable for solar panels. The first factor that influences the suitability of roofs to install solar panels on is the orientation towards the sun. The orientation of a solar panel should be between the south east and the west. Different orientations are not, or way less, suitable for solar panels, due to lack of sunlight. The second factor of influence is the presence of obstacles on the roofs that complicate the installation of solar panels, and the presence of obstacles nearby that cause inconveniences, such as shadow. Taking these restricting factors in account results in an availablity of around 18 percent of the total roof area in the AMA (Ministry of Infrastructure and Environment, 2017). The total roof area that is available for solar panels is assumed to be 18,5 square kilometers.

Currently, the average capacity of a solar panel of 1,7 square meters is 250 Wp. In order to calculate the amount of kWhs, the capacity should be multiplied by a conversion factor of 0,85 (van Sark & Muizebelt, 2016). Dividing this number by 1,7 gives the amount of kWh per square meter. This results in a yield of 125 kWh per square meter (Ministry of Infrastructure and Environment, 2017). The maximal potential utilized when the total roof area of 18,5 square kilometers is covered with solar panels.

Another possiblity is the placement of solar fields. Solar fields are large areas where lots of solar panels are placed together, in order create a large source of energy. The same limiting factors as for solar panels on roofs apply for solar fields. Besides these limiting factors, installing solar fields encounters the same kind of policy obstacles as wind energy. Depending on the liberalization of the policy, the total area that is available for solar fields can add up to 64 square kilometers. Again this should be understood as a theoretical maximum (Ministry of Infrastructure and Environment, 2017).

The land used for solar panels on roofs does not account for extra land use in a circular economy since it does not take up extra land as they are placed on roofs. However, it does affect the total amount of available roof area. Yet, solar fields do take up extra land. For both solar fields and solar panels on roofs the average yield per square meter is 125 kWh. Therefore, the following equations apply:

Solar field land use = (Solar fields * 0,85) / 125

Solar roof area = (Solar energy on roofs * 0,85)

Table 10: Potential solar capacity in a circular AMA

SOLAR ENERGY				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Solar energy on roofs	solar_roof	97,65	2721	GWp
Solar fields	solar_field	0	9412	GWp

Biomass is a energy source that comes in many various types. Biomass can be produced as an energy crop, but it can also be a by-product of other processes, such as waste, manure and sewage sludge. Comparing data from the Ministry of Infrastructure and Environment (2017) on the amount of sewage sludge available and the amount of sludge needed to produce energy, and data from Klimaatmonitor (2017) on the amount of energy that is already produced from sewage sludge, it can be concluded that producing energy from sewage sludge already lives up to its maximum potential. Therefore, this number is not expected to change.

Besides sewage sludge, the AMA produces biomass in the form of manure. It is possible to use animal manure to create biogas. When the manure is collected, it is fermented, which creates biogas (Ministry of Infrastructure and Environment, 2017). Each type of manure has its own efficiency to create biogas. The efficiencies per type of manure are:

- Beef manure: 0,7 GJ/ton
- Pork manure: 0,6 GJ/ton
- Chicken manure: 7,1 GJ/ton

The amount of energy produced with the fermentation of the manure depends on which share of the manure will be used for energy production, and what will be used for other purposes. According to the Ministry of Infrastructure and Environment (2017), the potential for energy generation with manure is not based on the complete amount of produced manure, since some fractions are difficult to acquire, and other fractions are already used for other purposes. In that scenario it is assumed that 50 percent of each type of manure is available.

Beef manure for energy = Beef manure * 0,5

Pork manure for energy = Pork manure * 0,5

Poultry manure for energy = Poultry manure * 0,5

Manure energy = (Beef manure) * (0,7 + Pork manure * 0,6) + (Poultry manure * 7,1)

Table 11: Potential manure for energy production capacity in a circular AMA

MANURE FOR ENERGY PRODUCTION			
Parameter	*Name in model*	*Value*	*Unit*
Manure energy	manure_energy	Function	TJ
Beef manure for energy	beef_manure_energy	Function	TJ
Pork manure for energy	pork_manure_energy	Function	TJ
Poultry manure for energy	poultry_manure_energy	Function	TJ

As stated earlier, the built environment, the agricultural sector and industries are responsible for the heat demand in the AMA. On the basis of a report of the Ministry of Infrastructure and Environment (2017) the new heat demand for the built environment is determined by means of placing heat pumps and insulation improvements. Both industrial and agricultural heat demand are not expected to change. In the previous chapter, it was already desribed that approximately 80 percent of the heat demand from industry can be categorized as high temperature heat. For a ciruclar AMA, it is assumed that this high temperature heat is not replaceable by renewable alternatives. Currently, industrial heat pumps can reach temperatures of 150 degrees Celsius, whereas 80 percent of the heat demand of industry in the Netherlands ranges from approximately 150 degrees Celsius to temperatures that exceed 1000 degrees Celsius (Boer & Pal, 2009; Spoelstra, 2014). Currently, heat pumps that are able to reach high temperature heat levels are being developed. These heat pumps can be an option when electricity is available to an extent where electricity is considered to be free. However, within the boundaries of the AMA this is not the case. An interconnected European (or global, in the future) grid based on renewable energy technologies could enable the use of these heat pumps. But these heat pumps are not taken into account in the modeling for the research.

An option for renewable heat is using geothermal heat for heat demand in the built environment and in the agricultural sector. Geothermal energy can be used to generate both electricity and heat. However, for this research it is assumed that geothermal energy only generates low temperature heat. In order for an geothermal energy installation to be productive, the heat using entity should be, at maximum, 1500 meters away from the installation, this decreases the potential of geothermal energy. This is due to energy losses in transport. Following this, the potential for residential sector is 0,8 PJ, which requires 6 installations (133,3 TJ per installation), and the potential of the agricultural sector is 1,5 PJ, which requires 15 installations (100 TJ per installation). These numbers are applicable in a situation in which the end user should be in a distance of at least 1500 meters of the installation. However, in case of some technology improvements that enable longer transport distance of heat without losses, these number might increase (Ministry of Infrastructure and Environment, 2017).

Besides the space that geothermal energy systems require under ground, which is neglected, each installation needs 4000 square meters (Ministry of Infrastructure and Environment, 2017). The following equations apply:

<u>Geothermal energy agriculture</u> = Geothermal energy installations agriculture * 133,3

<u>Geothermal energy residential</u> = Geothermal energy installations residential * 100

Geothermal energy land use = (Geothermal energy installations agriculture + Geothermal energy installations residential) * 4000

Table 12: Potential geothermal energy production capacity in a circular AMA

GEOTHERMAL ENERGY				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Geothermal energy installations agriculture	geothermal_agriculture	0	6	#
Geothermal energy installations residential	geothermal_residential	0	15	#
Parameter	*Name in model*	*Value*		*Unit*
Geothermal land use	geothermal_landuse	Function		m^2

Another option to meet the heat demand is to reuse excess heat from other sources. For a circular economy it is required that the excess heat comes from renewable energy technologies. With the state of the art technologies it is not possible to generate the total heat demand with renewable energy technologies. Using excess heat has a potential of 36 PJ in the AMA. However, this excess heat partly originates from fossil fuels. Hence, it is disputable if using this excess heat is a way forward in a transition towards a circular economy. In the strict sense of the term circular economy, using this excess heat is not contributing to a ciruclar economy when it originates from fossil fuels. When using a more flexible approach in assessing the term circular economy, one could argue that it does contribute to a more sustainable society, which is the ultimate goal. In spite of contributing to a more sustainable society, excess heat is not taken into account in this research. The first reason for not taking this into account is that using the excess heat creates a demand for inefficient processes where heat is released. Second, transporting heat over long distances is not yet an option, since lots of energy is required to keep the heat at a certain temperature. Transporting heat over long distances can result in a situation where transporting the heat costs more energy than the amount of energy of heat itself.

The intermittency and seasonal differences, as mentioned in chapter 5, are not yet covered. However, this remains an important subject in the energy transition. Besides phasing out energy production by fossil fuels, and replacing them with renewable energy technologies, the grid needs to be subjected to a transition. A society that fully runs on renewables needs a smart grid. This smart grid needs to ensure solid storage and distribution between producers and end-users, in a grid that is to a larger extent decentralized than the current grid. In the case of the AMA, both storage of electrical and thermal energy need energy storage. For this research, it is assumed that smart grids are installed, and that energy storage is in place. In the discussion section there will be elaborated on smart grids, including energy storage.

TRANSPORT SECTOR

As stated in the fifth chapter, the transport sector in a circular economy is characterized by a shift towards transport based on renewable energy technologies. The Ellen MacArthur Foundation (2015) provides two different scenarios regarding a transition towards a circular transport sector, ranging from a transition scenario based on current developments to a very optimistic transition scenario.

Currently, the car fleet of passenger cars is almost completely based on fossil fuels (gasoline and LPG). In a circular economy, the combustion engine only represents are small share of the car fleet, as electric vehicles are expected to replace cars with combustion engines. If prevailing trends persevere, electric vehicles are expected to cover up 60 percent car fleet of passenger cars. Optimistic expectations assume that the share of electric vehicles in the car fleet of passenger cars increases to 90 percent. One of the factors that influence the range of electric vehicles in the car fleet is the adoption of techniques such as autonomous driving. The adoption of autonomous driving could accelerate the penetration of electric vehicles in the car fleet, as autonomous driving cars are expected to be fully electric powered (Ellen MacArthur Foundation, 2015b). It is assumed that plug-in hybrids are completely replaced by electric vehicles in a circular transport sector.

Table 13: Potential percentage of EVs in a circular AMA

TRANSPORT				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Fraction EVs in individual cars	individual_cars_ev_fraction	0,6	0,9	#
Fraction EVs in commercial cars	commercial_cars_ev_fraction	0,6	0,9	#

Besides increased penetration of electric vehicles in the car fleet, the car fleet is expected to shrink, as a consequence of more widely adopted car sharing. Nowadays, the capacity of passenger cars is used very inefficient, as a passenger car, on average, has 5 available seats, of which on average 1,5 are used. Widely adopted car sharing would increase this efficiency. Following current trends, the utilization of the car capacity is expected to increase to 1,7 persons per car. More optimistic expectations assume that car sharing dominates the passenger transport sector, which allows it to increase the average number of person per car to 2,5. The total number of passenger cars is currently 1.131.265, which is based on 1,5 people per car. Converting this to a range of 1,7 to 2,5 persons per car gives the following values (Appendix F shows the calculations):

Table 14: Car fleet in a circular AMA

TRANSPORT				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Total passenger cars	cars	678759	998175	#

As mentioned earlier, public transport can already be called sustainable, when it is powered by electricity that is generated with renewable energy technologies. The Ellen MacArthur Foundation (2015) expects that public transport has the potential to represent one third of the traveled kilometers. Currently, 19 percent of the traveled kilometers that are due to the AMA are traveled with public transport. The expected range is lies between no change and a maximum of one third of the traveled kilometers.

Table 15: Share of public transport in a circular AMA

TRANSPORT				
Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Public transport factor	publictransport_fraction	0,19	0,33	#

CONSTRUCTION SECTOR

Circle Economy (2015) describes a circular construction sector as a sector that manages and recycles material streams in an efficient way and is based on renewable energy. As mentioned earlier, the AMA can be regarded as a rather mature region with an existing building stock that is not growing a lot. For this reason, the area is suitable for retrofitting. Retrofitting measures have already been discussed in the section on the energy sector. These measures included installing heat pumps and improved insulation. For energy use of the sector itself, apart from the shift to renewable energy technologies, the energy demand is not expected to change as a consequence of the transition towards a circular economy.

Circle Economy (2016) outlined what a circular construction sector in the AMA would look like. They state that the pillars for a circular construction sector in the AMA should be smart designing, efficient dismantling and separation, high value recovery and reuse of materials, and exchange of resources between market players.

The current import of materials for the construction sector amounts for 1,5 million tons on a yearly basis. Furthermore, the construction sector produces 0,585 million tons of construction and demolition waste per year. Designing the AMA in a circular way, as proposed by Circle Economy (2016), would lead to material savings of 500 kilotons each year. These material savings are the result of the interplay of different measures, such as the introduction of 3D printing and making better use of construction and demolition waste.

In order to have material savings of 500 kilton, the reycling percentage should increase. This concerns the sorted waste, since granulate can only be used in secondary recycling. The sorted waste stream can be recycled in a way that it decreases the import of raw materials. In case the full potential of 500 kilton material savings in a circular construction sector is fulfilled, recycling techniques should reach a level where all usable, non-hazardous construction and demolition waste is recycled as sorted waste. This means that granulate is no longer produced.

Table 16: Sorted waste percentage in a circular AMA

Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
Sorted waste percentage	sorted_waste_%	0,07	0,85	

WATER SECTOR

It has been pointed out in earlier sections that water use in a circular economy should decrease as a result of the implementation of precision agriculture. Furthermore, the use of potable water can be decreased as this is currently used for lots of processes that do not require potable water but can use non-potable water instead. Reusing rainwater for processes that do not require drinking water is the most promising solution. These processes include e.g. irrigation, toilet flushing and laundry washing.

On average, the yearly rainfall in the AMA is 54,65 mm[4]. This equals 141 million m^3 on a yearly basis. The most common way of harvesting rainwater is collecting rainwater from rooms. According to CAT

[4] Yearly national rainfall divided by the ratio of the AMA in the Netherlands

(2018) and Farreny et al. (2011), the potential of rainwater harvesting can be calculated with the following formula:

Roof area (m^2) x Annual rainfall (mm) x System efficiency x Run-off coefficient = Annual collection in liters

In the outlined future vision, the roof area is affected by the number of solar panels installed. The total roof area in the AMA is 101,2 square kilometers, and the total area suitable for solar panels adds up to 18,5 square kilometers. In order to know what amount of roof area is available for rainwater collection, the following equation determines the amount of roof area available for rainwater harvesting:

<u>Available rainwater harvesting roof area</u> = Roof area – Solar roof area

The system efficiency of rainwater harvesting systems generally lies between 75 and 90 percent. It is assumed that rainwater harvesting systems have an efficiency of 85 percent. The run-off coefficient is determined by the type of roof; a pitched roof has a coefficient of 0,75, and a flat roof has a run-off coefficient of 0,5 or less (CAT, 2018). It is assumed that the average run-off coefficient of roofs in the AMA is 0,625.

<u>Rainwater harvesting roof area</u> = Available rainwater harvesting roof area * RWH roof area used

<u>Rainwater collection</u> = Rainwater harvesting roof area x 0,85 x 0,625

<u>Total water use</u> = Residential water use + Commercial water use + Industrial water use + Agricultural water use - Rainwater collection

Another promising technique is nutrient recovery from waste water streams. The potential of this nutrient recovery from waste water streams is partly determined by a project executed in Sneek. The case study in Sneek is performed in a community of 32 houses. Black water was collected and transported by vacuum toilets followed by anaerobic treatment of the concentrated black water (black water from vacuum toilets is 25 times more concentrated than the black water from regular toilet) (Zeeman & Kujawa-Roeleveld, 2011). This technology allows nutrient recovery.

Both phosphorus and nitrogen can be recovered by the process of struvite precipitation. Especially the recovery of phosphorus is an important while this is a rapidly depleting (50-100 years) fossil resource that is one of the main components of artificial fertilizer. The recovery rates of nitrogen and phosphorus are 2,7 kg of nitrogen per person per year, and 0,22 kg of phosphorus per person per year (Zeeman & Kujawa-Roeleveld, 2011).

The potential recovery of phosphorus and nitrogen in the residential sector is respectively 0,53 kiloton and 6,5 kilotons. However, besides the residential sector, the commercial sector also supplies black water with potential for nutrient recovery. Based on different fractions of black water in a research of Gleick et al. (2003), the fraction of black water in commercial water use is assumed to be 12,9 percent, which is approximately 3 million m^3. This is 10 percent of the amount of black water supplied by the residential sector. The recoverable amount of phosphorus and nitrogen are therefore assumed to increase with 0,05 kiloton and 0,7 kilotons. The total potential of phosphorus and nitrogen recovery is stated in table 16.

Table 17: Potential rainwater harvesting in a circular AMA

Parameter	*Name in model*	*Min value*	*Max value*	*Unit*
RWH roof area used	RWH_roof_used	0	1	Percentage
Phosphorus recovery	P_recovery	0	0,58	Kiloton
Nutrient recovery	N_recovery	0	7,2	Kiloton

8. RESULTS

This chapter shows the results of modeling the AMA based on current practices and a circular AMA. The modeling results are presented by comparing the KPI outcomes of the baseline scenario with the circular AMA scenario, which consists of a minimum scenario and a maximum scenario. As the results for the circular AMA concern a future vision, the results a uncertain by nature, which is why these results are presented in two scenarios. The correct value lies within the range of the minimum and maximum scenario.

The variable 'solar fields' is excluded in the final results. This decision was made because of the large impact on land use and the marginal contribution to the renewable energy ratio. The comparison of the land use KPI with and without solar fields is shown in figure 15. In the maximum scenario, electricity production largely exceeds the electricity demand, as the total amount of produced electricity is 12 times higher than the actual electricity demand. Excluding solar fields in the maximum scenario still leaves a situation in which the electricity production largely exceeds the electricity consumption with 11 times the demand.

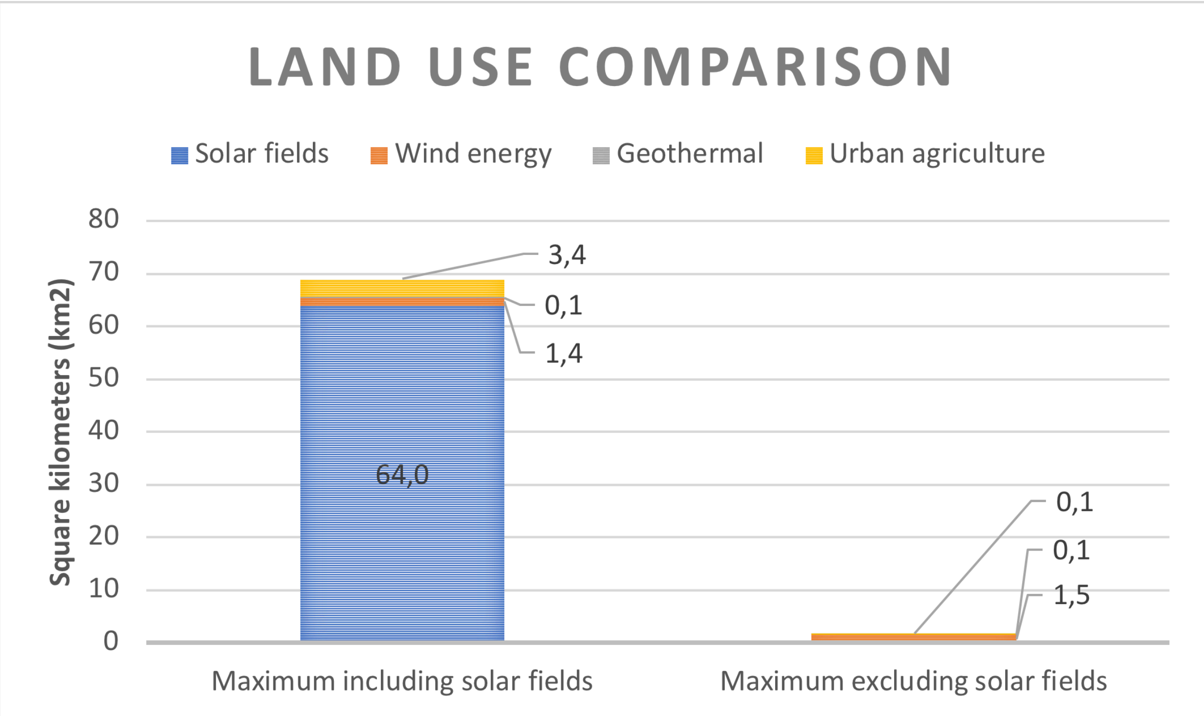

Figure 15: Land use comparison

As shown in figure 16, a transition towards a circular economy a circular economy is accompanied by a change in total energy demand (total of electricity and heat demand. Due to efficiency measures and the switch towards the use of heat pumps, the heat demand in a circular economy is approximately halved. Opposite of heat demand, electricity demand increases in a transition towards a circular economy. The largest driving force in the rise of electricity demand is the residential sector, as the electricity demand rises with 626 GWh (2253 TJ) between the baseline scenario and the maximum scenario. Another import driving force is the switch towards a transport system that is largely based on electricity, instead of fossil fuels. The switch towards an electricity-based transport sector is responsible for an increase of 206 GWh (742 TJ) between the baseline scenario and the maximum scenario.

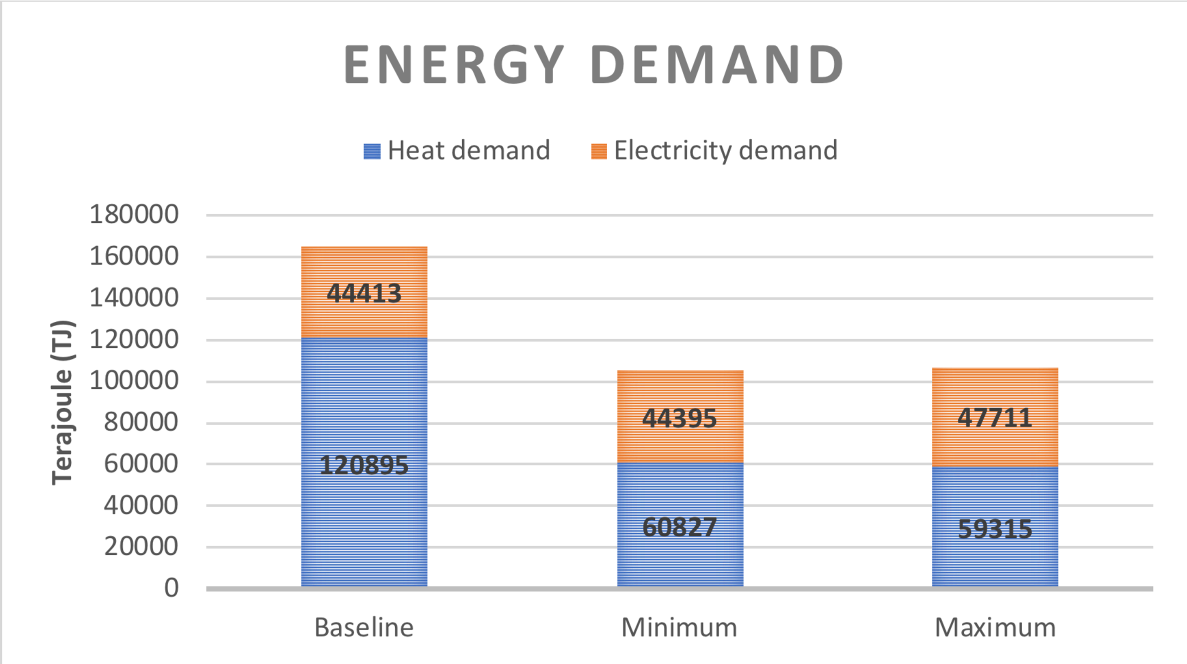

Figure 16: Energy demand

Despite the decreased energy demand, not all energy can be generated with renewable energy technologies. As stated earlier, under the conditions of the maximum scenario, 11 times more electricity is generated than there is electricity demand. The largest contributor to renewable electricity generation is wind energy with 4574 GWh, followed by solar roofs with 2312 GWh. However, the total heat demand cannot be met by renewable energy technologies. As shown in figure 17, in the maximum scenario, only 12,2 percent of the heat can be labeled as renewable. The higher fraction of renewable heat is attributable to the introduction of new energy sources, such as geothermal energy and energy from manure.

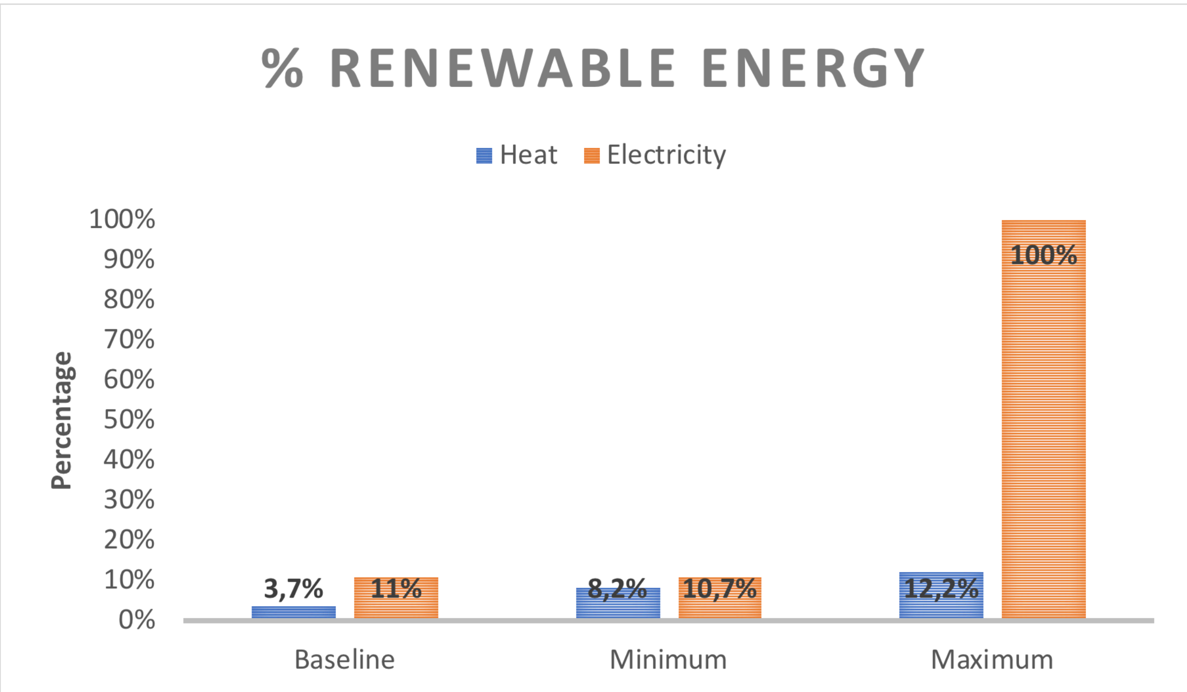

Figure 17: Percentage renewable energy

The model shows that a transition towards a circular economy is characterized by a decreasing water demand. The change in water demand is influenced by the introduction of precision agriculture technologies that cause an increase in water use efficiency in the agricultural sector, and by the collection and utilization of rainwater. Currently, the total water demand in the AMA accounts for 191,1 million m^3, of which 4,5 million m^3 is attributable to the agricultural sector. The introduction of precision agriculture decreases the total water demand to 2 million m^3 in the maximum scenario. However, the potential of water savings by using precision agriculture is quite small compared to the potential of rainwater collection. In the maximized scenario, 39 million m^3 of rainwater is collected and reused. After treatment, the collected rainwater can be utilized as a substitute for the use of potable water for e.g. grey water purposes in the residential and commercial sector, and also for cooling purposes in industries.

The amount of rainwater collection in the AMA depends on the roof area that is appointed for the collection of rainwater. The total AMA roof area accounts for 102 km^2. However, not all roof area is used for rainwater collection. As shown previously, the amount of roof area available for rainwater collection is affected by the roof area appointed to the use of solar panels on roofs. When all suitable roofs for solar panels are appointed to be used for solar panels, 18,5 km^2 of roof area is covered with solar panels. That leaves at least 83,5 km^2 is available for rainwater collection. The quantity of rainwater collected than depends on whether all available roof area is appointed to rainwater collection. To a certain extent, one could argue that there is a trade-off between rainwater collection and solar panels on roofs.

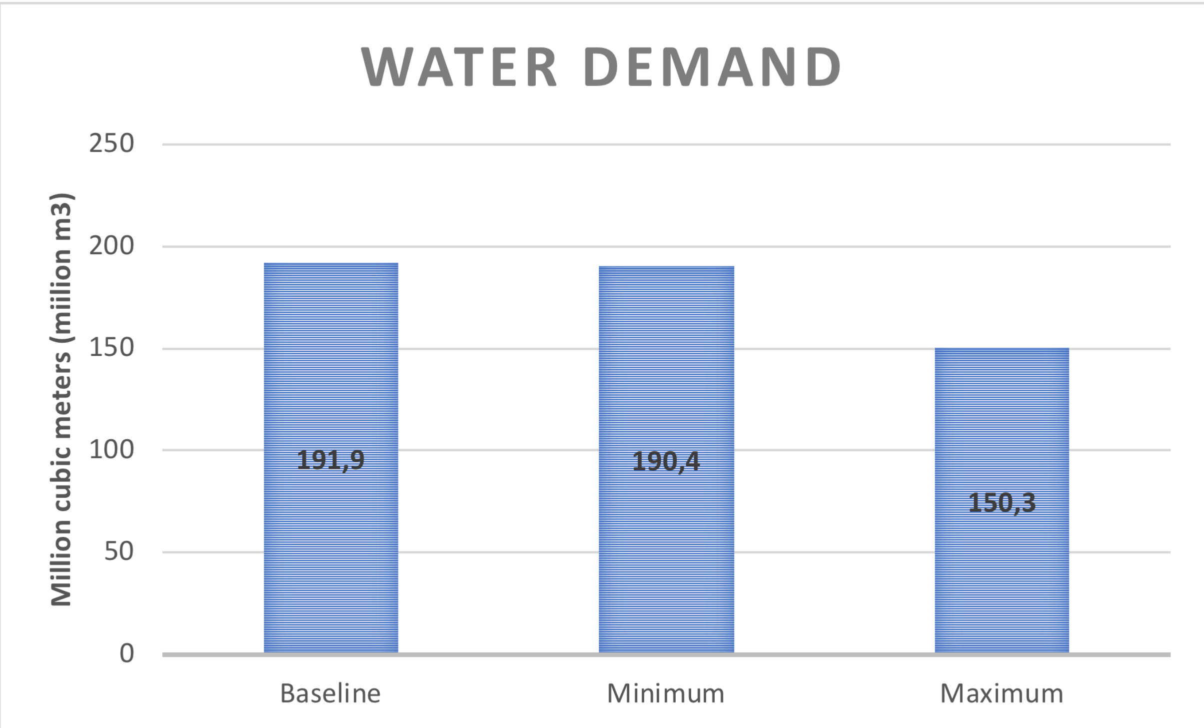

Figure 18: Water demand

The construction sector in the Netherlands is often referred to as nearly circular, because of the high recycling rates of construction and demolition waste. However, only a small fraction of the construction and demolition waste is being recycled in a way that it replaces imports of raw materials (which can be considered as the ultimate goal for the construction sector as it comes to implementing the circular economy). However, large amounts of recycled materials end up as granulate, which is used to construct highways. As this is considered to be a one-time cycle, it cannot be considered circular. This means that the sector remains heavily reliant on imports, as the applied recycling technologies do not result in a situation in which the construction sector can be self-sufficient.

As the model outcomes show, currently the construction sector is only 2,7 percent self-sufficient. The outcomes of the maximum scenario even show that if the full potential of circularity is reached, the construction sector can only reach a self-sufficiency rate of 33 percent.

The self-sufficiency rate of the construction sector is based on the ratio of the raw material requirements of the sector, which is assumed to equal the current raw material import level plus the recycled material that is of a high enough level to substitute raw materials, relative to the raw material imports. As the AMA is a quite mature region when it comes to the development of its built environment, the vast majority of the built environment exists of buildings that are not constructed in a way that resources are not easily retrieved. It is therefore assumed that the size of the construction and demolition waste flow will not change. The size of the construction and demolition waste flow is approximately one-third of the raw material requirements. So even if all construction and demolition waste is recycled, the construction sector cannot reach self-sufficiency.

In the model, the level of self-sufficiency of the construction sector fully depends on the extent to which the construction sector increases their ability to retrieve resources from the construction and demolition waste flow at a level that it can be used as a substitute for imported raw materials.

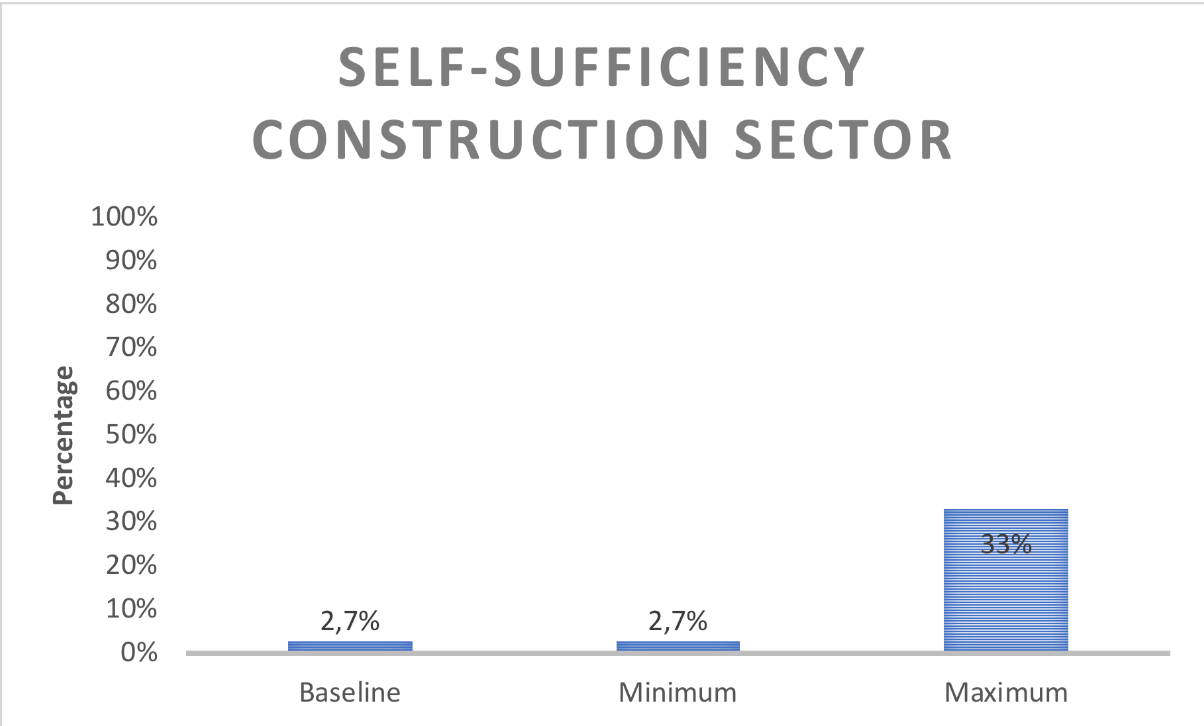

Figure 19: Self-sufficiency construction sector

The self-sufficiency of the food sector is not easily covered with one number; therefore, the self-sufficiency of the food sector is considered per food group. The model shows that the transition towards a circular economy within the AMA does not appear to result in radical changes in self-sufficiency. The changes that occur in a transition towards circular AMA are the result of the introduction of urban agriculture and a slight change in the diet of the inhabitants.

The food groups that are subject to changes in a circular AMA are legumes and meat. All other food groups are assumed to stay at the same level. The baseline scenario shows that only when it concerns potatoes and vegetables, the AMA produces enough to be self-sufficient. For all other food groups, the AMA is depending on imports.

The outcomes of the model show that the food group of legumes can reach self-sufficiency as a consequence of the introduction of urban agriculture that is assumed to produce at the same level as the demand for legumes. The demand for legumes is expected to change in a circular AMA. The degree to which the demand for legumes will change depends on the changing diet. Currently, a regular diet of a Dutch person contains 100 grams of meat per day. In this research it is assumed that there is potential for two meatless days per week that would be replaced by the consumption of legumes. The maximum level of self-sufficiency for meat is 48 percent, which implies that it will keep relying on imports.

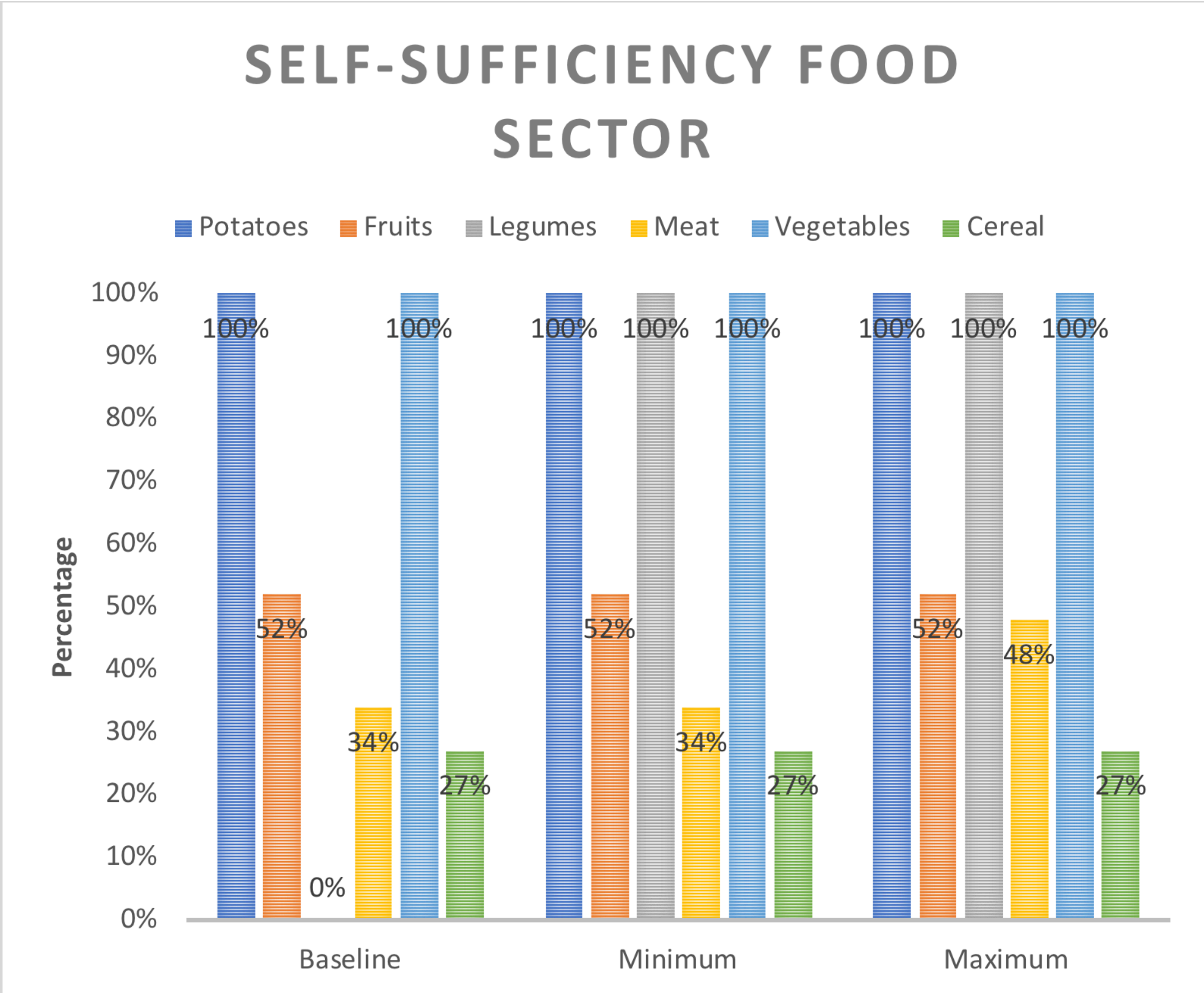

Figure 20: Self-sufficiency food sector

As introducing solar fields is obviously not a move in the right direction for the AMA, figure 21 shows the results without the introduction of solar fields. This changes the model outcomes of the land use KPI. The minimum and maximum scenario have land requirements of respectively 288.800 m^2 and 1.609.360 m^2.

Figure 21 shows that the largest contributor to the land use KPI is the placement of wind turbines on land. Wind energy on water surfaces has not been taken into account for the land use KPI. The reason for this is that the placement of wind turbines on water surfaces does not decrease the area availability for other purposes.

The remaining part of the required land for a transition towards a circular economy is due to the placement of geothermal installations and the introduction of urban agriculture. Both uncertain parameters have a relatively small impact on the land requirements. It should be noted that the impact of both parameters is rather small, but this could increase substantially due to technological breakthroughs. Both geothermal energy and urban agriculture have limited impact on land use as a consequence of the maturity of the technology. Geothermal technology can leap forward when a solution is found for transporting heat over larger distances and urban agriculture might be applied more often when a wider range of food groups can be produced with urban farming. Currently, only a very small variety of herbs, vegetables and legumes can be produced.

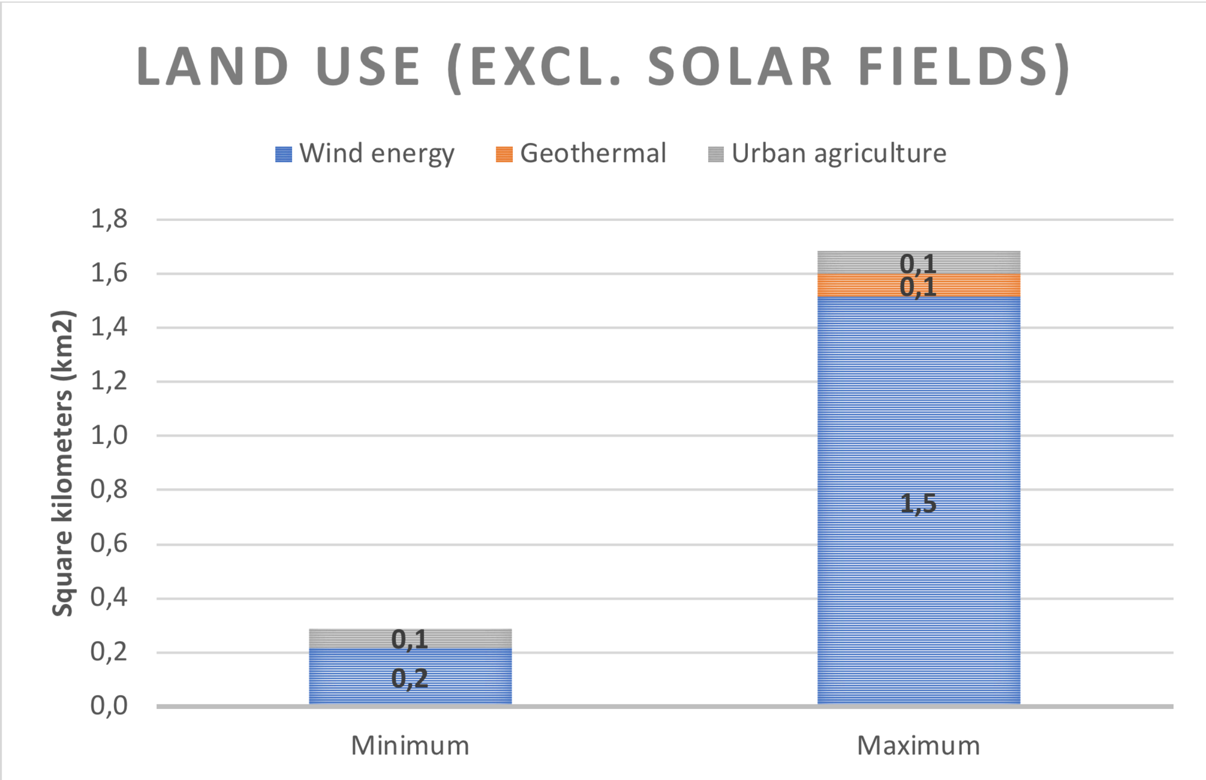

Figure 21: Land use (excluding solar fields)

Some of the key conclusions that can be drawn from the model outcomes are:

- Electricity demand increases with an increasing degree of circularity;
- Meeting the electricity demand with only renewable energy technologies is possible;
- Meeting the heat demand with only renewable energy technologies is currently impossible;
- The maximum level of self-sufficiency within the construction sector is 33%;
- Even in the maximum scenario, the food sector remains reliant on imports;
- Maximizing everything results in an enormous demand for land.

9. Discussion

In this section, the method and the results of this research are discussed. The first theme concerns the limitations of the research in terms of modeling practices. The focus lies on systemic limitations and the effect of the uncertain parameters on the key performance indicators and the simplifications that have been made in order to come up with the model of the future vision the AMA. Second, on the basis of gained insights, the viability of the idea of a circular metropolitan area is discussed. Third, some recommendations for future research are discussed.

9.1 Limitations

The goal of this research was to develop a method to model a well-founded estimation of the costs of a transition towards a circular economy for a metropolitan area. The challenge to represent a metropolitan area its main activities and the relations between them requires simplifications to enable modeling. Therefore, models cannot be considered as a true representation of reality.

In this research, the concept of a metropolitan area is delineated by the selection of five different sectors. Based on literature research, the sectors having the largest impact on the performance of a metropolitan area in terms of circularity are identified. Within these sectors, the main activities and their relations are highlighted to form the conceptual model. Limiting the conceptual model to five sectors means that some sectors, and therefore their impact as well, are left out of consideration. A sector that should be considered in future research is the IT-sector, since this sector is expected to grow as a consequence of the increased need for data centers, due to the introduction of demand side management, vehicle on demand, etc. Another component that should be considered in more detail is freight transport. This has not been taken into account for this research, due to the complexity of allocating the fraction of freight transport for which a metropolitan area is accountable. In case of more resources in terms of time and man power, it could be a consideration to analyze what fraction of freight transport is attributable to the metropolitan area.

On a conceptual model level, the waste and industry sector are taken into account to a limited extent for this research. Both are considered as a black box. However, both sectors are very complex in terms of variables and their relations. In order to create a more accurate view of a metropolitan area, these two sectors should be elaborated on more extensively.

In the following section, the limitations per sector and KPI are discussed.

9.1.1. Energy

For the energy sector there are three different topics of discussion identified. The first topic is the large impact of the maximum scenario on land use within the AMA and the societal resistance it will probably face. The second topic considers the indirect effects of the introduction of smart grid technologies such as energy storage and demand side management. The third topic concerns the potential of Power-to-X, which has not been taken into account in this research.

In the maximum scenario, the total amount of produced electricity is 11 times higher than the actual electricity demand. However, especially the maximum scenario is considered to be quite unlikely, since electricity generation from wind and solar is both assumed to be maximized. This implies that all available roofs are used for solar panels and the installation of wind mills on both land and water surface goes beyond all restrictions concerning (besides technical and safety restrictions). Maximizing all of these renewable energy technologies would have huge implications for the public space. Especially wind on water bears a huge potential (148283 GWh). The fact that wind on water has the largest potential is quite logical as electricity generation with wind on land has to take into account the built environment, which restricts the potential heavily. Living up to the full potential of wind energy on water implies that the lakes of the AMA are completely used. The following rules than apply (Ministry of Infrastructure and Environment, 2017):

- Four times the rotor diameter perpendicular to the prevailing wind direction and six times the rotor diameter in the prevailing wind direction
- Turbines are placed in lines
- Up to three lines in a row, then at least 1,5 kilometers of buffer zone because of regeneration of the air flow

Another reason that the maximum scenario for energy is considered to be unlikely, is the commotion and resistance that is coming about when it comes to installing wind turbines on both land and water surfaces. Currently, people seem to recognize the importance of the problem, but not consider it as urgent when it comes to installing the wind turbines. Wind energy in a metropolitan area will undoubtedly experience resistance.

As shown, it is possible to generate large amounts of electricity within the AMA. However, something that has not been taken into account in the model is the systemic change that is required for the grid if such large quantities of renewable energy are produced. As stated earlier, renewable energy technologies that form the basis of the large potential of electricity generation in the AMA are intermittent. These technologies such as wind and solar energy is that they do not deliver a fully controllable amount of energy. Naturally, the sun does not give us sunlight at night and also wind decreases at night (Kleijn, 2012). In other words, less energy is produced during the night time. However, during the energy peak lies during the evening (Yekini et al., 2014). Besides such daily variations, seasonal variations may have an even larger impact on the system. An example of seasonal variation are the longer periods of low solar generation during winter (Verzijlbergh et al., 2017). Therefore, in order to cope with peak load and peak supply on both long and short term, an energy system based on renewables requires advanced balancing options (Niemi et al., 2012).

Once 20 percent, or more, of the electricity demand is fulfilled with renewable energy technologies, the grid has to become 'smart' in order to increase the share of renewables. A smart grid differs from the current grid in a way that a smart grid is better able to manage highly variable supply and demand of energy (Lund et al., 2015). Technologies that allow managing high variability are energy storage and demand side management. Earlier in this research, several energy storage technologies were mentioned. Currently, there are lots of different possibilities for energy storage. However, energy storage is out of the scope of this research due to its complexity and uncertainty. In an energy system that is highly depending on renewable energy, an energy storage system should fulfill many different functions, such as load levelling, peak shaving, load following, investment deferral, frequency response, intermittency mitigation, etc. Each type of energy storage and every function that it has in an energy system have their own characteristics to enable different functions and an interplay of different methods should make up the energy storage system (Ferreira et al., 2013; Lott & Kim, 2014). An example of this are the timescales on which they function, ranging from microseconds (frequency response) to months (seasonal storage). There are no storage systems that fulfill every function (Verzijlbergh et al., 2017). Despite that this is known, the benefits of each type of storage have not yet been quantified. Furthermore, different types of energy storage display various levels of maturity, and require further development in order to cope with future storage needs (Ferreira et al., 2013; Verzijlbergh et al., 2017). Due to the complexity and uncertainty of energy storage, this has not been taken into account when building the model. Nevertheless, it should be stated that energy storage plays an essential role in the transition towards a circular economy, and it is very likely to influence model KPIs such as land use. It is assumed that energy storage is present in a future circular AMA.

In addition to 'traditional' energy storage, such as batteries, pumped water and compressed air, there is a recent technology that allows to transform excess energy in other types of uses. This technology is called Power-to-X. One of the most well-known applications of Power-to-X is to produce hydrogen with excess electricity. Another application would be Power-to-Heat. With Power-to-Heat, excess electricity is used to produce low temperature heat by industrial electric boilers. This technology becomes increasingly interesting under the conditions of low electricity prices, because it is very flexible when it comes to responding to short-term price variations. It is likely that electricity prices will drop in the future as a consequence of increased renewable energy capacity. Low electricity costs and high amounts of electricity production are favorable conditions for Power-to-X. However, it is questionable whether this is a viable option within the AMA, due to the relatively small scale. In a circular economy on a larger scale this has a greater chance of successful implementation.

Besides energy storage, demand side management could influence the transition towards a circular energy system. Demand side management could be of importance when it comes to synchronizing supply and demand of energy. In some cases this is very closely related to energy storage, e.g. when batteries of EVs are used in periods of high electricity production (Verzijlbergh et al., 2017). Several types of demand side management make use of IT services in order to effectuate a more responsive energy system (IRENA, 2016). This responsiveness is based on data exchange between producers and consumers that is used to optimize supply and demand in an energy system. Increasingly present demand side management tools require increased amounts of data storage. Besides demand side management, the transport sector is expected to contribute to increased data storage requirements. It is strongly believed that the number of cars in a circular economy will decrease as a result of increased use of car sharing, enabled by the Internet of Things (Ellen MacArthur Foundation, 2015b). Increased amounts of data storage require more data centers to be built. According to Avgerinou et al. (2017), the number of data centers keeps increasing, parallel to applications based internet data. Data centers run all day, and all year long and use quite significant amount of energy for cooling, power distribution, lighting, etc. Since it is very complex to attribute certain amounts of energy and land use to the transition towards a circular economy, this has not been taken into account in modeling a future circular AMA. However, it is very likely that energy demand and land use will increase as a consequence of the growing need for data storage.

9.1.2. WATER

Something that has not been taken into account in the model is the need for rainwater storage tanks, which is one of the biggest issues concerning rainwater collection (Goyal, 2015). Larger storage tanks can obviously store larger amount of rainwater; however, large tanks are not always emptied, which extends the water cycle process significantly and cause health issues. Furthermore, it is the question whether storage tanks are placed underground or aboveground (Goyal, 2015). Assuming that most storage tanks are placed underground, this would probably have a slight effect on the land use KPI. Future research should take this into account.

9.1.3. FOOD

There are two identified themes of discussion for the food sector. First, the simplification of the food market for modeling the AMA. And second, the diet of inhabitants for the Netherlands.

The mentioned ratios of self-sufficiency for the food sector in this research should be approached with a certain level of care, since these numbers are vastly simplified. Collected data showed numbers on the amount of food produced and the amount of food consumed per food group. The assumption was made that production levels minus consumption levels represented a surplus or a deficit. This approach is based on the underlying assumption that food is initially produced for the local market, and that each form of surplus is exported and deficits are supplemented with imports. In reality some food is exclusively produced in order to be exported to other parts of the world, instead of production for the local market. To create a more realistic representation of a regional food sector, lots of data on import and export flows of food on the level of a metropolitan area is required.

Furthermore, the consumption pattern of Dutch citizens has a much larger variety than what is produced in the AMA itself. The Dutch food market is generally designed to produce large quantities of the same product. Becoming self-sufficient requires the production of a more diverse range of products. The levels of self-sufficiency should therefore be considered as potential self-sufficiency rate, rather than actual self-sufficiency.

9.1.4. LAND USE

Something that has been taken into account in the model is the impact of indirect land use. While this is not taken into account it is of great importance to mention this. Despite the fact that the boundary of this research is the AMA, lots of negative impacts on the sustainability performances occur outside of the boundaries of the metropolitan area as a result of actions that occur within the boundaries of the metropolitan area. The values of the KPIs would surely look very different if there was accounted for these actions. This is especially the case for sectors that heavily rely on imports, which in the case of the AMA are the construction sector and the food sector. The best example to illustrate this situation arises from the food/agricultural sector. Several material flows enter the AMA in order to produce food, such as animal feed and fertilizer. These products enter the AMA as final products, but the impact of these products have impact during their production process. The production of animal feed uses huge amounts of land, and the same applies for the mining of phosphorus for artificial fertilizer. The impact of these products lies outside of the AMA boundaries, but the demand is created within its boundaries. When these products were to be produced within the boundaries of the AMA, one would face an enormous deficit in land. Naturally, this goes for every imported final product.

9.2 CIRCULAR METROPOLITAN AREA

Having created and modeled a vision for a circular AMA gives insight in what a circular economy could look like. Despite the discussed limitations of this model, it shows in what order of magnitude one should think when it comes to a circular metropolitan area in Amsterdam.

One of the key findings of the research is that a fully circular metropolitan area is rather an ambition that gives direction towards a desired situation, than an achievable end goal. A metropolitan area on itself cannot become fully circular. As stated in section 3.2, one of the principles of the circular economy is to think in systems. Combining this principle with the ambition of the AMA to become a circular metropolitan area, one should conclude that this ambition only makes sense when the metropolitan area is seen as a part of the bigger picture to create a circular economy at a larger scale. E.g. an energy system that fully runs on renewables is unachievable within the boundaries of a metropolitan area, due to the earlier mentioned variances in production and demand on both short and long term.

The same applies for the construction and food sector. Within the boundaries of a metropolitan area there is not enough land to produce everything that is needed to become completely self-sufficient. Therefore, thinking about a circular economy is something that should not be bound to only a metropolitan area, but it should be approach from a wider perspective.

Despite the fact that the model does not give a perfect representation of a circular economy within a metropolitan area. The presented method of modeling does allow getting insight in the order magnitude of the challenge that the transition towards a circular economy brings. Considering the context of the transition, which is one of lacking investments in the real economy, the model contributes to understanding which elements of the transition towards a circular economy have the largest positive impact and what the corresponding costs related to these elements are.

9.3 RESEARCH AGENDA

The ambition to have this research result in an estimation of the transition costs of towards a circular economy for the AMA has not succeeded. At the beginning of this research it was already stated that part of the ambition was to explore how to address such a problem, being aware of the time constraints of this research. In support of answering the main research question, five different sub-questions were composed to function as a guideline in reaching the desired result. The five sub-questions were:

1. How to conceptualize and delineate a circular economy in metropolitan areas?
2. How to operationalize a circular economy in a metropolitan area?
3. What would a circular economy in the Amsterdam metropolitan area look like?
4. What are the most important resources for a transition towards a circular economy?
5. What costs have to be considered related to the transition towards a circular economy?

In the process of exploring the subject and trying to get to an answer on the main research question, progressive insight showed that answering this question is an ambition too big to fulfill given the constraint of time. However, I have been able to answer three of the five sub-questions. Despite not having been able to answer the fourth and fifth sub-question, these questions are still very relevant, and I recommend that these questions are further explored.

The fourth sub-question, *'What are the most important resources for a transition towards a circular economy?'*, remains a relevant question. In addition of this research, mapping the most important resources for a transition towards a circular economy would be of a great added value. Since the future vision of a circular AMA is given, this could form the basis of a research on the material requirements of a circular AMA. Mapping the material requirements of a circular AMA could give insight in whether such a transition is possible, or if e.g. the amount of steel needed for such a transition is so big that it is considered not to be possible. To answer this question the created model could be linked with a Life Cycle Inventory (LCI). LCIs are the databases that are used to perform life cycle analyses. The databases contain information on raw materials, energy, water, emissions, etc. The model of this research could be used to identify the processes and technologies that are relevant for a circular AMA, e.g. the energy production of wind turbines, production of food, distances traveled per different transport modes, etc.

Having identified these processes and products allows to link them to the right processes and products in an LCI. The result of this link gives insight in how much material and energy are required per function that needs to be fulfilled in a circular economy. Besides the material and energy requirements, the link to an LCI can also be helpful to assess the environmental impact of a circular AMA in comparison the current situation. The data in LCIs is connected to certain impact categories in order to measure the impact of several function within a system. Impact categories that might be relevant for this research are land use competition, depletion of abiotic resources and climate change (Guinée, 2001).

The fifth posed sub-question was *'What costs have to be considered related to the transition towards a circular economy?'*. As already elaborated on in section 3.3, operationalizing the cost concept was an ambition too big given the restriction in time. However, this question is still an interesting one for further research. As already stated, there are several methods available that sufficient when it comes to quantifying the actions to be undertaken to reach a circular economy in monetary terms (the EPS 2000, the Stepwise 2006, and the Ecotax). The focus should lie on data collection via in willingness to pay studies in order to get a clear view on the right value for the monetarization of externalities that are not taken into account when forming the market price.

10. CONCLUSION

During the course of this research, the ambition of the AMA to become a circular metropolitan area has been examined. This has been done by conceptualizing a metropolitan area, in order to develop a clear framework to approach the AMA. Subsequently, conceptualization of a metropolitan area has been operationalized to make the concept measurable. This was projected on the AMA and quantified to create a baseline scenario. Finally, based on literature, a future vision for a circular AMA was created. On the basis of five sub-questions, the main research question has been tried to answer.

The first sub question *'How to conceptualize and delineate a circular economy in metropolitan areas?'*, has been answered in the section 3.1 and chapter 5. Section 3.1 shows, on the basis of a literature review, which sectors are taken into account when it comes to defining a circular economy on the scale of a metropolitan area. Literature showed that the following sectors should be taken into account when conceptualizing a circular economy in a circular economy: energy supply, food/agriculture, transport, water, waste, construction/built environment, industry. As waste is embedded in each of the other sectors, it has been decided to not approach the waste sector as a separate sector. Subsequently in chapter 5, the main variables and relations between them have been pointed out per sector. On the basis of these identified variables and relations, the fundamental system limitations have been determined per sector. As the fundamental limitations have been pointed out, this enabled drawing the outlines of a circular design of each sector. This resulted in a conceptual model for a circular economy in a metropolitan area

The second sub question *'How to operationalize a circular economy in a metropolitan area'*, has been answered in chapter 6. Based on the conceptualization of a circular economy in metropolitan area, the conceptualization has been operationalized for the AMA. The identified variables and relations within each outlined sector were translated to sets of equations to make them quantifiable. The created equations serve as simplified representations of reality and are based on assumptions that are outlined in chapter 6.

The third sub question *'What would a circular economy in the Amsterdam metropolitan area look like?'*, has been answered in chapter 6. In answering this question, the operationalized conceptual model (i.e. the sets of equations) was quantified. When possible, the quantification of the equations was based on literature about a transition towards a circular economy in the AMA. Otherwise, data on transitions towards a circular economy from other metropolitan areas, or transitions towards a circular economy in general, are translated for the situation of the AMA. The quantification has been put in a simple linear Python model that returns values on several key performance indicators for two different scenarios (minimum change and maximum change). The KPIs that were used are energy use (both heat and electricity), water use, land use, self-sufficiency of the construction sector, and self-sufficiency of the food sector. The results showed that a fully circular AMA is not possible, since no sector can be completely self-sufficient and the energy demand cannot fully be met by energy production from renewable technologies. A circular AMA is therefore more an ambition that gives direction towards a desired situation, than an achievable end goal.

As stated in the discussion section, the fourth and fifth sub question have not been answered. From the start it was clear that this research was very ambitious. For that reason, this master thesis has been set up as an exploratory research.

Although not every sub question has been answered, due to constraints in time, the main research question *'How to model a well-founded estimation of the costs of a transition towards a circular economy for a metropolitan area?'* can be answered to a certain extent.

The method for modeling an estimation of the costs of a transition towards a circular economy for a metropolitan area, starts with specifying the conceptual model of a metropolitan area to the metropolitan area of interest. As the conceptual model gives a general outline of the most important variables within a metropolitan area, these variables require further decomposition in order to quantify them. Since the availability of data probably differs per metropolitan area, the variables and their relations should be decomposed to a level that allows it to perform decent estimations about on the built up and quantification of these variables. When the current situation of the metropolitan area is modeled, this functions as a baseline scenario.

In order to assess the performances of the metropolitan area in terms of circularity, the quantified baseline scenario requires a link to key performance indicators. KPIs that assess the circularity performances are energy use, water demand, self-sufficiency of the construction sector and self-sufficiency of the food sector. For the purpose of completeness, a KPI on the emission of greenhouse gasses should be added.

When the baseline scenario has been created and the link to the KPIs has been made, the next step is to construct a vision on how circular economy principles would apply to the metropolitan area of interest, and how this translates to changes in the values of variables and new relations between variables. As it concerns a future vision which is inherently uncertain, changed variables require a denotation in a minimum and a maximum value. The values of the KPIs provide insight to what extent it is possible to get to a circular metropolitan area.

Having quantified a vision for a circular metropolitan area, the next step is to identify the resources, processes and technologies that enable the transition towards a circular economy. Combining LCI databases with the constructed model of the metropolitan area. The result of this link gives insight in how much material and energy are required per function that needs to be fulfilled in a circular economy. Besides the material and energy requirements, the link to an LCI can also be helpful to assess the environmental impact of a circular AMA in comparison the current situation.

Based on the mapped resources and impacts, the translation to expressing these in a monetary value is required to estimate the costs of a transition towards a circular economy. Research should focus on willingness to pay studies that quantify environmental externalities and pricing them.

11. LITERATURE

Abdel-Magid, I. M., & Faris, F. G. (2014). *Food waste: Reduce, reuse, recycle, re-think*.

ADEME. (2015). *White paper on the circular economy of greater Paris*.

AEB. (2015). *Annual report 2015*.

Afvalmonitor. (2016). Ingezamelde hoeveelheden en scheidingspercentages huishoudelijk afval 2016. Retrieved March 23, 2018, from https://afvalmonitor.databank.nl//Jive/

Aghion, P., Hepburn, C., Teytelboym, A., & Zenghelis, D. (2014). Path dependence, innovation and the economics of climate change. *The New Climate Change Economy*, (November). Retrieved from http://2014.newclimateeconomy.report/wp-content/uploads/2014/11/Path-dependence-and-econ-of-change.pdf

Amsterdam Economic Board. (2016). *Circulaire Economie*.

Amsterdam Economic Board. (2017). Amsterdam Metropolitan Area. Retrieved from https://www.amsterdameconomicboard.com/en/amsterdam-metropolitan-area

Avgerinou, M., Bertoldi, P., & Castellazzi, L. (2017). Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency. *Energies*, *10*(10). https://doi.org/10.3390/en10101470

Barrett, J., Vallack, H., Jones, A., & Haq, G. (2002). *A Material Flow Analysis and Ecological Footprint of York*. https://doi.org/10.13140/RG.2.1.3258.6085

BBSR. (2011). *Metropolitan areas in Europe*. Bonn.

Bodouroglou, C., Islam, N., Julca, A., Montes, M., Lancourt, M. P., Popov, V., … Vos, R. (2010). Reforming the international financial architecture, 103–131. Retrieved from http://www.un.org/esa/analysis/wess/

Boer, R. De, & Pal, M. Van Der. (2009). *Ontwikkeling van een hoge temperatuur chemische warmtepomp Openbare eindrapportage OPTISORP project*.

Bourguignon, D. (2016). Closing the loop New circular economy package. *European Parliamentary Research Service*, (January), 9.

Bouton, S., Hannon, E., Rogers, M., Swartz, S., Johnson, R., Gold, A., … Staples, M. (2016). *The circular economy: Moving from theory to practice*.

Brown, J. H., Burger, J. R., Burnside, W. R., Chang, M., Davidson, A. D., Fristoe, T. S., … Okie, J. G. (2014). Macroecology meets macroeconomics : Resource scarcity and global sustainability. *Ecological Engineering*, *65*, 24–32. https://doi.org/10.1016/j.ecoleng.2013.07.071

Brunner, P., & Rechberger, H. (2005). *Practical Handbook of Material Flow Analysis*. *Complete Casting Handbook*. Lewis Publishers. https://doi.org/10.1016/B978-1-85617-809-9.10003-9

Caplow, T. (2009). Building integrated agriculture: Philosophy and practice. In *Urban development and urban lifestyles for the future* (pp. 54–58).

CAT. (2018). Water and sewage.

CBS. (2016a). Elektriciteitsproductie uit steenkool opnieuw hoger. Retrieved from https://www.cbs.nl/nl-nl/nieuws/2016/26/elektriciteitsproductie-uit-steenkool-opnieuw-hoger

CBS. (2016b). Kwartaalmonitor Luchtvaart - Eerste kwartaal 2016. Retrieved from https://www.cbs.nl/nl-nl/achtergrond/2016/26/kwartaalmonitor-luchtvaart-eerste-kwartaal-2016

CBS. (2016c). Luchtvracht neemt gestaag toe. Retrieved from https://www.cbs.nl/nl-nl/nieuws/2016/26/luchtvracht-neemt-gestaag-toe

CBS. (2017a). *Landbouw; gewassen, dieren en grondgebruik naar regio*.

CBS. (2017b). *Landbouw; vanaf 1851*. Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/71904ned/table?ts=1516199791235

CBS. (2017c). Regionale kerncijfers Nederland. Retrieved December 13, 2017, from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/70072ned/table?ts=1513091729290

Census. (1994). Metropolitan Areas. In *Geographic areas reference manual* (pp. 1–12).

CIA. (2017). The World Factbook. Retrieved December 13, 2017, from https://www.cia.gov/library/publications/the-world-factbook/fields/2147.html

Circle Economy. (2015). *Circular construction - The foundation under a renewed sector*.

Circle Economy. (2016). *Circular Amsterdam: A vision and action agenda for the city and metropolitan area*.

Circulaire Westas. (2017). *Ruimtelijk-economische verkenning: De Circulaire Westas*. Amsterdam.

CITIES. (2011). *Farming the city: Amsterdam's local food system*.

CLO. (2016a). Jaarlijkse hoeveelheid neerslag in Nederland, 1910-2015. Retrieved December 14, 2017, from http://www.clo.nl/indicatoren/nl0508-jaarlijkse-hoeveelheid-neerslag-in-nederland

CLO. (2016b). Watergebruik in de land- en tuinbouw, 2001-2014. Retrieved from http://www.clo.nl/indicatoren/nl0014-watergebruik-landbouw

Consumentenbond. (2016). Plug-in hybrides verbruiken veel meer dan fabrikant opgeeft. Retrieved from https://www.consumentenbond.nl/zuinige-auto/plug-in-hybrides

Correljé, A. F., & Groenewegen, J. P. M. (2009). Public values in the energy sector: economic perspectives.

Cramer, J. (2017). The Raw Materials Transition in the Amsterdam Metropolitan Area: Added Value for the Economy, Well-Being, and the Environment. *Environment: Science and Policy for Sustainable Development*, *59*(3), 14–21. https://doi.org/10.1080/00139157.2017.1301167

Davis, M. J. M., Jácome Polit, D., & Lamour, M. (2016). Social Urban Metabolism Strategies (SUMS) for Cities. *Procedia Environmental Sciences*, *34*, 309–327. https://doi.org/10.1016/j.proenv.2016.04.028

Deng, Z., Mol, S., & Van Der Hoek, J. P. (2016). Shower heat exchanger: Reuse of energy from heated drinking water for CO2 reduction. *Drinking Water Engineering and Science*, *9*(1), 1–8. https://doi.org/10.5194/dwes-9-1-2016

Depleted UF6 Management Information Network. (2017). Energy from Uranium. Retrieved from http://web.ead.anl.gov/uranium/guide/facts/

Despommier, D. (2013). *Farming up the city: the rise of urban vertical farms* (Vol. 31). Elsevier Ltd. https://doi.org/10.1016/j.tibtech.2013.03.008

Dieleman, H. (2017). Urban agriculture in Mexico City; balancing between ecological, economic, social and symbolic value. *Journal of Cleaner Production*, *163*, S156–S163. https://doi.org/10.1016/j.jclepro.2016.01.082

EASAC. (2016). *Indicators for a circular economy*. Retrieved from http://www.easac.eu/home/reports-and-statements/detail-view/article/circular-eco-1.html

EEA. (2016). *Transitions towards a more sustainable mobility system*.

EIA. (2016a). Approximate Heat Content of Natural Gas. Retrieved from https://www.eia.gov/totalenergy/data/monthly/pdf/sec13_4.pdf

EIA. (2016b). Average Operating Heat Rate for Selected Energy Sources. Retrieved from https://www.eia.gov/electricity/annual/html/epa_08_01.html

EIA. (2017). How much coal, natural gas, or petroleum is used to generate a kilowatthour of electricity? Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=667&t=8

EIA. (2018). Approximate Heat Content of Coal and Coal Coke. Retrieved from https://www.eia.gov/totalenergy/data/monthly/pdf/sec13_5.pdf

Ellen MacArthur Foundation. (2012). *Towards the circular economy: Economic and business rationale for an accelerated transition*. https://doi.org/10.1080/02690940320000073807

Ellen MacArthur Foundation. (2015a). *Circularity indicators*. https://doi.org/10.1016/j.giq.2006.04.004

Ellen MacArthur Foundation. (2015b). Growth within: a circular economy vision for a competitive europe. *Ellen MacArthur Foundation*, 100. https://doi.org/Article

Ellen MacArthur Foundation. (2015c). *Why the circular economy matters*. *Delivering the Circular Economy: A Toolkit for Policymakers*.

Ellingsen, E. C., & Despommier, D. (2008). The vertical farm - The origin of a 21st century architectural typology. *CTBUH Journal*, *3*, 26–34.

European Commission. (2016). *Towards Low-Emission Mobility*.

European Commission. (2017). *EU Energy in figures: statistical pocketbook 2017*. Luxembourg. https://doi.org/10.2833/16497

EV Database. (2017). Stroomverbruik van een plug-in hybride of elektrische auto. Retrieved from https://ev-database.nl/informatie/brandstof-verbruik-plug-in-hybride

Evans, A., Strezov, V., & Evans, T. J. (2010). Sustainability considerations for electricity generation from biomass. *Renewable and Sustainable Energy Reviews*, *14*(5), 1419–1427. https://doi.org/10.1016/j.rser.2010.01.010

FAO. (1997). Urban and peri-urban agriculture. Retrieved from http://www.fao.org/unfao/bodies/COAG/COAG15/x0076e.htm#P106_11554

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J., & Gabarrell, X. (2011). Roof selection for rainwater harvesting: Quantity and quality assessments in Spain. *Water Research*, *45*(10), 3245–3254. https://doi.org/10.1016/j.watres.2011.03.036

Ferreira, H. L., Garde, R., Fulli, G., Kling, W., & Lopes, J. P. (2013). Characterisation of electrical energy storage technologies. *Energy*, *53*, 288–298. https://doi.org/10.1016/j.energy.2013.02.037

Frosch, R. a. (1992). Industrial ecology: a philosophical introduction. *Proceedings of the National Academy of Sciences of the United States of America*, *89*(3), 800–803. https://doi.org/10.1073/pnas.89.8.3669c

Galiana, F., & Conejo, A. (2008). Economics of Electricity Generation. In *Electric Energy Systems Analysis and Operation*. CRC Press.

Game, I., & Primus, R. (2015). *Urban Agriculture*.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – a new sustainability paradigm? *Journal of Cleaner Production*, *143*(under review), 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gemeente Amsterdam. (2017). *Kantorenstrategie 2017*. Amsterdam.

Geng, Y., & Doberstein, B. (2008). Developing the circular economy in China: Challenges and opportunities for achieving'leapfrog development'. *International Journal of Sustainable Development & World Ecology*, *15*(April 2016), 231–239. https://doi.org/10.3843/SusDev.15.3

Genovese, A., Acquaye, A. A., Figueroa, A., & Lenny Koh, S. . (2015). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*, *66*, 1–14. https://doi.org/10.1016/j.omega.2015.05.015

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Gleick, P. H., Haasz, D., Henges-Jeck, C., Srinivasan, V., Wolff, G., Kao Cushing, K., & Mann, A. (2003). *Waste Not, Want Not: The Potential for Urban Water Conservation in California*. Retrieved from http://www.pacinst.org/reports/urban_usage/

Goldstein, B., Hauschild, M., Fernández, J., & Birkved, M. (2016). Urban versus conventional agriculture, taxonomy of resource profiles: a review. *Agronomy for Sustainable Development*, *36*(1), 1–19. https://doi.org/10.1007/s13593-015-0348-4

Goyal, R. (2015). Rooftop Rainwater Harvesting : Issues and Challenges, (MAY 2014).

Grewal, S. S., & Grewal, P. S. (2012). Can cities become self-reliant in food? *Cities*, *29*(1), 1–11. https://doi.org/10.1016/j.cities.2011.06.003

Guinée, J. (2001). Handbook on life cycle assessment. *The International Journal of Life Cycle Assessment*, *6*(5), 255–255.

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *Journal of Industrial Ecology*, *19*(5), 765–777. https://doi.org/10.1111/jiec.12244

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2016). How Circular Is the Global Economy ? A Sociometabolic Analysis. In H. Haberl, M. Fischer-Kowalski, F. Krausmann, & V. Winiwarter (Eds.), *Social-Ecology: Society-nature relations across time and space*. Springer International Publishing. https://doi.org/10.1007/978-3-319-33326-7

Hardie, I., & Howarth, D. (2013). Framing Market-Based Banking and the Financial Crisis. In *Market-Based Banking & the International Financial Crisis* (pp. 22–55). Oxford: Oxford University Press.

Hawkins, T. R., Hendrickson, C., Higgins, C., Matthews, H. S., & Suh, S. (2007). A Mixed-Unit Input-Output Model for Environmental Life-Cycle Assessment and Material Flow Analysis. *Environmental Science & Technology*, *41*(3), 1024–1031. https://doi.org/10.1021/es060871u

Heinimo, J., & Junginger, M. (2009). Production and trading of biomass for energy – An overview of the global status. *Biomass and Bioenergy*, *33*(9), 1310–1320. https://doi.org/10.1016/j.biombioe.2009.05.017

Hobson, K., & Lynch, N. (2016). Diversifying and de-growing the circular economy: Radical social transformation in a resource-scarce world. *Futures*, *82*, 15–25. https://doi.org/10.1016/j.futures.2016.05.012

Huffington Post. (2016). Airports going green.

IEA. (2012). *Energy Technology Perspectives 2012*. https://doi.org/10.1787/energy_tech-2012-en

IEA. (2014). *Energy policies of IEA countries - The Netherlands*.

Inés, C., Martínez, P., & Alfonso, W. H. (2014). Urban material flow analysis: An approach for Bogotá, Colombia. *Ecological Indicators*, *42*, 32–42. https://doi.org/10.1016/j.ecolind.2013.10.035

International Energy Agency. (2015). Fossil Fuel Subsidy Database. Retrieved from http://www.worldenergyoutlook.org/resources/energysubsidies/fossilfuelsubsidydatabase/

IRENA. (2016). *Renewable energy in Cities*. Abu Dhabi.

IRENA. (2017). *Renewable energy in district heating and cooling*. Abu Dhabi.

Ishida, Y., & Chiba, R. (2015). Fermi estimate on the web: Placing sensor networks on the web with noise. *Procedia Computer Science*, *60*(1), 1753–1762. https://doi.org/10.1016/j.procs.2015.08.285

IWA. (2016). *Water Utility Pathways in a Circular Economy*.

Jacobsson, R., & Jacobsson, S. (2012). The emerging funding gap for the European Energy Sector - Will the financial sector deliver? *Environmental Innovation and Societal Transitions*, *5*, 49–59. https://doi.org/10.1016/j.eist.2012.10.002

Jonkhoff, E., & van der Kooij, E. (2013). *Towards the Amsterdam Circular Economy*. Amsterdam.

Jurgilevich, A., Birge, T., Kentala-lehtonen, J., Korhonen-kurki, K., Pietikäinen, J., Saikku, L., & Schösler, H. (2016). Transition towards Circular Economy in the Food System. *Sustainability*, *8*(69). https://doi.org/10.3390/su8010069

Kleijn, R. (2012). *Materials and energy: a story of linkages*. *Department of Industrial Ecology, Institute of Environmental Sciences (CML)* (Vol. Doctoral T). https://doi.org/ISBN 978-90-9026938-2

Klimaatmonitor. (2017). Klimaatmonitor databank.

Kobza, N., & Schuster, A. (2016). Building a responsible Europe - the value of circular economy. *IFAC-PapersOnLine*, *49*(29), 111–116. https://doi.org/10.1016/j.ifacol.2016.11.067

Kousksou, T., Bruel, P., Jamil, A., Rha, T. El, & Zeraouli, Y. (2014). Solar Energy Materials & Solar Cells Energy storage: Applications and challenges. *Solar Energy Materials & Solar Cells*, *120*, 59–80.

https://doi.org/10.1016/j.solmat.2013.08.015

Lan, T., Nguyen, T., Laratte, B., Guillaume, B., & Hua, A. (2016). Quantifying environmental externalities with a view to internalizing them in the price of products, using different monetization models. *Resources, Conservation and Recycling*, *109*, 13–23. https://doi.org/10.1016/j.resconrec.2016.01.018

Leach, J., Hunt, D. V. L., Leach, J. M., Lee, E., Bouch, C., & Braithwaite, P. (2014). *Material Flow Analysis (MFA) for Liveable Cities*. https://doi.org/10.3390/wsf-4-f010

Levelt, M., & Janssen-Jansen, L. (2013). The Amsterdam Metropolitan Area challenge : opportunities for inclusive coproduction in city-region governance, *31*(2008), 540–555. https://doi.org/10.1068/c11216

Lott, M. C., & Kim, S.-I. (2014). *Technology Roadmap: Energy storage*. *Energy Technology Perspectives*. https://doi.org/10.1007/SpringerReference_7300

Lund, P. D., Mikkola, J., & Ypyä, J. (2015). Smart energy system design for large clean power schemes in urban areas. *Journal of Cleaner Production*, *103*, 437–445. https://doi.org/10.1016/j.jclepro.2014.06.005

LWARB. (2017). *London's Circular Economy Route Map: Executive Summary*.

MacKay, D. (2009). *Sustainable energy - Without the hot air*. Cambridge: UIT Cambridge Ltd.

Martin, A., Kersley, H., & Greenham, T. (2014). *Inequality and financialisation*.

Mat, N., Cerceau, J., Shi, L., Park, H., Junqua, G., & Lopez-ferber, M. (2016). Socio-ecological transitions toward low-carbon port cities: trends, changes and adaptation processes in Asia and Europe. *Journal of Cleaner Production*, *114*, 362–375. https://doi.org/10.1016/j.jclepro.2015.04.058

Metropoolregio Amsterdam. (2017). Braakliggende terreinen geschikt voor zonnepanelen en biomassa. Retrieved December 18, 2017, from https://metropoolregioamsterdam.nl/artikel/20171120-braakliggende-terreinen-geschikt-voor-zonnepanelen-e

Miccoli, S., Finucci, F., & Murro, R. (2016). Feeding the Cities Through Urban Agriculture The Community Esteem Value, *8*, 128–134. https://doi.org/10.1016/j.aaspro.2016.02.017

Ministry of Infrastructure and Environment. (2016). *A Circular Economy in the Netherlands by 2050*.

Ministry of Infrastructure and Environment. (2017). *Ruimtelijke verkenning energietransitie MRA*.

Morrison, P. (1963). Fermi Questions. *American Journal of Physics*, *31*(8), 626–627. https://doi.org/10.1119/1.1969701

MRDH. (2016). *Roadmap Next Economy*.

Nasir, M. H. A., Genovese, A., Acquaye, A. A., Koh, S. C. L., & Yamoah, F. (2016). Comparing linear and circular supply chains: A case study from the construction industry. *International Journal of Production Economics*, *183*, 1–16. https://doi.org/10.1016/j.ijpe.2016.06.008

Niemi, R., Mikkola, J., & Lund, P. D. (2012). Urban energy systems with smart multi-carrier energy networks and renewable energy generation. *Renewable Energy*, *48*, 524–536. https://doi.org/10.1016/j.renene.2012.05.017

NRCS. (2017). Animal Manure Management. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/rca/?cid=nrcs143_014211

NS. (2016). Energie. Retrieved December 13, 2017, from http://www.nsjaarverslag.nl/jaarverslag-2016/energie3/a1128_Energie

OECD. (2015a). Material Resources, Productivity and the Environment, 172. https://doi.org/10.1787/9789264190504-en

OECD. (2015b). *OECD Companion to the Inventory of Support Measures for Fossil Fuels 2015*. Paris.

Pickard, W. F. (2010). The future of biomass energy: A Fermi-calculation perspective. *Energy Policy*, *38*(4), 1672–1674. https://doi.org/10.1016/j.enpol.2009.11.075

PlanAmsterdam. (2016). *The Amsterdam Metropolitan Area*.

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment : A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Prendeville, S., Cherim, E., & Bocken, N. (2017). Circular Cities: Mapping Six Cities in Transition. *Environmental Innovation and Societal Transitions*. https://doi.org/10.1016/j.eist.2017.03.002

Preston, F. (2012). A Global Redesign? Shaping the Circular Economy. *Energy, Environment and Resource Governance*, (March), 1–20. https://doi.org/10.1080/0034676042000253936

Prodeon. (2017). Nederland is te klein voor grote windmolens: FABEL. Retrieved April 2, 2018, from http://www.prodeon.nl/feiten-fabels-en-onzekerheden/wind/detail.php?ID=39

REPAiR. (2017). Amsterdam.

Ritchie, H., & Roser, M. (2018). Meat and Seafood Production & Consumption. Retrieved from https://ourworldindata.org/meat-and-seafood-production-consumption

Rood, T., Muilwijk, H., & Westhoek, H. (2017). *Food for the Circular Economy*.

Roser, M., & Ortiz-Ospina, E. (2017). World Population Growth. Retrieved May 8, 2018, from https://ourworldindata.org/world-population-growth

Satterthwaite, D. (2011). How urban societies can adapt to resource shortage and climate change. *Philosophical Transactions of the Royal Society*, 1762–1783. https://doi.org/10.1098/rsta.2010.0350

Sawin, J. L., Seyboth, K., & Sverrisson, F. (2016). *Renewables 2016: Global Status Report*. https://doi.org/ISBN 978-3-9818107-0-7

Schneider Electric. (n.d.). Urban mobility in the smart city age.

Schut, E., Crielaard, M., & Mesman, M. (2015). *Circular economy in the Dutch construction sector*.

SenterNovem. (2009). *Warmte in Nederland*.

Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*. https://doi.org/10.1073/pnas.1211658109

Shafie, F. A., Omar, D., Karuppannan, S., & Shariffuddin, N. (2016). Urban-scale Material Flow Analysis for Cities in Greater Kuala. *Procedia - Social and Behavioral Sciences*, *234*, 424–433. https://doi.org/10.1016/j.sbspro.2016.10.260

Soethoudt, H., & Timmermans, T. (2013). *Food Waste Monitor*.

Soons, O. (2016). *Inequality and Financialization* (No. 492).

Specht, K., Siebert, R., Hartmann, I., Freisinger, U. B., Sawicka, M., Werner, A., … Dierich, A. (2014). Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. *Agriculture and Human Values*, *31*(1), 33–51. https://doi.org/10.1007/s10460-013-9448-4

Spoelstra, S. (2014). *R&D on Industrial Heat Pumps*. Retrieved from https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-L--14-039

Stahel, W., & Reday, G. (1976). The Potential for Substituting Manpower for Energy.

Stupak, I., Asikainen, A., Jonsell, M., Karltun, E., Lunnan, A., & Mizaraite, D. (2007). Sustainable utilisation of forest biomass for energy — Possibilities and problems : Policy , legislation , certification , and recommendations and guidelines in the Nordic , Baltic , and other European countries, *31*, 666–684. https://doi.org/10.1016/j.biombioe.2007.06.012

Sustainable Finance Lab. (2015). Finance in a Circular Economy. Retrieved from http://sustainablefinancelab.nl/en/finance-in-a-circular-economy/

UNEP. (2015). *Effects of financial system size and structure on the real economy*.

United Nations. (1999). Handbook of Input-Output Table Compilation and Analysis. New York: United Nations.

van Bueren, E., van Bohemen, H., Itard, L., & Visscher, H. (2012). *Sustainable Urban Environments*. Springer. https://doi.org/10.1007/978-94-007-1294-2

van den Bosch, F. A. J., Nijdam, M. H., Hollen, R. M. A., & de Jong, O. (2013). *Strategische waarde haven van Amsterdam*.

van Rossum, C. T. M., Buurma-Rethans, E. J. M., Vennemann, F. B. C., Beukers, M., Brants, H. A. M., de Boer, E. J., & Ocké, M. C. (2016). *The diet of the Dutch*.

van Sark, W., & Muizebelt, P. (2016). *Inventarisatie PV markt Nederland*.

van Timmeren, A. (2014). *The Concept of the Urban Metabolism (UM)*.

Verzijlbergh, R. A., Vries, L. J. De, Dijkema, G. P. J., & Herder, P. M. (2017). Institutional challenges caused by the integration of renewable energy sources in the European electricity sector. *Renewable and Sustainable Energy Reviews*, *75*(October 2016), 660–667. https://doi.org/10.1016/j.rser.2016.11.039

Voedingscentrum. (2018). Schijf van vijf - Vis, peulvruchten, vlees, ei, noten en zuivel. Retrieved April 29, 2018, from http://www.voedingscentrum.nl/nl/gezond-eten-met-de-schijf-van-vijf/wat-staat-er-in-de-vakken-van-de-schijf-van-vijf/vis-peulvruchten-vlees-ei-noten-en-zuivel.aspx

Ward, S. M., Holden, N. M., White, E. P., & Oldfield, T. L. (2016). *The "circular economy" applied to the agriculture (livestock production) sector*.

Waternet. (2017). Gemiddeld waterverbruik. Retrieved from https://www.waternet.nl/ons-water/drinkwater/gemiddeld-waterverbruik/

Weinstein, L. (2012). *Guesstimation 2.0: Solving today's problems on the back of a napkin*. Princeton: Princeton University Press.

Wikipedia. (2017a). Amsterdam Metropolitan Area. Retrieved December 14, 2017, from https://en.wikipedia.org/wiki/Amsterdam_Metropolitan_Area

Wikipedia. (2017b). Fermi problem. Retrieved from https://en.wikipedia.org/wiki/Fermi_problem

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*(August 2016), 825–833. https://doi.org/10.1016/j.rser.2016.09.123

World Bank. (2017). DataBankWorld Development Indicators.

World Economic Forum. (2016). *Shaping the Future of Construction A Breakthrough in Mindset and Technology*.

Wüstenhagen, R., & Menichetti, E. (2012). Strategic choices for renewable energy investment: Conceptual framework and opportunities for further research. *Energy Policy*, *40*(1), 1–10. https://doi.org/10.1016/j.enpol.2011.06.050

Yekini, M., Wazir, M., & Bashir, N. (2014). Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Renewable and Sustainable Energy Reviews*, *35*, 499–514. https://doi.org/10.1016/j.rser.2014.04.009

Zeeman, G., & Kujawa-Roeleveld, K. (2011). Resource recovery from source separated domestic waste(water) streams; full scale results. *Water Science and Technology*, *64*(10), 1987–1992. https://doi.org/10.2166/wst.2011.562

12. APPENDICES

APPENDIX A: MODEL EQUATIONS

Pork production = Production NL * (# of animals AMA/ # of animals NL)

Poultry production = Production NL * (# of animals AMA/ # of animals NL)

Sheep production = Production NL * (# of animals AMA/ # of animals NL)

Poultry eggs production = Production NL * (# of animals AMA/ # of animals NL)

Beef milk production = Production NL * (# of animals AMA/ # of animals NL)

Fruits open ground production = Production NL * (Purpose area AMA / Purpose area NL)

Vegetables greenhouse production = Production NL * (Purpose area AMA / Purpose area NL)

Vegetables open ground production = Production NL * (Purpose area AMA / Purpose area NL)

Cereals production = Production NL * (Purpose area AMA / Purpose area NL)

Potatoes production = Production NL * (Purpose area AMA / Purpose area NL)

Legumes production = Production NL * (Purpose area AMA / Purpose area NL)

Meat production = Beef production + Pork production + Poultry production + Sheep production

Dairy production = Beef milk production + Poultry eggs production

Fruits production = Fruits greenhouse production + Fruits open ground production

Vegetable production = Vegetables greenhouse production + Vegetables open ground production

Food production = Meat production + Dairy production + Fruits production + Vegetable production + Legumes production + Cereals production + Potatoes production

Potato consumption = Consumption per person per day * Inhabitants AMA * 365

Legume consumption = Consumption per person per day * Inhabitants AMA * 365

Meat consumption = Consumption per person per day * Inhabitants AMA * 365

Fruit consumption = Consumption per person per day * Inhabitants AMA * 365

Egg consumption = Consumption per person per day * Inhabitants AMA * 365

Fish consumption = Consumption per person per day * Inhabitants AMA * 365

Dairy consumption = Consumption per person per day * Inhabitants AMA * 365

Poultry consumption = Meat consumption * 0,31

Beef consumption = Meat consumption * 0,24

Pork consumption = Meat consumption * 0,45

Sheep consumption = Meat consumption * 0,01

Food waste to food bank = Food waste * Food bank fraction

Food waste to animal feed = Food waste * Animal feed fraction

Food waste to incineration = Food waste * Incineration fraction

Beef animal feed = Animal feed per kg * Beef production

Pork animal feed = Animal feed per kg * Pork production

Poultry animal feed = Animal feed per kg * Poultry production

Eggs animal feed = Animal feed per kg * Poultry eggs production

Sheep animal feed = Animal feed per kg * Sheep production

Beef milk animal feed = Animal feed per kg * Beef milk production

Manure = Liquid manure + Solid manure

Liquid manure = ((# Beef animals * $2,3 \times 10^{-2}$) + (# Pork animals * $2,3 \times 10^{-3}$) + (# Poultry animals * $6,8 \times 10^{-5}$) + (# Eggs animals * $6,8 \times 10^{-5}$) + (# Milk animals * $1,6 \times 10^{-2}$) + (# Sheep animals * $2,2 \times 10^{-3}$))

Solid manure = ((# Beef animals * 9×10^{-4}) + (# Pork animals * $9,2 \times 10^{-5}$) + (# Poultry animals * $2,7 \times 10^{-6}$) + (# Eggs animals * $1,9 \times 10^{-6}$) + (# Milk animals * $6,4 \times 10^{-4}$) + (# Sheep animals * $8,7 \times 10^{-5}$))

Beef manure = ((# Beef animals * $2,3 \times 10^{-2}$) + (# Milk animals * $1,6 \times 10^{-2}$) + (# Beef animals * 9×10^{-4}) + (# Milk animals * $6,4 \times 10^{-4}$))

Pork manure = ((# Pork animals * $2,3 \times 10^{-2}$) + (# Pork animals * $9,2 \times 10^{-5}$))

Poultry manure = ((# Poultry animals * $6,8 \times 10^{-5}$) + (# Eggs animals * $6,8 \times 10^{-5}$) + (# Poultry animals * $2,7 \times 10^{-6}$) + (# Eggs animals * $1,9 \times 10^{-6}$))

Vegetable import/export = Vegetable production – Vegetable consumption

Fruit import/export = Fruits production – Fruits consumption

Potato import/export = Potato production – Potato consumption

Cereal import/export = Cereal production – Cereal consumption

Meat import/export = Meat production – Meat consumption

Water use agriculture = Average water use per company * # of companies

Fertilizer use = Agricultural land * Fertilizer use per ha

Electricity use of rail transport = (Distance by train + (0,66 * Distance by metro/bus/tram)) * Electricity input per traveler km

Electricity use of electric cars = ((Kilometers per car * EVs) * 0,16) + ((Kilometers per car * PHEVs) * 0,08)

Electricity use of transport = Electricity use of rail transport + Electricity use of electric cars

Total electricity use = Electricity households + Electricity commercial + Electricity agriculture + Electricity construction + Electricity transport + Electricity industries

Electricity origin = Fossil electricity + Renewable electricity

Wind energy = Installed capacity * Full load hours per year

Solar energy = Installed capacity (Wp) * 850

Residual waste = Consumer waste + 175

Waste incineration electricity = Residual waste * 1,02

Biogas sewage sludge electricity = Sewage sludge * 0,2

Renewable electricity = Wind energy + Solar energy + Biogas co-fermentation + Waste incineration electricity + Biogas sewage electricity + Decentral biomass + Landfill gas

Natural gas electricity = Fossil electricity * 0,5

Coal electricity = Fossil electricity * 0,42

Nuclear electricity = Fossil electricity * 0,08

Coal for electricity = Coal electricity / 2

Natural gas for electricity = Natural gas electricity / 4,7

Uranium = Nuclear electricity * 25

Waste incineration heat = Residual waste * 0,76

Biogas sewage sludge heat = Sewage sludge * 6,6

Total heat demand = Residential heat + Commercial heat + Agriculture heat + Industry heat

Distance by car = Total distance traveled * Car transport percentage

Distance by public transport = Total distance traveled * Public transport percentage

Distance by train = Distance by public transport * 0,676

Distance by metro/bus/tram = Distance by public transport * 0,324

Passenger fossil cars = Total passenger cars * Passenger fossil percentage

Passenger electric cars = Total passenger cars * Passenger electric percentage

Passenger hydrogen cars = Total passenger cars * Passenger hydrogen percentage

Passenger EVs = All electric cars * Passenger EV percentage

Passenger PHEVs = All electric cars * Passenger PHEV percentage

Passenger cars on gasoline = Passenger fossil cars * Passenger gasoline percentage

Passenger cars on LPG = Passenger fossil cars * Passenger LPG percentage

Commercial cars = Commercial cars petrol + Commercial cars natural gas + Commercial EVs + Commercial cars hydrogen

Granulate percentage = 0,85 – Sorted waste percentage

Sorted waste = C&D waste * Sorted waste percentage

Granulate = C&D waste * Granulate percentage

Steel = (Metal import * 0,95) + (Sorted waste * 0,5)

Copper = (Metal import * 0,03) + (Sorted waste * 0,125)

Aluminum = (Metal import * 0,02) + (Sorted waste * 0,125)

Bricks = Mineral import * 0,03

Gravel = Mineral import * 0,09

Concrete = (Mineral import * 0,68) + (Granulate * 0,02)

Asphalt = (Mineral import * 0,2) + (Sorted waste * 0,25)

Raw material import = Raw material requirements – Sorted waste

Total water use = Residential water use + Commercial water use + Industrial water use + Agricultural water use

Residential water use = (Shower + Toilet + Laundry + Dish washing + Bath + Food preparation + Coffee and tea + Drinking + Bathroom + Other) * Inhabitants * 365

Black water = Toilet

Grey water = Residential water use – Drinking – Coffee and tea – Toilet

Appendix B: Model parameter overview

GENERAL			
Parameter	*Name in model*	*Value*	*Unit*
# of inhabitants	inhabitants	2410960	#
# of households	households	1083799	#
Average household size	avg_household	2.2	Average
Surface area AMA	area_AMA	2580	Km^2
Surface area NL	area_NL	41543	Km^2
FOOD			
Parameter	*Name in model*	*Value*	*Unit*
Agricultural land	agricultural_land	64395	Ha
Average water use of agricultural companies	average_water_use	2111	M^3/ company
# of agricultural companies	companies	2150	#
FOOD PRODUCTION			
Parameter	*Name in model*	*Value*	*Unit*
Food production	food_production	Function	Kton
Meat production	meat_production	Function	Kton
Dairy production	dairy_production	Function	Kton
Fruits production	fruit_production	Function	Kton
Vegetable production	vegetable_production	Function	Kton
Legume production	legume_production	Function	Kton
Cereal production	cereal_production	Function	Kton
Potato production	potato_production	Function	Kton
Beef production	beef_production	Function	Kton
Pork production	pork_production	Function	Kton
Poultry production	poultry_production	Function	Kton
Sheep production	sheep_production	Function	Kton
Egg production	egg_production	Function	Kton
Milk production	milk_production	Function	Kton
Fruits greenhouse production	Fruits_greenhouse_production	Function	Kton
Fruits open ground production	fruits_openground_production	Function	Kton
Vegetable greenhouse production	vegetable_greenhouse_production	Function	Kton
Vegetable open ground production	vegetable_openground_production	Function	Kton
Beef production NL	beef_production_NL	416	Kton
# beef animals AMA	beef_AMA	6199	#
# beef animals NL	beef_NL	1179000	#
Poultry production NL	poultry_production_NL	1037	Kton
# poultry animals AMA	poultry_AMA	623727	#
# poultry animals NL	poultry_NL	43846000	#
Pork production NL	pork_production_NL	1453	Kton
# pork animals AMA	pork_AMA	12154	#
# pork animals NL	pork_NL	1249000	#
Sheep production NL	sheep_production_NL	14	Kton
# sheep animals AMA	sheep_AMA	38507	#
# of sheep animals NL	sheep_NL	784000	#
Egg production NL	egg_production_NL	672	Kton

# egg animals AMA	eggs_AMA	300499	#
# egg animals NL	eggs_NL	46212000	#
Milk production NL	milk_production_NL	14324	Kton
# milk animals AMA	milk_AMA	68306	#
# milk animals NL	milk_NL	3072000	#
Fruits greenhouse production NL	fruits_greenhouse_production_NL	691	Kton
Fruits greenhouse area AMA	fruits_greenhouse_area_AMA	0	#
Fruits greenhouse area NL	fruits_greenhouse_area_NL	1600	#
Fruits open ground production NL	fruits_openground_production_NL	691	#
Fruits open ground area NL	fruits_openground_area_AMA	1680	#
Fruits open ground area NL	fruits_openground_area_NL	20367	#
Vegetables greenhouse production NL	vegetables_greenhouse_production_NL	3511	Kton
Vegetables greenhouse area NL	vegetables_greenhouse_area_AMA	24	Ha
Vegetables greenhouse area NL	vegetables_greenhouse_area_NL	39100	Ha
Vegetables open ground production NL	vegetables_openground_production_NL	1270	Kton
Vegetables open ground area AMA	vegetables_openground_area_AMA	708	Ha
Vegetables open ground area NL	vegetables_openground_area_NL	2300	Ha
Cereal production NL	cereal_production_NL	1316	Kton
Cereal area AMA	cereal_area_AMA	6198	Ha
Cereal area NL	cereal_area_NL	175000	Ha
Potato production NL	potato_production_NL	6703	Kton
Potato area AMA	potato_area_AMA	3185	Ha
Potato area NL	potato_area_NL	157000	Ha
Legume production NL	legume_production_NL	3	Kton
Legume area AMA	legume_area_AMA	4	Ha
Legume area NL	legume_area_NL	1000	Ha
FOOD WASTE			
Parameter	*Name in model*	*Value*	*Unit*
Food waste	total_foodwaste	Function	Kton/year
Consumer waste	foodwaste_consumer	47.25	Kg/person/year
Processing waste	foodwaste_processing	21.6	Kg/person/year
Distribution waste	foodwaste_distribution	12.21	Kg/person/year
Production waste	foodwaste_production	37.8	Kg/person/year
Storage waste	foodwaste_storage	16.2	Kg/person/year
ANIMAL FEED			
Parameter	*Name in model*	*Value*	*Unit*
Total animal feed	animalfeed	Function	Kton
Animal feed for beef	beef_animalfeed	Function	Kton
Animal feed for pork	pork_animalfeed	Function	Kton
Animal feed for poultry	poultry_animalfeed	Function	Kton
Animal feed for egg	egg_animalfeed	Function	Kton
Animal feed for sheep	sheep_animalfeed	Function	Kton
Animal feed for milk	milk_animalfeed	Function	Kton

Beef feed per kg product	beef_feed	25	Kg
Pork feed per kg product	pork_feed	6.4	Kg
Poultry feed per kg product	poultry_feed	3.3	Kg
Egg feed per kg product	egg_feed	2.3	Kg
Sheep feed per kg product	sheep_feed	14	Kg
Milk feed per kg product	milk_feed	259	Kg
FOOD WASTE DESTINATION			
Parameter	*Name in model*	*Value*	*Unit*
Waste food to food bank	foodbank	Function	Kton
Waste food to feed	food_to_feed	Function	Kton
Waste food incineration	food_incineration	Function	Kton
Food bank fraction	foodbank_fraction	0.01	Fraction
Animal feed fraction	animalfeed_fraction	0.2	Fraction
Incineration fraction	incineration_fraction	0.4	Fraction
FOOD CONSUMPTION			
Parameter	*Name in model*	*Value*	*Unit*
Potato consumption	potato_consumption	Function	Kton
Vegetable consumption	vegetable_consumption	Function	Kton
Meat consumption	meat_consumption	Function	Kton
Legume consumption	legume_consumption	Function	Kton
Cereal consumption	cereal_consumption	Function	Kton
Fruit consumption	fruit_consumption	Function	Kton
Egg consumption	egg_consumption	Function	Kton
Fish consumption	fish_consumption	Function	Kton
Dairy consumption	dairy_consumption	Function	Kton
Potato consumption per day	potato_consumption_day	0.000000073	Kton
Vegetable consumption per day	vegetable_consumption_day	0.000000124	Kton
Meat consumption per day	meat_consumption_day	0.000000101	Kton
Legume consumption per day	legume_consumption_day	0.000000004	Kton
Cereal consumption per day	cereal_consumption_day	0.000000192	Kton
Fruit consumption per day	fruit_consumption_day	0.000000122	Kton
Egg consumption per day	egg_consumption_day	0.000000012	Kton
Fish consumption per day	fish_consumption_day	0.000000015	Kton
Dairy consumption per day	dairy_consumption_day	0.000000355	Kton
MEAT CONSUMPTION			
Parameter	*Name in model*	*Value*	*Unit*
Beef consumption	beef_consumption	Function	
Pork consumption	pork_consumption	Function	
Poultry consumption	poultry_consumption	Function	
Sheep consumption	sheep_consumption	Function	
FOOD TRADE			
Parameter	*Name in model*	*Value*	*Unit*
Vegetable import / export	vegetable_import	Function	
Fruit import / export	fruit_import	Function	
Potato import / export	potato_import	Function	
Cereal import / export	cereal_import	Function	
Meat import / export	meat_import	Function	
MANURE			
Parameter	*Name in model*	*Value*	*Unit*
Total manure	total_manure	Function	

Liquid manure	liquid_manure	Function	Kton
Solid manure	solid_manure	Function	kton
FERTILIZER			
Parameter	***Name in model***	***Value***	***Unit***
Total fertilizer use	fertilizer_use	Function	Kton
Fertilizer use per ha	fertilizer_use_ha	2.58×10^{-4}	Kton/ ha
TRANSPORT			
Parameter	***Name in model***	***Value***	***Unit***
Total traveled distance	total_traveled_distance	Function	Billion km
Distance traveled by car	distance_car	18.03	Billion km
Distance traveled by train	distance_train	2.79	Billion km
Distance traveled by metro/tram	distance_metrotram	0.9	Billion km
Distance traveled by bus	distance_bus	0.45	Billion km
CAR FLEET			
Parameter	***Name in model***	***Value***	***Unit***
Total number of cars	cars	Function	#
Passenger cars	individual_cars	Function	#
Passenger cars on petrol	individual_cars_petrol	1097731	#
Passenger cars on natural gas	individual_cars_gas	1531	#
Passenger cars EV	individual_cars_ev	4236	#
Passenger cars PHEV	individual_cars_phev	27763	#
Passenger cars on hydrogen	individual_cars_hydrogen	4	#
Commercial cars	commercial_cars	Function	#
Commercial cars on petrol	commercial_cars_petrol	130813	#
Commercial cars on natural gas	commercial_cars_gas	508	#
Commercial cars EV	commercial_cars_ev	486	#
Commercial cars on hydrogen	commercial_cars_hydrogen	0	#
FUEL USE			
Parameter	***Name in model***	***Value***	***Unit***
Total fuel use road transport	total_fuel_use_road	Function	Million liters
Gasoline use	gasoline_road	720.5	Million liters
LPG use	lpg_road	41.1	Million liters
Diesel use	diesel_road	677.4	Million liters
CHARGING POINTS			
Parameter	***Name in model***	***Value***	***Unit***
Fast charging points	fast_charging	37	#
Semi-public charging points	semipublic_charging	6117	#
Hydrogen stations	hydrogenstation	0	#
ENERGY USE			
Parameter	***Name in model***	***Value***	***Unit***
Average electricity use of households	average_electricity_households	3400	kWh/year
Sun hours	sun_hours	1521	Hours
Energy storage capacity	energy_storage	0	
Electricity use per rail kilometer	electricity_rail_km	71.9	kWh/km
Electricity use of rail transport	electricity_rail	Function	
ELECTRICITY USE			
Parameter	***Name in model***	***Value***	***Unit***
Total electricity use	total_electricity	Function	

Electricity use of households	electricity_households	2874	
Commercial electricity use	electricity_commercial	4679	
Electricity use of agriculture	electricity_agriculture	213	
Electricity use of construction	electricity_construction	127	
Electricity use of transport	electricity_transport	Function	
RENEWABLE ELECTRICITY			
Parameter	*Name in model*	*Value*	*Unit*
Installed wind energy capacity	installed_windcapacity	0.3276	GW
Installed solar energy capacity	installed_solarcapacity	97,65	MWp
Full load hours	full_load_hours	2118	Hours
Total renewable electricity	renewable_electricity	Function	GWh
Wind energy	wind_energy	Function	GWh
Solar energy	solar_energy	Function	GWh
Biogas co-fermentation	biogas_cofermentation_elec	2	GWh
Waste incineration	waste_incineration_elec	548	GWh
Biogas sewage sludge	biogas_sewage_elec	25	GWh
Biomass	Biomass_elec	10	GWh
Landfill gas	landfill_gas_elec	1	GWh
FOSSIL ELECTRICITY			
Parameter	*Name in model*	*Value*	*Unit*
Fossil electricity	fossil_electricity	Function	GWh
Electricity from coal	coal_electricity	Function	GWh
Electricity from nuclear	nuclear_electricity	Function	GWh
Electricity from natural gas	naturalgas_electricity	Function	GWh
FOSSIL FUELS			
Parameter	*Name in model*	*Value*	*Unit*
Coal for electricity generation	coal_for_electricity	Function	Kton
Gas for electricity generation	naturalgas_for_electricity	Function	Million m^3
Uranium for electricity generation	uranium	Function	Kg
HEAT			
Parameter	*Name in model*	*Value*	*Unit*
Total heat	total_heat	Function	TJ
Heat for agriculture	agriculture_heat	5995	TJ
Heat for households	households_heat	36931	TJ
Heat for commercial	commercial_heat	10437	TJ
Heat for industries	industry_heat	9814	TJ
RENEWABLE HEAT			
Parameter	*Name in model*	*Value*	*Unit*
Waste incineration	waste_incineration_heat	406	TJ
Biogas sewage heat	biogas_sewage_heat	826	TJ
Biomass boilers	biomas_boiler	1551	TJ
Wood stoves	wood_stoves	868	TJ
Charcoal	charcoal	33	TJ
ATES	ates	634	TJ
Landfill gas	landfill_gas_heat	14	TJ
Decentral biomass	decentral_biomass	16	TJ
Geothermal	geothermal	75	TJ
CONSTRUCTION			
Parameter	*Name in model*	*Value*	*Unit*

Housing stock	housing_stock	1122674	#
Construction/demolition waste	cd_waste	585000	Tonnes
Granulate	granulate	Function	Tonnes
Sorted waste	sorted_waste	Function	Tonnes
MATERIAL IMPORT			
Parameter	***Name in model***	***Value***	***Unit***
Import of raw materials	raw_material_input	Function	Tonnes
Import of metals	metals_import	37500	Tonnes
Import of biomass	biomass_import	75000	Tonnes
Import of minerals	minerals_import	1275000	Tonnes
Other import	other_import	112500	Tonnes
MATERIALS			
Parameter	***Name in model***	***Value***	***Unit***
Copper	copper	Function	Tonnes
Aluminum	aluminum	Function	Tonnes
Steel	steel	Function	Tonnes
Wood	wood	Function	Tonnes
Glass	glass	Function	Tonnes
Plastics	plastics	Function	Tonnes
Bricks	bricks	Function	Tonnes
Gravel	gravel	Function	Tonnes
Concrete	concrete	Function	Tonnes
Asphalt	asphalt	Function	Tonnes
WATER			
Parameter	***Name in model***	***Value***	***Unit***
Rainfall in the NL	rainfall_NL	880	mm
Rainfall in the AMA	rainwater_AMA	Function	mm
HOUSEHOLD WATER			
Parameter	***Name in model***	***Value***	***Unit***
Total household water use	residential_water	Function	
Households black water	black_water_households	Function	
Households shower	shower	48.6	Liter/ person/ day
Households toilet	toilet	33.7	Liter/ person/ day
Households laundry	laundry	15.4	Liter/ person/ day
Households dishes	dishes	6.1	Liter/ person/ day
Households bath	bath	2.8	Liter/ person/ day
Households kitchen sink	kitchen_sink	5.3	Liter/ person/ day
Households food preparation	food_prep	1.4	Liter/ person/ day
Households coffee/tea	coffee_tea	1.2	Liter/ person/ day
Households drinking	drinking	0.6	Liter/ person/ day

Households bathroom sink	bathroom_sink	5	Liter/ person/ day
SECTORS			
Parameter	***Name in model***	***Value***	***Unit***
Water use agriculture	agricultural_water	Function	Million m^3
Water use industry	industry_water	58,9	Million m^3
Water use commercial sector	commercial_water	23,5	Million m^3
SECTORS			
Parameter	***Name in model***	***Value***	***Unit***
Sewage sludge	sewage_sludge	125	kton

Appendix C: Manure calculation

NRCS (2017) states the manure production per type of livestock. The measurement unit is lbs/day/1000-lb animal unit. The unit 1000-lb animal unit stands for a 1000 pounds animal. A cow generally weighs about 1400 pounds (1,4 animal unit). Hogs and pigs weigh between 200 and 300 pounds. It is assumed that the same goes for sheep. Chicken weigh between 4 and 5 pounds. It can be calculated how many animals of each type of livestock account for 1000-lb animal unit.

- Beef: 1000/1400 = 0,71 animals per 1000-lb animal unit
- Pork/sheep: 1000/200 = 5 animals per 1000-lb animal unit
- Poultry: 1000/4 = 250 animals per 1000-lb animal unit

When converting the lbs to kg, NRCS (2017) gives the following production rates of manure per livestock type.

Livestock type	Total manure production
Kg/day/1000-lb animal unit	
Beef	36
Dairy	26,6
Hogs and pigs	28,4
Chicken (layers)	27,2
Chicken (broilers	36

Figure 22: Manure production per type of livestock (NRCS, 2017)

Combining this data with the data from CBS (2017a) on the number of animals in the AMA, it gives the following calculations:

- Beef:	6199 * (36/0,71)	=	314315,5	kg per day	10%
- Pork:	12154 * (28,4/5)	=	69034,7	kg per day	2%
- Poultry:	623727* (36/250)	=	89816,7	kg per day	3%
- Poultry eggs:	300499 * (27,2/250)	=	32694,3	kg per day	1%
- Milk:	68306 * (26,6/0,71)	=	2559069,9	kg per day	78%
- Sheep:	38507 * (28,4/5)	=	218719,8	kg per day	6%
			-- +		
			3283650,9	kg per day	100%
			1198,5	kton per year	

When percentage distribution, resulting from these calculations, is combined with the data from CBS (2017a) on the quantity of manure produced in the AMA, the following calculations apply for liquid and solid manure:

- Beef:	1405 * 0,1	=	145	kton liquid manure/year
- Pork:	1405 * 0,02	=	28,1	kton liquid manure /year
- Poultry:	1405 * 0,03	=	42,15	kton liquid manure /year
- Poultry eggs:	1405 * 0,01	=	14,05	kton liquid manure /year
- Milk:	1405 * 0,78	=	1095,9	kton liquid manure /year
- Sheep:	1405 * 0,06	=	84,3	kton liquid manure /year

- Beef:	56 * 0,1	=	5,6	kton solid manure/year
- Pork:	56 * 0,02	=	1,12	kton solid manure /year

- Poultry: 56 * 0,03 = 1,68 kton solid manure /year
- Poultry eggs: 56 * 0,01 = 0,56 kton solid manure /year
- Milk: 56 * 0,78 = 43,68 kton solid manure /year
- Sheep: 56 * 0,06 = 3,36 kton solid manure /year

In order to calculate how much manure each type of livestock produces, based on the result of the previous calculations, the calculated quantity of manure production per livestock type should be divided by the number of animals.

- Beef: 145 / 6199 = $2,3 \times 10^{-2}$ kton liquid manure/year/animal
- Pork: 28,1 / 12154 = $2,3 \times 10^{-3}$ kton liquid manure/year/animal
- Poultry: 42,15 / 623727 = $6,8 \times 10^{-5}$ kton liquid manure/year/animal
- Poultry eggs: 14,05 /300499 = $4,7 \times 10^{-5}$ kton liquid manure/year/animal
- Milk: 1095,9 / 68306 = $1,6 \times 10^{-2}$ kton liquid manure/year/animal
- Sheep: 84,3 / 38507 = $2,2 \times 10^{-3}$ kton liquid manure/year/animal

- Beef: 5,6 / 6199 = 9×10^{-4} kton solid manure /year/animal
- Pork: 1,12 / 12154 = $9,2 \times 10^{-5}$ kton solid manure /year/animal
- Poultry: 1,68 / 623727 = $2,7 \times 10^{-6}$ kton solid manure /year/animal
- Poultry eggs: 0,56 / 300499 = $1,9 \times 10^{-6}$ kton solid manure /year/animal
- Milk: 43,68 / 68306 = $6,4 \times 10^{-4}$ kton solid manure /year/animal
- Sheep: 3,36 / 38507 = $8,7 \times 10^{-5}$ kton solid manure /year/animal

Appendix D: Conversion factors

In order to determine how much coal, natural gas and uranium are needed to produce their fraction of fossil electricity, it is required to calculate conversion factors. The conversion factor for natural gas can be calculated by the following function (EIA, 2017):

$$\frac{Fuel\ heat\ content}{Heat\ rate} = kWh\ per\ unit\ of\ fuel$$

The heat content of natural gas is equal to 1037 Btu per f^3 (EIA, 2016a). The heat rate is equal to 7876 Btu per kWh (EIA, 2016b). This gives the following equation:

1037 Btu per f^3 / 7876 per kWh = 0,13 kWh per ft^3
1 ft^3 = 0,028 m^3
0,13 kWh per ft^3/ 0,028 m^3
4,7 kWh per m^3 of natural gas

The conversion factor for coal can be calculated with the same function. The heat content of coal is equal to 9,459 million Btu per short ton of coal (EIA, 2018). The heat rate is equal to 10493 Btu per kWh (EIA, 2016b). This gives the following equation:

9,459 million Btu per short ton / 10493 Btu per kWh = 1854,47 kWh per short ton
Short ton = 907,18 kg
1854,47 kWh per short ton / 907,18 kg
2 kWh per kg of coal

According to the Depleted UF6 Management Information Network (2017), it is possible to produce more than 40.000 kWh of electricity with 1000 kg of uranium. It is assumed that 1000 kg of uranium produces 40.000 kWh of electricity. This gives the following equation:

1000 kg of uranium = 40.000.000 kWh
1 kg of uranium = 40.000 kWh

Appendix E: Diet conversion

According to van Rossum et al. (2016), in the current situation, the consumption values of meat and legumes are as follows:

- 101 grams of meat per person per day
- 4 grams of legumes per person per day

As it is assumed that the diet composition of people in the AMA may change towards two meatless days per week, new amounts of meat consumption per person per day are expected. The following equations determine the new value of meat consumption per person per day.

$$\text{Meat consumption per person per day: 101 grams}$$

$$\text{Week of meat consumption per person: 7 x 101 grams} = \text{707 grams per person}$$

$$\text{Meat consumption per person in 5 days: 5 x 101 grams} = \text{505 grams per person}$$

$$\frac{505\ grams}{707\ grams} = 71\ grams\ meat\ consumption\ per\ person\ per\ day$$

The assumption is made that meat consumption is directly replaced by the consumption of legumes. The applicable ratio for this is 135 grams of legumes per 100 grams of meat (Voedingscentrum, 2018). A week with two meatless days brings therefore results in an increase of legume consumption of 270 grams per week. Adding up the current legume production with the increase of legume production results in a total of 274 grams of legumes per person per day. The maximum legume consumption is therefore:

$$\frac{274\ grams}{7\ days} = 39\ grams\ legume\ consumption\ per\ person\ per\ day$$

The values representing the maximum change are -30 grams for meat consumption and +35 for legume production. On the basis of the equation below, it can be concluded that each gram of meat that is eaten less, legume consumption increases with 1,16 grams.

$$\frac{35}{30} = 1{,}16$$

Appendix F: Heat and electricity demand calculations

The report by the Ministry of Infrastructure and Environment (2017) states the expected energy prospects for the year 2040. The energy prospects are given with two different scenarios. The first scenario assumes moderate energy savings and the second scenario assumes maximum energy savings. In these scenarios, energy use per sector is subject to expected changes such as population growth, expected growth of certain sectors, etc.

Since the goal of this thesis is to get an idea of the implications of a circular metropolitan area, it is calculated which part of the changes are attributable to changes based on the circular economy, and not on expected changes that do not attribute to a circular economy.

Households

For the energy use of households, the assumption that is not attributable to a transition towards a circular economy is the population growth. The report assumes an increase to 1,35 million households in 2040. Currently, the number of households is 1,08 million. The conversion factor can be calculated by dividing 1,08 by 1,35.

$$\frac{1{,}08\, million}{1{,}35\, million} = 0{,}8$$

This gives the following functions:

$$\text{Heat} \times \text{Conversion factor} = \text{Heat with current number of households}$$

$$1\ \text{PJ} = 277{,}8\ \text{GWh}$$

Considering the data from the report Ministry of Infrastructure and Environment (2017), the following calculations can be made to get to a situation that accounts only for changes due to a transition towards a circular economy:

$$\text{Heat (moderate)}: 40 \times 0{,}8 = 32\ \text{PJ}$$

$$\text{Heat (maximum)}: 27{,}2 \times 0{,}8 = 21{,}8\ \text{PJ}$$

$$\text{Electricity (moderate)}: 13{,}3 \times 0{,}8 = 10\ \text{PJ} = 2778\ \text{GWh}$$

$$\text{Electricity (maximum)}: 15{,}7 \times 0{,}8 = 12{,}6\ \text{PJ} = 3500\ \text{GWh}$$

On top of the mentioned energy savings, additional energy savings are achievable by using heat exchangers in showers. Currently, heated water used for showering is only used once, despite the fact that the heat in this water bears the potential to be reused. By installing heat exchangers, the total energy demand can be reduced. Deng et al (2016) argue that, based on experiments in the city of Amsterdam, a total of 4 percent of the current energy consumption be recovered. The current heat demand is 47600 TJ, so 4 percent of this equals 1904 TJ, or 1,9 PJ. Heat exchangers for showers are considered to be passive as it comes to energy use. Therefore, it the heat exchanger do not contribute to electricity use. The new heat demand in the maximum savings scenario is:

$$\text{Heat (maximum)}: 27{,}2 \times 0{,}8 = 21{,}8\ \text{PJ} - 1{,}9\ \text{PJ} = 19{,}9\ \text{PJ}$$

Future heat demand ranges from 32 PJ to 19,9 PJ, whereas the electricity demand ranges from 2778 GWh to 3500 GWh. Since the heat exchangers are assumed not to account for extra electricity, the simplified relation between heat and electricity demand is that each additional GWh in electricity demand for households causes a decrease in heating demand of 0,016759 PJ.

COMMERCIAL

For the commercial sector, the report assumes a growth of the floor area. Currently, the total floor area for the commercial sector adds up to 43 million m^2. The assumption for future scenarios is that the total floor area will increase to an amount of 52 million m^2. Therefore, the conversion factor can be calculated by dividing 43 million by 52 million.

$$\frac{43\ million}{52\ million} = 0{,}83$$

Considering the data from the report Ministry of Infrastructure and Environment (2017), the following calculations can be made to get to a situation that accounts only for changes due to a transition towards a circular economy:

$$\text{Heat (moderate)}: 17{,}3 \times 0{,}83 = 14{,}4\ \text{PJ}$$

$$\text{Heat (maximum)}: 15{,}5 \times 0{,}83 = 12{,}9\ \text{PJ}$$

$$\text{Electricity (moderate)}: 25{,}1 \times 0{,}83 = 20{,}8\ \text{PJ} = \ 5777\ \text{GWh}$$

$$\text{Electricity (maximum)}: 25{,}1 \times 0{,}83 = 20{,}8\ \text{PJ} = \ 5777\ \text{GWh}$$

INDUSTRY

For the commercial sector, the report assumes a growth of the floor area. Currently, the total floor area for the commercial sector adds up to 43 million m^2. The assumption for future scenarios is that the total floor area will increase to an amount of 52 million m^2. Therefore, the conversion factor can be calculated by dividing 43 million by 52 million.

Appendix G: Car capacity calculation

Total number of passenger cars = 1131265

Now: 1,5 people per car

Current: 1,7 people per car

Circular: 2,5 people per car

1131265 * 1,5 = 1696898

1696898 / 1,7 = 998175

1696898 / 2,5 = 678759

Appendix H: Waste incineration fractions

To come up with the energy fractions that are produced with the incineration of residual waste, the data of the Klimaatmonitor (2017) on energy sources is combined with the data of the Afvalmonitor (2016) on the waste production in the AMA.

According to the Afvalmonitor (2016), on average, each inhabitant of the AMA produces 222 kilograms of residual waste. This adds up to 535 kilotons per year in the AMA. The separated waste is not in included in this number, since it is assumed that this waste is not being incinerated but meant to be recycled. As stated by Klimaatmonitor (2017), the electricity production that is a result of waste incineration is 548 GWh. For heat production, this number is 406 TJ.

$$Electricity\ production = \frac{535\ kiloton}{548\ GWh} = 1{,}02\ GWh\ per\ kiloton$$

$$Heat\ production = \frac{535\ kiloton}{406\ TJ} = 0{,}76\ TJ\ per\ kiloton$$

The results of this calculation are checked with data from AEB (2015) to check if the order of magnitude of the calculated numbers are in accordance with data from AEB (2015). After comparing data, the order of magnitude of the calculated numbers seems right.

Appendix I: Model code (baseline)

```
from __future__ import division


def AMA_future_model(

inhabitants = 2410960,

households = 1083799,

avg_household = 2.2,

area_NL = 41543,

area_AMA = 2580,

roof_area = 102.1,

beef_production_NL = 416,

beef_AMA = 6199,

beef_NL = 1179000,

pork_production_NL = 1453,

pork_AMA = 12154,

pork_NL = 1249000,

poultry_production_NL = 1037,

poultry_AMA = 623727,

poultry_NL = 43846000,

sheep_production_NL = 14,

sheep_AMA = 38507,

sheep_NL = 784000,

egg_production_NL = 672,

eggs_AMA = 300499,

eggs_NL = 46212000,

milk_production_NL = 14324,

milk_AMA = 68306,

milk_NL = 3072000,
```

fruits_greenhouse_production_NL = 691,

fruits_greenhouse_area_AMA = 0,

fruits_greenhouse_area_NL = 1600,

fruits_openground_production_NL = 691,

fruits_openground_area_AMA = 1680,

fruits_openground_area_NL = 20367,

vegetables_greenhouse_production_NL = 3511,

vegetables_greenhouse_area_AMA = 24,

vegetables_greenhouse_area_NL = 39100,

vegetables_openground_production_NL = 1270,

vegetables_openground_area_AMA = 708,

vegetables_openground_area_NL = 2300,

cereal_production_NL = 1316,

cereal_area_AMA = 6198,

cereal_area_NL = 175000,

potato_production_NL = 6703,

potato_area_AMA = 3185,

potato_area_NL = 157000,

legume_production_NL = 3,

legume_area_AMA = 4,

legume_area_NL = 1000,

beef_feed = 25,

pork_feed = 6.4,

poultry_feed = 3.3,

egg_feed = 2.3,

sheep_feed = 14,

milk_feed = 25,

potato_consumption_day = 0.000000073,

vegetable_consumption_day = 0.000000124,

meat_consumption_day = 0.000000101,

legume_consumption_day = 0.000000004,

cereal_consumption_day = 0.000000192,

fruit_consumption_day = 0.000000122,

egg_consumption_day = 0.000000012,

fish_consumption_day = 0.000000015,

dairy_consumption_day = 0.000000355,

companies = 2150,

average_water_use = 2111,

foodwaste_consumer = 47.25,

foodwaste_processing = 21.6,

foodwaste_distribution = 12.15,

foodwaste_production = 37.8,

foodwaste_storage = 16.2,

foodbank_fraction = 0.01,

animalfeed_fraction = 0.2,

fertilizer_use_km2 = 2.581,

total_distance = 22.16,

publictransport_fraction = 0.1864,

individual_cars_ev_fraction = 0.028,

commercial_cars_ev_fraction = 0.0037,

cars = 1263072,

gasoline_road = 720.5,

lpg_road = 41.1,

diesel_road = 677.4,

electricity_rail_km = 71.9,

fast_charging = 37,

semipublic_charging = 6117,

hydrogenstation = 0,

people_per_trip = 1.5,

average_electricity_households = 3400,

installed_windcapacity = 0.3276,

installed_solarcapacity = 0.0947,

full_load_hours = 2118,

sewage_sludge = 125,

electricity_households = 2874,

electricity_commercial = 5693,

electricity_agriculture = 213,

electricity_construction = 127,

electricity_industry = 3166,

biogas_cofermentation = 2,

biomass = 10,

landfill_gas_elec = 1,

agriculture_heat = 5995,

households_heat = 47600,

commercial_heat = 26900,

industry_heat = 40400,

biomass_boilers = 1551,

geothermal = 75,

wood_stoves = 868,

charcoal = 33,

ATES = 634,

```
landfill_gas_heat = 14,
decentral_biomass = 16,
housing_stock = 1122674,
raw_material_requirements = 15040.95,                    #in kilotons
cd_waste = 585,
recyclable_fraction = 0.85,
sorted_waste_percentage = 0.07,
rainfall_NL = 880,
shower = 48.6,
toilet = 33.7,
laundry = 15.4,
dishes = 6.1,
bath = 2.8,
kitchen_sink = 5.3,
food_prep = 1.4,
coffee_tea = 1.2,
drinking = 0.6,
bathroom_sink = 5,
commercial_water = 23.5,
industrial_water = 58.9):
##########################   GENERAL   ##############################
    area_residential = area_AMA * 0.092
    area_agriculture = area_AMA * 0.266
    area_infrastructure = area_AMA * 0.034
    area_miscellaneous = area_AMA * 0.177
    area_water = area_AMA * 0.381
    area_commercial = area_AMA * 0.049
```

```
### FOOD PRODUCTION
    beef_production = int(beef_production_NL * (beef_AMA / beef_NL))
    pork_production = int(pork_production_NL * (pork_AMA / pork_NL))
    poultry_production = int(poultry_production_NL * (poultry_AMA / poultry_NL))
    sheep_production = int(sheep_production_NL * (sheep_AMA / sheep_NL))
    egg_production = int(egg_production_NL * (eggs_AMA / eggs_NL))
    milk_production = int(milk_production_NL * (milk_AMA / milk_NL))
    fruits_greenhouse_production = int(fruits_greenhouse_production_NL * (fruits_greenhouse_area_AMA / fruits_greenhouse_area_NL))
    fruits_openground_production = int(fruits_openground_production_NL * (fruits_openground_area_AMA / fruits_openground_area_NL))
    vegetables_greenhouse_production = int(vegetables_greenhouse_production_NL * (vegetables_greenhouse_area_AMA / vegetables_greenhouse_area_NL))
    vegetables_openground_production = int(vegetables_openground_production_NL * (vegetables_openground_area_AMA / vegetables_openground_area_NL))
    cereal_production = int(cereal_production_NL * (cereal_area_AMA / cereal_area_NL))
    potato_production = int(potato_production_NL * (potato_area_AMA / potato_area_NL))
    legume_production = int(legume_production_NL * (legume_area_AMA / legume_area_NL))
    meat_production = beef_production + pork_production + poultry_production + sheep_production
    dairy_production = milk_production + egg_production
    fruit_production = fruits_greenhouse_production + fruits_openground_production
    vegetable_production = vegetables_greenhouse_production + vegetables_openground_production
    food_production = meat_production + dairy_production + fruit_production + vegetable_production + legume_production + cereal_production + potato_production
### FOOD WASTE
    total_foodwaste = ((foodwaste_consumer + foodwaste_processing + foodwaste_distribution + foodwaste_production + foodwaste_storage) * inhabitants) / 1000000
### FOOD WASTE DESTINATION
    foodbank = total_foodwaste * 0.01
    food_to_feed = total_foodwaste * 0.2
```

```
### ANIMAL FEED
    beef_animalfeed = beef_feed * beef_production                    #Feed is per kg
    pork_animalfeed = pork_feed * pork_production
    poultry_animalfeed = poultry_feed * poultry_production
    egg_animalfeed = egg_feed * egg_production
    sheep_animalfeed = sheep_feed * sheep_production
    milk_animalfeed = milk_feed * milk_production
    animalfeed = beef_animalfeed + pork_animalfeed + poultry_animalfeed + egg_animalfeed +
sheep_animalfeed + milk_animalfeed - food_to_feed
### FOOD CONSUMPTION
    potato_consumption = int(potato_consumption_day * inhabitants * 365)
    vegetable_consumption = int(vegetable_consumption_day * inhabitants * 365)
    meat_consumption = int(meat_consumption_day * inhabitants * 365)
    legume_consumption = int(legume_consumption_day * inhabitants * 365)
    cereal_consumption = int(cereal_consumption_day * inhabitants * 365)
    fruit_consumption = int(fruit_consumption_day * inhabitants * 365)
    egg_consumption = int(egg_consumption_day * inhabitants * 365)
    fish_consumption = int(fish_consumption_day * inhabitants * 365)
    dairy_consumption = int(dairy_consumption_day * inhabitants * 365)
### MEAT CONSUMPTION
    poultry_consumption = int(meat_consumption * 0.31)
    beef_consumption = int(meat_consumption * 0.24)
    pork_consumption = int(meat_consumption * 0.45)
    sheep_consumption = int(meat_consumption * 0.01)
### IMPORT/EXPORT
    vegetable_import = vegetable_production - vegetable_consumption
    fruit_import = fruit_production - fruit_consumption
    potato_import = potato_production - potato_consumption
```

```
    cereal_import = cereal_production - cereal_consumption

    meat_import = meat_production - meat_consumption

    legume_import = legume_production - legume_consumption

### MANURE

    liquid_manure = (beef_AMA * 0.023) + (pork_AMA * 0.0023) + (poultry_AMA * 0.000068) +
(eggs_AMA * 0.000068) + (milk_AMA * 0.012) + (sheep_AMA * 0.0022)

    solid_manure = (beef_AMA * 0.0009) + (pork_AMA * 0.000092) + (poultry_AMA * 0.0000027) +
(eggs_AMA * 0.0000019) + (milk_AMA * 0.00064) + (sheep_AMA * 0.000087)

    total_manure = liquid_manure + solid_manure

### FERTILIZER

    fertilizer_use = area_agriculture * fertilizer_use_km2

##########################   TRANSPORT    ##############################

    car_fraction = 1 - publictransport_fraction

    distance_car = total_distance * car_fraction

    distance_publictransport = total_distance * publictransport_fraction

    distance_train = distance_publictransport * 0.676

    distance_metrotram = distance_publictransport * 0.216

    distance_bus = distance_publictransport * 0.108

    total_traveled_distance = int(distance_train + distance_car + distance_metrotram + distance_bus)

### CAR FLEET

    individual_cars = cars * 0.896

    commercial_cars = cars * 0.104

    individual_cars_ev_phev = individual_cars * individual_cars_ev_fraction

    individual_cars_phev = individual_cars_ev_phev * 0.87

    individual_cars_ev = individual_cars_ev_phev * 0.13

    individual_cars_fossil = individual_cars - individual_cars_ev

    individual_cars_petrol = individual_cars_fossil * 0.999

    individual_cars_gas = individual_cars_fossil * 0.001
```

```
    commercial_cars_ev = commercial_cars * commercial_cars_ev_fraction

    commercial_cars_fossil = commercial_cars - commercial_cars_ev

    commercial_cars_petrol = commercial_cars_fossil * 0.996

    commercial_cars_gas = commercial_cars_fossil * 0.004

    km_car = distance_car / cars

### FUEL USE

    total_fuel_use_road = int(gasoline_road + lpg_road + diesel_road)

### ELECTRICITY TRANSPORT

    electricity_rail = int((distance_train + distance_metrotram) * electricity_rail_km)

    electricity_EV = ((km_car * individual_cars_ev) + (km_car * commercial_cars_ev)) * 0.16

    electricity_PHEV = (km_car * individual_cars_phev) * 0.08

    electricity_cars = electricity_EV + electricity_PHEV

###########################   ENERGY    ###############################

    residual_waste = ((175 + foodwaste_consumer) * inhabitants) / 1000000

    electricity_transport = electricity_rail + electricity_cars

    total_electricity = int(electricity_households + electricity_commercial + electricity_agriculture +
electricity_construction + electricity_industry + electricity_transport)

### RENEWABLE ELECTRICITY

    wind_energy = int(installed_windcapacity * full_load_hours)

    solar_energy = int(installed_solarcapacity * 850)

    waste_incineration_elec = residual_waste * 1.02

    biogas_sewage_elec = sewage_sludge * 0.2

    renewable_electricity = wind_energy + solar_energy + biogas_cofermentation +
waste_incineration_elec + biogas_sewage_elec + biomass + landfill_gas_elec

### FOSSIL ELECTRICITY

    fossil_electricity = total_electricity - renewable_electricity

    coal_electricity = int(fossil_electricity * 0.5)

    nuclear_electricity = int(fossil_electricity * 0.42)
```

```
    naturalgas_electricity = int(fossil_electricity * 0.08)

    coal_for_electricity = int(coal_electricity / 2)

    naturalgas_for_electricity = int(naturalgas_electricity / 4.7)

    uranium = int(nuclear_electricity * 25)

### HEAT

    total_heat = agriculture_heat + households_heat + commercial_heat + industry_heat

    waste_incineration_heat = residual_waste * 0.76

    biogas_sewage_heat = sewage_sludge * 6.6

    renewable_heat = waste_incineration_heat + biogas_sewage_heat + biomass_boilers + geothermal
+ wood_stoves + charcoal + ATES + landfill_gas_heat + decentral_biomass

    fossil_heat = total_heat - renewable_heat

###########################   CONSTRUCTION    ###############################

### RAW MATERIALS

    granulate_percentage = recyclable_fraction - sorted_waste_percentage

    granulate = int(cd_waste * granulate_percentage)

    sorted_waste = int(cd_waste * sorted_waste_percentage)

    raw_material_import = raw_material_requirements - sorted_waste

    metals_import = raw_material_import * 0.025

    biomass_import = raw_material_import * 0.05

    minerals_import = raw_material_import * 0.85

    other_import = raw_material_import * 0.075

    copper = int(metals_import * 0.03 + (sorted_waste * 0.125))

    aluminum = int(metals_import * 0.02 + (sorted_waste * 0.125))

    steel = int(metals_import * 0.95 + (sorted_waste * 0.5))

    wood = biomass_import

    glass = int(other_import * 0.93)

    plastics = int(other_import * 0.07)

    bricks = int(minerals_import * 0.03)
```

```
    gravel = int(minerals_import * 0.09)

    concrete = int((minerals_import * 0.68) + (0.02 * granulate))

    asphalt = int((minerals_import * 0.2) + (sorted_waste * 0.25))

##########################   WATER    ##############################

    rainwater_AMA = int((area_AMA / area_NL) * rainfall_NL)

### WATER USE

    grey_water_households = int(((shower + laundry + dishes + bath + kitchen_sink + food_prep +
bathroom_sink) * inhabitants * 365) / 1000000000)

    black_water_households = int((toilet * inhabitants * 365) / 1000000000)

    residential_water = int(((shower + toilet + laundry + dishes + bath + kitchen_sink + food_prep +
coffee_tea + drinking + bathroom_sink) * inhabitants * 365) / 1000000000)

    agricultural_water = int(companies * average_water_use) / 1000000

    total_water_use = residential_water + commercial_water + industrial_water + agricultural_water

##########################   KEY PERFORMANCE INDICATORS
##############################

    KPI_electricity = total_electricity

    KPI_electricity_renewable_fraction = (renewable_electricity / total_electricity) * 100

    KPI_heat = total_heat

    KPI_heat_renewable_fraction = (renewable_heat / total_heat) * 100

    KPI_energy = (total_electricity * 3.6) + total_heat

    KPI_energy_renewable_fraction = ((renewable_heat + (renewable_electricity * 3.6)) / KPI_energy) *
100

    KPI_water = total_water_use

    KPI_construction_selfsufficiency = (1 - (raw_material_import / raw_material_requirements)) * 100

    KPI_selfsufficiency_meat = meat_import

    KPI_selfsufficiency_vegetables = vegetable_import

    KPI_selfsufficiency_fruits = fruit_import

    KPI_selfsufficiency_cereal = cereal_import

    KPI_selfsufficiency_potato = potato_import
```

```
KPI_selfsufficiency_legume = legume_import


return {'KPI electricity': KPI_electricity,
        'Renewable electricity fraction': KPI_electricity_renewable_fraction,
        'KPI heat': KPI_heat,
        'Renewable heat fraction': KPI_heat_renewable_fraction,
        'KPI energy': KPI_energy,
        'Renewable energy fraction': KPI_energy_renewable_fraction,
        'KPI water': KPI_water,
        'KPI selfsufficiency construction': KPI_construction_selfsufficiency,
        'KPI selfsufficiency meat': KPI_selfsufficiency_meat,
        'KPI selfsufficiency vegetables': KPI_selfsufficiency_vegetables,
        'KPI selfsufficiency fruits': KPI_selfsufficiency_fruits,
        'KPI selfsufficiency cereal': KPI_selfsufficiency_cereal,
        'KPI selfsufficiency potato': KPI_selfsufficiency_potato,
        'KPI selfsufficiency legume': KPI_selfsufficiency_legume}
```

Appendix J: Model code (Minimum scenario)

```
from __future__ import division


def AMA_future_model(

inhabitants = 2410960,

households = 1083799,

avg_household = 2.2,

area_NL = 41543,

area_AMA = 2580,

roof_area = 102.1,

beef_production_NL = 416,

beef_AMA = 6199,

beef_NL = 1179000,

pork_production_NL = 1453,

pork_AMA = 12154,

pork_NL = 1249000,

poultry_production_NL = 1037,

poultry_AMA = 623727,

poultry_NL = 43846000,

sheep_production_NL = 14,

sheep_AMA = 38507,

sheep_NL = 784000,

egg_production_NL = 672,

eggs_AMA = 300499,

eggs_NL = 46212000,

milk_production_NL = 14324,

milk_AMA = 68306,

milk_NL = 3072000,
```

fruits_greenhouse_production_NL = 691,

fruits_greenhouse_area_AMA = 0,

fruits_greenhouse_area_NL = 1600,

fruits_openground_production_NL = 691,

fruits_openground_area_AMA = 1680,

fruits_openground_area_NL = 20367,

vegetables_greenhouse_production_NL = 3511,

vegetables_greenhouse_area_AMA = 24,

vegetables_greenhouse_area_NL = 39100,

vegetables_openground_production_NL = 1270,

vegetables_openground_area_AMA = 708,

vegetables_openground_area_NL = 2300,

cereal_production_NL = 1316,

cereal_area_AMA = 6198,

cereal_area_NL = 175000,

potato_production_NL = 6703,

potato_area_AMA = 3185,

potato_area_NL = 157000,

legume_production_NL = 3,

legume_area_AMA = 4,

legume_area_NL = 1000,

beef_feed = 25,

pork_feed = 6.4,

poultry_feed = 3.3,

egg_feed = 2.3,

sheep_feed = 14,

milk_feed = 25,

```
potato_consumption_day = 0.000000073,
vegetable_consumption_day = 0.000000124,
meat_consumption_day = 0.000000101,
meat_consumption_day_new = 0.000000101,          #0.000000071, 0.000000101
legume_consumption_day = 0.000000004,
cereal_consumption_day = 0.000000192,
fruit_consumption_day = 0.000000122,
egg_consumption_day = 0.000000012,
fish_consumption_day = 0.000000015,
dairy_consumption_day = 0.000000355,
companies = 2150,
average_water_use = 1689,                #1161, 1689
foodwaste_consumer = 30.7,               #9.5, 30.7
foodwaste_processing = 10.8,             #4.3, 10.8
foodwaste_distribution = 6,              #2.4, 6
foodwaste_production = 18.9,             #7.6, 18.9
foodwaste_storage = 8.1,                 #3.2, 8.1
foodbank_fraction = 0.01,                #0.01, 0.012
animalfeed_fraction = 0.25,              #0.25, 0.26
fertilizer_use_km2 = 206.5,              #180.7, 206.5
total_distance = 22.16,
publictransport_fraction = 0.19,         #0.19, 0.33
individual_cars_ev_fraction = 0.6,       #0.6, 0.9
commercial_cars_ev_fraction = 0.6,       #0.6, 0.9
cars = 998175,                           #678759, 998175
gasoline_road = 720.5,
lpg_road = 41.1,
```

```
diesel_road = 677.4,

electricity_rail_km = 71.9,

fast_charging = 37,

semipublic_charging = 6117,

hydrogenstation = 0,

people_per_trip = 1.5,

average_electricity_households = 3400,

installed_windcapacity_land = 327.6,        #327.6, 2160

installed_windcapacity_water = 0,       #0, 70011

installed_solarcapacity = 97.65,            #97.65, 2721

installed_solarfieldcapacity = 0,       #0, 9412

full_load_hours = 2118,

sewage_sludge = 125,

electricity_households = 2778,            #2778, 3500

electricity_commercial = 5777,

electricity_agriculture = 213,

electricity_construction = 127,

electricity_industry = 3166,

biogas_cofermentation = 2,

biomass = 10,

landfill_gas_elec = 1,

agriculture_heat = 5995,

commercial_heat = 14400,                  #12.9, 14.4

industry_heat = 40400,

biomass_boilers = 1551,

geothermal = 75,

geothermal_agriculture_instal = 0,      #0, 6
```

```
geothermal_residential_instal = 0,      #0, 15
wood_stoves = 868,
charcoal = 33,
ATES = 634,
landfill_gas_heat = 14,
decentral_biomass = 16,
housing_stock = 1122674,
raw_material_requirements = 15040.95,      #in kilotons
cd_waste = 5850,
recyclable_fraction = 0.85,
sorted_waste_percentage = 0.07,          #0.07, 0.85
rainfall_NL = 880,
shower = 48.6,
toilet = 33.7,
laundry = 15.4,
dishes = 6.1,
bath = 2.8,
kitchen_sink = 5.3,
food_prep = 1.4,
coffee_tea = 1.2,
drinking = 0.6,
bathroom_sink = 5,
commercial_water = 23.5,
industrial_water = 58.9,
UA_yield = 0.00005,                  #0.00005, 0.0004
UA_electricity_input = 0.00000007,            #0.00000001, 0.00000007
RWH_roof_used = 0,                 #0, 1
```

```
P_recovery = 0,                    #0, 0.58

N_recovery = 0):                    #0, 7.2

##########################   GENERAL    ##############################

   area_residential = area_AMA * 0.092

   area_agriculture = area_AMA * 0.266

   area_infrastructure = area_AMA * 0.034

   area_miscellaneous = area_AMA * 0.177

   area_water = area_AMA * 0.381

   area_commercial = area_AMA * 0.049

   meat_consumption_change = meat_consumption_day - meat_consumption_day_new

### FOOD PRODUCTION

   beef_production = int(beef_production_NL * (beef_AMA / beef_NL))

   pork_production = int(pork_production_NL * (pork_AMA / pork_NL))

   poultry_production = int(poultry_production_NL * (poultry_AMA / poultry_NL))

   sheep_production = int(sheep_production_NL * (sheep_AMA / sheep_NL))

   egg_production = int(egg_production_NL * (eggs_AMA / eggs_NL))

   milk_production = int(milk_production_NL * (milk_AMA / milk_NL))

   fruits_greenhouse_production = int(fruits_greenhouse_production_NL *
(fruits_greenhouse_area_AMA / fruits_greenhouse_area_NL))

   fruits_openground_production = int(fruits_openground_production_NL *
(fruits_openground_area_AMA / fruits_openground_area_NL))

   vegetables_greenhouse_production = int(vegetables_greenhouse_production_NL *
(vegetables_greenhouse_area_AMA / vegetables_greenhouse_area_NL))

   vegetables_openground_production = int(vegetables_openground_production_NL *
(vegetables_openground_area_AMA / vegetables_openground_area_NL))

   cereal_production = int(cereal_production_NL * (cereal_area_AMA / cereal_area_NL))

   potato_production = int(potato_production_NL * (potato_area_AMA / potato_area_NL))

   UA_production = meat_consumption_change * 1.16
```

legume_production = int(legume_production_NL * (legume_area_AMA / legume_area_NL) + UA_production)

meat_production = beef_production + pork_production + poultry_production + sheep_production

dairy_production = milk_production + egg_production

fruit_production = fruits_greenhouse_production + fruits_openground_production

vegetable_production = vegetables_greenhouse_production + vegetables_openground_production

food_production = meat_production + dairy_production + fruit_production + vegetable_production + legume_production + cereal_production + potato_production

FOOD WASTE

total_foodwaste = ((foodwaste_consumer + foodwaste_processing + foodwaste_distribution + foodwaste_production + foodwaste_storage) * inhabitants) / 1000000

FOOD WASTE DESTINATION

foodbank = total_foodwaste * foodbank_fraction

food_to_feed = total_foodwaste * animalfeed_fraction

ANIMAL FEED

beef_animalfeed = beef_feed * beef_production #Feed is per kg

pork_animalfeed = pork_feed * pork_production

poultry_animalfeed = poultry_feed * poultry_production

egg_animalfeed = egg_feed * egg_production

sheep_animalfeed = sheep_feed * sheep_production

milk_animalfeed = milk_feed * milk_production

animalfeed = beef_animalfeed + pork_animalfeed + poultry_animalfeed + egg_animalfeed + sheep_animalfeed + milk_animalfeed - food_to_feed

FOOD CONSUMPTION

potato_consumption = potato_consumption_day * inhabitants * 365

vegetable_consumption = vegetable_consumption_day * inhabitants * 365

meat_consumption = meat_consumption_day_new * inhabitants * 365

legume_consumption = legume_consumption_day * inhabitants * 365

cereal_consumption = cereal_consumption_day * inhabitants * 365

```
    fruit_consumption = fruit_consumption_day * inhabitants * 365

    egg_consumption = egg_consumption_day * inhabitants * 365

    fish_consumption = fish_consumption_day * inhabitants * 365

    dairy_consumption = dairy_consumption_day * inhabitants * 365


    legume_consumption_new = (legume_consumption_day * inhabitants * 365) + (((0.000000101 - meat_consumption_day_new) * 1.16) * inhabitants * 365)

    UA_production = legume_consumption_new - legume_production


### MEAT CONSUMPTION

    poultry_consumption = int(meat_consumption * 0.31)

    beef_consumption = int(meat_consumption * 0.24)

    pork_consumption = int(meat_consumption * 0.45)

    sheep_consumption = int(meat_consumption * 0.01)

### IMPORT/EXPORT

    vegetable_import = vegetable_production - vegetable_consumption

    fruit_import = fruit_production - fruit_consumption

    potato_import = potato_production - potato_consumption

    cereal_import = cereal_production - cereal_consumption

    meat_import = meat_production - meat_consumption

    legume_import = (legume_production + UA_production) - legume_consumption_new

### MANURE

    liquid_manure = (beef_AMA * 0.023) + (pork_AMA * 0.0023) + (poultry_AMA * 0.000068) + (eggs_AMA * 0.000068) + (milk_AMA * 0.012) + (sheep_AMA * 0.0022)

    solid_manure = (beef_AMA * 0.0009) + (pork_AMA * 0.000092) + (poultry_AMA * 0.0000027) + (eggs_AMA * 0.0000019) + (milk_AMA * 0.00064) + (sheep_AMA * 0.000087)

    poultry_manure_energy = ((poultry_AMA * 0.000068) +  (eggs_AMA * 0.000068) + (poultry_AMA * 0.0000027) +  (eggs_AMA * 0.0000019)) * 0.5
```

```
    beef_manure_energy = ((beef_AMA * 0.023) + (beef_AMA * 0.0009) + (milk_AMA * 0.012)+
(milk_AMA * 0.00064)) * 0.5

    pork_manure_energy = ((pork_AMA * 0.0023) + (pork_AMA * 0.000092)) * 0.5

    total_manure = liquid_manure + solid_manure

### FERTILIZER

    fertilizer_use = area_agriculture * fertilizer_use_km2

### LANDUSE UA

    UA_landuse = UA_production / UA_yield

##########################   TRANSPORT    ##############################

    car_fraction = 1 - publictransport_fraction

    distance_car = total_distance * car_fraction

    distance_publictransport = total_distance * publictransport_fraction

    distance_train = distance_publictransport * 0.676

    distance_metrotram = distance_publictransport * 0.216

    distance_bus = distance_publictransport * 0.108

    total_traveled_distance = int(distance_train + distance_car + distance_metrotram + distance_bus)

### CAR FLEET

    individual_cars = cars * 0.896

    commercial_cars = cars * 0.104

    individual_cars_ev_phev = individual_cars * individual_cars_ev_fraction

    individual_cars_phev = individual_cars_ev_phev * 0.87

    individual_cars_ev = individual_cars_ev_phev * 0.13

    individual_cars_fossil = individual_cars - individual_cars_ev

    individual_cars_petrol = individual_cars_fossil * 0.999

    individual_cars_gas = individual_cars_fossil * 0.001

    commercial_cars_ev = commercial_cars * commercial_cars_ev_fraction

    commercial_cars_fossil = commercial_cars - commercial_cars_ev

    commercial_cars_petrol = commercial_cars_fossil * 0.996
```

```
    commercial_cars_gas = commercial_cars_fossil * 0.004

    km_car = distance_car / cars

### FUEL USE

    total_fuel_use_road = int(gasoline_road + lpg_road + diesel_road)

### ELECTRICITY TRANSPORT

    electricity_rail = int((distance_train + distance_metrotram) * electricity_rail_km)

    electricity_EV = ((km_car * individual_cars_ev) + (km_car * commercial_cars_ev)) * 0.16

    electricity_PHEV = (km_car * individual_cars_phev) * 0.08

    electricity_cars = electricity_EV + electricity_PHEV

##########################   ENERGY    ##############################

    residual_waste = ((175 + foodwaste_consumer) * inhabitants) / 1000000

    electricity_transport = electricity_rail + electricity_cars

    electricity_UA = UA_production * UA_electricity_input

    electricity_agriculture_new = electricity_agriculture + electricity_UA

    total_electricity = int(electricity_households + electricity_commercial + electricity_agriculture_new
+ electricity_construction + electricity_industry + electricity_transport)

### RENEWABLE ELECTRICITY

#    wind_energy = int(((installed_windcapacity_land + installed_windcapacity_water) *
full_load_hours) / 1000)

    wind_energy = int(((installed_windcapacity_land) * full_load_hours) / 1000)

    solar_energy = int(installed_solarcapacity * 0.85)

    solar_roof_area = ((installed_solarcapacity * 0.85) / 125)

 #   solar_field_landuse = (installed_solarfieldcapacity * 0.85 * 1000000) / 125

    waste_incineration_elec = residual_waste * 1.02

    biogas_sewage_elec = sewage_sludge * 0.2

    renewable_electricity = wind_energy + solar_energy + biogas_cofermentation +
waste_incineration_elec + biogas_sewage_elec + biomass + landfill_gas_elec

    wind_landuse = (installed_windcapacity_land / 3) * 2000

### FOSSIL ELECTRICITY
```

fossil_electricity = total_electricity - renewable_electricity

coal_electricity = int(fossil_electricity * 0.5)

nuclear_electricity = int(fossil_electricity * 0.42)

naturalgas_electricity = int(fossil_electricity * 0.08)

coal_for_electricity = int(coal_electricity / 2)

naturalgas_for_electricity = int(naturalgas_electricity / 4.7)

uranium = int(nuclear_electricity * 25)

HEAT

elec_demand_change = electricity_households - 2778

households_heat = 32 - (elec_demand_change * 0.016759)

total_heat = agriculture_heat + households_heat + commercial_heat + industry_heat

waste_incineration_heat = residual_waste * 0.76

biogas_sewage_heat = sewage_sludge * 6.6

geothermal_agriculture = geothermal_agriculture_instal * 133.3

geothermal_residential = geothermal_residential_instal * 100

geothermal_landuse = (geothermal_agriculture_instal + geothermal_residential_instal) * 4000

manure_energy = (beef_manure_energy * 0.7) + (pork_manure_energy * 0.6) + (poultry_manure_energy * 7.1)

renewable_heat = waste_incineration_heat + biogas_sewage_heat + biomass_boilers + geothermal + wood_stoves + charcoal + ATES + landfill_gas_heat + decentral_biomass + geothermal_agriculture + geothermal_residential + manure_energy

fossil_heat = total_heat - renewable_heat

########################## CONSTRUCTION ##############################

RAW MATERIALS

granulate_percentage = recyclable_fraction - sorted_waste_percentage

granulate = int(cd_waste * granulate_percentage)

sorted_waste = int(cd_waste * sorted_waste_percentage)

raw_material_import = raw_material_requirements - sorted_waste

metals_import = raw_material_import * 0.025

```
    biomass_import = raw_material_import * 0.05

    minerals_import = raw_material_import * 0.85

    other_import = raw_material_import * 0.075

    copper = int(metals_import * 0.03 + (sorted_waste * 0.125))

    aluminum = int(metals_import * 0.02 + (sorted_waste * 0.125))

    steel = int(metals_import * 0.95 + (sorted_waste * 0.5))

    wood = biomass_import

    glass = int(other_import * 0.93)

    plastics = int(other_import * 0.07)

    bricks = int(minerals_import * 0.03)

    gravel = int(minerals_import * 0.09)

    concrete = int((minerals_import * 0.68) + (0.02 * granulate))

    asphalt = int((minerals_import * 0.2) + (sorted_waste * 0.25))

##########################   WATER   ###############################

    rainwater_AMA = 880

    available_RWH_area = roof_area - solar_roof_area

    RWH_area = (available_RWH_area * 1000000) * RWH_roof_used

    RW_collection = (RWH_area * rainwater_AMA * 0.85 * 0.625) / 1000000000

### WATER USE

    grey_water_households = int(((shower + laundry + dishes + bath + kitchen_sink + food_prep +
bathroom_sink) * inhabitants * 365) / 1000000000)

    black_water_households = int((toilet * inhabitants * 365) / 1000000000)

    residential_water = int(((shower + toilet + laundry + dishes + bath + kitchen_sink + food_prep +
coffee_tea + drinking + bathroom_sink) * inhabitants * 365) / 1000000000)

    agricultural_water = int((companies * average_water_use) / 1000000)

    total_water_use = residential_water + commercial_water + industrial_water + agricultural_water -
RW_collection

##########################   KEY PERFORMANCE INDICATORS
###############################
```

```
KPI_electricity = total_electricity

KPI_electricity_renewable_fraction = (renewable_electricity / total_electricity)

KPI_heat = total_heat

KPI_heat_renewable_fraction = (renewable_heat / total_heat) * 100

KPI_energy = (total_electricity * 3.6) + total_heat

KPI_energy_renewable_fraction = ((renewable_heat + (renewable_electricity * 3.6)) / KPI_energy)

KPI_water = total_water_use

KPI_landuse = geothermal_landuse + UA_landuse + wind_landuse

KPI_construction_selfsufficiency = 1 - (raw_material_import / raw_material_requirements)

KPI_selfsufficiency_meat = meat_import

KPI_selfsufficiency_vegetables = vegetable_import

KPI_selfsufficiency_fruits = fruit_import

KPI_selfsufficiency_cereal = cereal_import

KPI_selfsufficiency_potato = potato_import

KPI_selfsufficiency_legume = legume_import


return {'KPI electricity': KPI_electricity,

    'Renewable electricity fraction': KPI_electricity_renewable_fraction,

    'KPI heat': KPI_heat,

    'Renewable heat fraction': KPI_heat_renewable_fraction,

    'KPI energy': KPI_energy,

    'Renewable energy fraction': KPI_energy_renewable_fraction,

    'KPI water': KPI_water,

    'KPI land use': KPI_landuse,

    'KPI selfsufficiency construction': KPI_construction_selfsufficiency,

    'KPI selfsufficiency meat': KPI_selfsufficiency_meat,

    'KPI selfsufficiency vegetables': KPI_selfsufficiency_vegetables,
```

```
    'KPI selfsufficiency fruits': KPI_selfsufficiency_fruits,
    'KPI selfsufficiency cereal': KPI_selfsufficiency_cereal,
    'KPI selfsufficiency potato': KPI_selfsufficiency_potato,
    'KPI selfsufficiency legume': KPI_selfsufficiency_legume}
]
```

Appendix K: Model code (Maximum scenario)

```
from __future__ import division


def AMA_future_model(

inhabitants = 2410960,

households = 1083799,

avg_household = 2.2,

area_NL = 41543,

area_AMA = 2580,

roof_area = 102.1,

beef_production_NL = 416,

beef_AMA = 6199,

beef_NL = 1179000,

pork_production_NL = 1453,

pork_AMA = 12154,

pork_NL = 1249000,

poultry_production_NL = 1037,

poultry_AMA = 623727,

poultry_NL = 43846000,

sheep_production_NL = 14,

sheep_AMA = 38507,

sheep_NL = 784000,

egg_production_NL = 672,

eggs_AMA = 300499,

eggs_NL = 46212000,

milk_production_NL = 14324,

milk_AMA = 68306,

milk_NL = 3072000,
```

fruits_greenhouse_production_NL = 691,

fruits_greenhouse_area_AMA = 0,

fruits_greenhouse_area_NL = 1600,

fruits_openground_production_NL = 691,

fruits_openground_area_AMA = 1680,

fruits_openground_area_NL = 20367,

vegetables_greenhouse_production_NL = 3511,

vegetables_greenhouse_area_AMA = 24,

vegetables_greenhouse_area_NL = 39100,

vegetables_openground_production_NL = 1270,

vegetables_openground_area_AMA = 708,

vegetables_openground_area_NL = 2300,

cereal_production_NL = 1316,

cereal_area_AMA = 6198,

cereal_area_NL = 175000,

potato_production_NL = 6703,

potato_area_AMA = 3185,

potato_area_NL = 157000,

legume_production_NL = 3,

legume_area_AMA = 4,

legume_area_NL = 1000,

beef_feed = 25,

pork_feed = 6.4,

poultry_feed = 3.3,

egg_feed = 2.3,

sheep_feed = 14,

milk_feed = 25,

```
potato_consumption_day = 0.000000073,
vegetable_consumption_day = 0.000000124,
meat_consumption_day = 0.000000101,
meat_consumption_day_new = 0.000000071,      #0.000000071, 0.000000101
legume_consumption_day = 0.000000004,
cereal_consumption_day = 0.000000192,
fruit_consumption_day = 0.000000122,
egg_consumption_day = 0.000000012,
fish_consumption_day = 0.000000015,
dairy_consumption_day = 0.000000355,
companies = 2150,
average_water_use = 1161,                 #1161, 1689
foodwaste_consumer = 9.5,                 #9.5, 30.7
foodwaste_processing = 4.3,               #4.3, 10.8
foodwaste_distribution = 2.4,             #2.4, 6
foodwaste_production = 7.6,               #7.6, 18.9
foodwaste_storage = 3.2,                  #3.2, 8.1
foodbank_fraction = 0.012,                #0.01, 0.012
animalfeed_fraction = 0.26,               #0.25, 0.26
fertilizer_use_km2 = 180.7,               #180.7, 206.5
total_distance = 22.16,
publictransport_fraction = 0.33,          #0.19, 0.33
individual_cars_ev_fraction = 0.9,        #0.6, 0.9
commercial_cars_ev_fraction = 0.9,        #0.6, 0.9
cars = 678759,                            #678759, 998175
gasoline_road = 720.5,
lpg_road = 41.1,
```

```
diesel_road = 677.4,

electricity_rail_km = 71.9,

fast_charging = 37,

semipublic_charging = 6117,

hydrogenstation = 0,

people_per_trip = 1.5,

average_electricity_households = 3400,

installed_windcapacity_land = 2160,        #327.6, 2160

installed_windcapacity_water = 70011,       #0, 70011

installed_solarcapacity = 2721,           #97.65, 2721

installed_solarfieldcapacity = 9412,       #0, 9412

full_load_hours = 2118,

sewage_sludge = 125,

electricity_households = 3500,            #2778, 3500

electricity_commercial = 5777,

electricity_agriculture = 213,

electricity_construction = 127,

electricity_industry = 3166,

biogas_cofermentation = 2,

biomass = 10,

landfill_gas_elec = 1,

agriculture_heat = 5995,

commercial_heat = 12900,                 #12.9, 14.4

industry_heat = 40400,

biomass_boilers = 1551,

geothermal = 75,

geothermal_agriculture_instal = 6,      #0, 6
```

```
geothermal_residential_instal = 15,       #0, 15
wood_stoves = 868,
charcoal = 33,
ATES = 634,
landfill_gas_heat = 14,
decentral_biomass = 16,
housing_stock = 1122674,
raw_material_requirements = 15040.95,       #in kilotons
cd_waste = 5850,
recyclable_fraction = 0.85,
sorted_waste_percentage = 0.85,            #0.07, 0.85
rainfall_NL = 880,
shower = 48.6,
toilet = 33.7,
laundry = 15.4,
dishes = 6.1,
bath = 2.8,
kitchen_sink = 5.3,
food_prep = 1.4,
coffee_tea = 1.2,
drinking = 0.6,
bathroom_sink = 5,
commercial_water = 23.5,
industrial_water = 58.9,
UA_yield = 0.0004,                         #0.00005, 0.0004
UA_electricity_input = 0.00000001,              #0.00000001, 0.00000007
RWH_roof_used = 1,                     #0, 1
```

```
P_recovery = 0.58,                    #0, 0.58

N_recovery = 7.1):                    #0, 7.2

##########################   GENERAL   ##############################

    area_residential = area_AMA * 0.092

    area_agriculture = area_AMA * 0.266

    area_infrastructure = area_AMA * 0.034

    area_miscellaneous = area_AMA * 0.177

    area_water = area_AMA * 0.381

    area_commercial = area_AMA * 0.049

### FOOD PRODUCTION

    beef_production = int(beef_production_NL * (beef_AMA / beef_NL))

    pork_production = int(pork_production_NL * (pork_AMA / pork_NL))

    poultry_production = int(poultry_production_NL * (poultry_AMA / poultry_NL))

    sheep_production = int(sheep_production_NL * (sheep_AMA / sheep_NL))

    egg_production = int(egg_production_NL * (eggs_AMA / eggs_NL))

    milk_production = int(milk_production_NL * (milk_AMA / milk_NL))

    fruits_greenhouse_production = int(fruits_greenhouse_production_NL *
(fruits_greenhouse_area_AMA / fruits_greenhouse_area_NL))

    fruits_openground_production = int(fruits_openground_production_NL *
(fruits_openground_area_AMA / fruits_openground_area_NL))

    vegetables_greenhouse_production = int(vegetables_greenhouse_production_NL *
(vegetables_greenhouse_area_AMA / vegetables_greenhouse_area_NL))

    vegetables_openground_production = int(vegetables_openground_production_NL *
(vegetables_openground_area_AMA / vegetables_openground_area_NL))

    cereal_production = int(cereal_production_NL * (cereal_area_AMA / cereal_area_NL))

    potato_production = potato_production_NL * (potato_area_AMA / potato_area_NL)

    legume_production = int(legume_production_NL * (legume_area_AMA / legume_area_NL))

    meat_production = beef_production + pork_production + poultry_production + sheep_production

    dairy_production = milk_production + egg_production
```

```
    fruit_production = fruits_greenhouse_production + fruits_openground_production

    vegetable_production = vegetables_greenhouse_production + vegetables_openground_production

    food_production = meat_production + dairy_production + fruit_production + vegetable_production + legume_production + cereal_production + potato_production

### FOOD WASTE

    total_foodwaste = ((foodwaste_consumer + foodwaste_processing + foodwaste_distribution + foodwaste_production + foodwaste_storage) * inhabitants) / 1000000

### FOOD WASTE DESTINATION

    foodbank = total_foodwaste * foodbank_fraction

    food_to_feed = total_foodwaste * animalfeed_fraction

### ANIMAL FEED

    beef_animalfeed = beef_feed * beef_production                              #Feed is per kg

    pork_animalfeed = pork_feed * pork_production

    poultry_animalfeed = poultry_feed * poultry_production

    egg_animalfeed = egg_feed * egg_production

    sheep_animalfeed = sheep_feed * sheep_production

    milk_animalfeed = milk_feed * milk_production

    animalfeed = beef_animalfeed + pork_animalfeed + poultry_animalfeed + egg_animalfeed + sheep_animalfeed + milk_animalfeed - food_to_feed

### FOOD CONSUMPTION

    potato_consumption = potato_consumption_day * inhabitants * 365

    vegetable_consumption = vegetable_consumption_day * inhabitants * 365

    meat_consumption = meat_consumption_day_new * inhabitants * 365

    legume_consumption = legume_consumption_day * inhabitants * 365

    cereal_consumption = cereal_consumption_day * inhabitants * 365

    fruit_consumption = fruit_consumption_day * inhabitants * 365

    egg_consumption = egg_consumption_day * inhabitants * 365

    fish_consumption = fish_consumption_day * inhabitants * 365

    dairy_consumption = dairy_consumption_day * inhabitants * 365
```

legume_consumption_new = (legume_consumption_day * inhabitants * 365) + (((0.000000101 - meat_consumption_day_new) * 1.16) * inhabitants * 365)

UA_production = legume_consumption_new - legume_production

MEAT CONSUMPTION

poultry_consumption = int(meat_consumption * 0.31)

beef_consumption = int(meat_consumption * 0.24)

pork_consumption = int(meat_consumption * 0.45)

sheep_consumption = int(meat_consumption * 0.01)

IMPORT/EXPORT

vegetable_import = vegetable_production - vegetable_consumption

fruit_import = fruit_production - fruit_consumption

potato_import = potato_production - potato_consumption

cereal_import = cereal_production - cereal_consumption

meat_import = meat_production - meat_consumption

legume_import = (legume_production + UA_production) - legume_consumption_new

MANURE

liquid_manure = (beef_AMA * 0.023) + (pork_AMA * 0.0023) + (poultry_AMA * 0.000068) + (eggs_AMA * 0.000068) + (milk_AMA * 0.012) + (sheep_AMA * 0.0022)

solid_manure = (beef_AMA * 0.0009) + (pork_AMA * 0.000092) + (poultry_AMA * 0.0000027) + (eggs_AMA * 0.0000019) + (milk_AMA * 0.00064) + (sheep_AMA * 0.000087)

poultry_manure_energy = ((poultry_AMA * 0.000068) + (eggs_AMA * 0.000068) + (poultry_AMA * 0.0000027) + (eggs_AMA * 0.0000019)) * 0.5

beef_manure_energy = ((beef_AMA * 0.023) + (beef_AMA * 0.0009) + (milk_AMA * 0.012)+ (milk_AMA * 0.00064)) * 0.5

pork_manure_energy = ((pork_AMA * 0.0023) + (pork_AMA * 0.000092)) * 0.5

total_manure = liquid_manure + solid_manure

FERTILIZER

fertilizer_use = area_agriculture * fertilizer_use_km2

```
### LANDUSE UA
    UA_landuse = UA_production / UA_yield
##########################   TRANSPORT    ##############################
    car_fraction = 1 - publictransport_fraction
    distance_car = total_distance * car_fraction
    distance_publictransport = total_distance * publictransport_fraction
    distance_train = distance_publictransport * 0.676
    distance_metrotram = distance_publictransport * 0.216
    distance_bus = distance_publictransport * 0.108
    total_traveled_distance = int(distance_train + distance_car + distance_metrotram + distance_bus)
### CAR FLEET
    individual_cars = cars * 0.896
    commercial_cars = cars * 0.104
    individual_cars_ev_phev = individual_cars * individual_cars_ev_fraction
    individual_cars_phev = individual_cars_ev_phev * 0.87
    individual_cars_ev = individual_cars_ev_phev * 0.13
    individual_cars_fossil = individual_cars - individual_cars_ev
    individual_cars_petrol = individual_cars_fossil * 0.999
    individual_cars_gas = individual_cars_fossil * 0.001
    commercial_cars_ev = commercial_cars * commercial_cars_ev_fraction
    commercial_cars_fossil = commercial_cars - commercial_cars_ev
    commercial_cars_petrol = commercial_cars_fossil * 0.996
    commercial_cars_gas = commercial_cars_fossil * 0.004
    km_car = distance_car / cars
### FUEL USE
    total_fuel_use_road = int(gasoline_road + lpg_road + diesel_road)
### ELECTRICITY TRANSPORT
```

```
   electricity_rail = int((distance_train + distance_metrotram) * electricity_rail_km)

   electricity_EV = ((km_car * individual_cars_ev) + (km_car * commercial_cars_ev)) * 0.16

   electricity_PHEV = (km_car * individual_cars_phev) * 0.08

   electricity_cars = electricity_EV + electricity_PHEV

##########################   ENERGY    ##############################

   residual_waste = ((175 + foodwaste_consumer) * inhabitants) / 1000000

   electricity_transport = electricity_rail + electricity_cars

   electricity_UA = UA_production * UA_electricity_input

   electricity_agriculture_new = electricity_agriculture + electricity_UA

   total_electricity = int(electricity_households + electricity_commercial + electricity_agriculture_new
+ electricity_construction + electricity_industry + electricity_transport)

### RENEWABLE ELECTRICITY

#    wind_energy = int(((installed_windcapacity_land + installed_windcapacity_water) *
full_load_hours) / 1000)

   wind_energy = int(((installed_windcapacity_land) * full_load_hours) / 1000)

   solar_energy = int(installed_solarcapacity * 0.85)

#    solar_energy = int((installed_solarcapacity + installed_solarfieldcapacity) * 0.85)

   solar_field = installed_solarfieldcapacity * 0.85

   solar_roof_area = ((installed_solarcapacity * 0.85) / 125)

   #solar_field_landuse = (installed_solarfieldcapacity * 0.85 * 1000000) / 125

   waste_incineration_elec = residual_waste * 1.02

   biogas_sewage_elec = sewage_sludge * 0.2

   renewable_electricity = wind_energy + solar_energy + biogas_cofermentation +
waste_incineration_elec + biogas_sewage_elec + biomass + landfill_gas_elec

   wind_landuse = (installed_windcapacity_land / 3) * 2000

### FOSSIL ELECTRICITY

   fossil_electricity = total_electricity - renewable_electricity

   coal_electricity = int(fossil_electricity * 0.5)

   nuclear_electricity = int(fossil_electricity * 0.42)
```

```
    naturalgas_electricity = int(fossil_electricity * 0.08)

    coal_for_electricity = int(coal_electricity / 2)

    naturalgas_for_electricity = int(naturalgas_electricity / 4.7)

    uranium = int(nuclear_electricity * 25)

### HEAT

    elec_demand_change = electricity_households - 2778

    households_heat = 32 - (elec_demand_change * 0.016759)

    total_heat = agriculture_heat + households_heat + commercial_heat + industry_heat

    waste_incineration_heat = residual_waste * 0.76

    biogas_sewage_heat = sewage_sludge * 6.6

    geothermal_agriculture = geothermal_agriculture_instal * 133.3

    geothermal_residential = geothermal_residential_instal * 100

    geothermal_landuse = (geothermal_agriculture_instal + geothermal_residential_instal) * 4000

    manure_energy = (beef_manure_energy * 0.7) + (pork_manure_energy * 0.6) +
(poultry_manure_energy * 7.1)

    renewable_heat = waste_incineration_heat + biogas_sewage_heat + biomass_boilers + geothermal
+ wood_stoves + charcoal + ATES + landfill_gas_heat + decentral_biomass + geothermal_agriculture +
geothermal_residential+ manure_energy

    fossil_heat = total_heat - renewable_heat

##########################   CONSTRUCTION   ##############################

### RAW MATERIALS

    granulate_percentage = recyclable_fraction - sorted_waste_percentage

    granulate = int(cd_waste * granulate_percentage)

    sorted_waste = int(cd_waste * sorted_waste_percentage)

    raw_material_import = raw_material_requirements - sorted_waste

    metals_import = raw_material_import * 0.025

    biomass_import = raw_material_import * 0.05

    minerals_import = raw_material_import * 0.85

    other_import = raw_material_import * 0.075
```

```
    copper = int(metals_import * 0.03 + (sorted_waste * 0.125))
    aluminum = int(metals_import * 0.02 + (sorted_waste * 0.125))
    steel = int(metals_import * 0.95 + (sorted_waste * 0.5))
    wood = biomass_import
    glass = int(other_import * 0.93)
    plastics = int(other_import * 0.07)
    bricks = int(minerals_import * 0.03)
    gravel = int(minerals_import * 0.09)
    concrete = int((minerals_import * 0.68) + (0.02 * granulate))
    asphalt = int((minerals_import * 0.2) + (sorted_waste * 0.25))
##########################   WATER    ##############################
    rainwater_AMA = 880
    available_RWH_area = roof_area - solar_roof_area
    RWH_area = (available_RWH_area * 1000000) * RWH_roof_used
    RW_collection = (RWH_area * rainwater_AMA * 0.85 * 0.625) / 1000000000
### WATER USE
    grey_water_households = int((((shower + laundry + dishes + bath + kitchen_sink + food_prep +
bathroom_sink) * inhabitants * 365) / 1000000000)
    black_water_households = int((toilet * inhabitants * 365) / 1000000000)
    residential_water = int((((shower + toilet + laundry + dishes + bath + kitchen_sink + food_prep +
coffee_tea + drinking + bathroom_sink) * inhabitants * 365) / 1000000000)
    agricultural_water = int((companies * average_water_use) / 1000000)
    total_water_use = residential_water + commercial_water + industrial_water + agricultural_water -
RW_collection
##########################   KEY PERFORMANCE INDICATORS
##############################
    KPI_electricity = total_electricity
    KPI_electricity_renewable_fraction = (renewable_electricity / total_electricity)
    KPI_heat = total_heat
```

```
KPI_heat_renewable_fraction = (renewable_heat / total_heat)

KPI_energy = (total_electricity * 3.6) + total_heat

KPI_energy_renewable_fraction = ((renewable_heat + (renewable_electricity * 3.6)) / KPI_energy)

KPI_water = total_water_use

KPI_landuse = geothermal_landuse + UA_landuse + wind_landuse

KPI_construction_selfsufficiency = 1 - (raw_material_import / raw_material_requirements)

KPI_selfsufficiency_meat = meat_import

KPI_selfsufficiency_vegetables = vegetable_import

KPI_selfsufficiency_fruits = fruit_import

KPI_selfsufficiency_cereal = cereal_import

KPI_selfsufficiency_potato = potato_import

KPI_selfsufficiency_legume = legume_import


return {'KPI electricity': KPI_electricity,

    'Renewable electricity fraction': KPI_electricity_renewable_fraction,

    'KPI heat': KPI_heat,

    'Renewable heat fraction': KPI_heat_renewable_fraction,

    'KPI energy': KPI_energy,

    'Renewable energy fraction': KPI_energy_renewable_fraction,

    'KPI water': KPI_water,

    'KPI land use': KPI_landuse,

    'KPI selfsufficiency construction': KPI_construction_selfsufficiency,

    'KPI selfsufficiency meat': KPI_selfsufficiency_meat,

    'KPI selfsufficiency vegetables': KPI_selfsufficiency_vegetables,

    'KPI selfsufficiency fruits': KPI_selfsufficiency_fruits,

    'KPI selfsufficiency cereal': KPI_selfsufficiency_cereal,

    'KPI selfsufficiency potato': KPI_selfsufficiency_potato,
```

'KPI selfsufficiency legume': KPI_selfsufficiency_legume}