MSc Program
Environmental Technology & International Affairs

The Introduction of E-Mobility in Austria from a Resource Perspective

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, **NICHOLAS PERPMER**, hereby declare

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Abstract

50% of the resources that have ever been consumed by human kind, have been consumed during the last 25 years. A major part of that is made up by the resource consumption related to traffic. This is mainly due to the skyrocketing demand for oil. However, the material consumption of traffic does not only include oil, but also the resources needed to produce a car. In the last couple of months, the issue of electro mobility raises more and more awareness. A lot of research has been done in the area of emission reduction and energy input of electric cars. However, there is hardly any research about the resource consumption of electric cars. This thesis tries to overcome this gap by investigating how material consumption in the model region (Austria) would change if a society switches to electro mobility.

In order to reach this target, the following 4 steps are necessary. First of all, two scenarios are created, one reflecting the status quo (assumption 100% gasoline cars), the other one assuming that the whole society drives electric cars. To show this graphically and quantitatively, four "Material Flow Analyses" (MFA) are performed. The next step aims at collecting data in order to quantify the two scenarios. Subsequently, the major differences in material input, output and stock of the two scenarios are indicated. This will finally lead to the answering of the question raised above in the first paragraph.

Finally, the following results are obtained: In Austria, a total switch to electric mobility would decrease the material inputs into the system (defined as Austria) from 13.730kg to 58kg per capita and year. The output would shrink from 13.680kg to 0.5 kg per capita and year. In contrast, the stocks would slightly increase from 56,2 kg to 57,2 kg per capita and year. Furthermore, if only the materials for the production of a car are taken into account, the most important materials are ferrous metals (66%), plastics (11%) and non-iron metals (8%) for conventional mobility. This would change for the scenario of electro mobility. In fact, ferrous metals become less important (54%), and plastic (13%) as well as non-iron metals (24%) get more significant. The reason for that is that engineers try to compensate the heavy batteries with lighter material such as plastics and aluminium (non-iron metals).

Acknowledgements

First of all, I would like to thank my supervisor, Prof. Paul H. Brunner, that he navigated me to this topic. I always wanted to write something about electric cars, proposing to investigate the topic from a resource point of view was the perfect decision. Furthermore, I want to thank all my colleagues of ETIA8 that made the two years so special. I would like to thank also Prof. Puxbaum and his assistants who were always caring about us.

A very special thanks goes to my parents. They have accompanied me for the last 18 years of education and for the last 24 years of my life. They were always an immensely important backup and I could always consult them in any case of urgent problems. The last 18 years of education have formed my personality and were decisive for the person I am today.

Moreover, I would like to thank all my friends who have accompanied me through life. Without those friends and colleagues, life would have not been the same. I would like to keep the balance between studying /working and free time as I have managed this so far and I think this is crucial for a happy life. The pursuit of happiness, I think a state that every human kind is aiming for. I hereby want to cite Albert Schweizer who said

> "Happiness is the only thing that doubles if you share it"

I would like to share this thesis and the end of my master's degree with my family, all my friends and all the people that I will meet in the future and last but not least, with all the people that have not had so much luck as myself. I hope I can contribute to something good in the future!

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1. Introduction

1.1 Problem/Relevance

The Paris conference 2015 ended with an ambitious goal, namely limiting global warming to 1,5°C. In particular, the European Union revealed that it aims at reducing carbon dioxide emissions by at least 40% by 2030, in order to achieve the global temperature goal (European Commission, 2016). However, if the stated goals are closely investigated, it has to be mentioned that it will be really hard to achieve those in practice.

A major part of the climate problem is directly related to transport. According to the International Energy Agency (IEA), one fifth of global carbon dioxide emissions is emitted by the transport sector. Additionally, it is stated that this share could double by 2050, mainly due to a strong increase in private cars in emerging markets like China, India or Brazil (IEA, 2015). In order to achieve better air quality in major cities, it is widely accepted that a shift to electric cars would be the solution. The issue of CO2 emissions is a different story, because it is crucial for the emission balance of electric cars how the electricity was produced. If 100% of a country's electricity were produced with coal, the CO2 emission would rise substantially with an introduction of e-mobility. In fact, one had lower emissions in inner cities, but the pollution would be transferred to the regions where electricity is produced. (Ly et al., 2012)

This thesis focuses on the electric mobility introduction in Austria. As Austria's electricity mix is based on 76% renewable energies, it would make perfectly sense for this country to encourage its population to switch to electric cars from an emission point of view (IEA, 2014). The figure below compares the greenhouse gas emissions in Austria between petrol cars and electric cars along their whole life-cycle, using the current electricity mix in Austria, which is as follows (IEA, 2014):

- 24% fossil fuels
- 10% wind, biomass, photovoltaic, geothermal power plants
- 66% hydro power

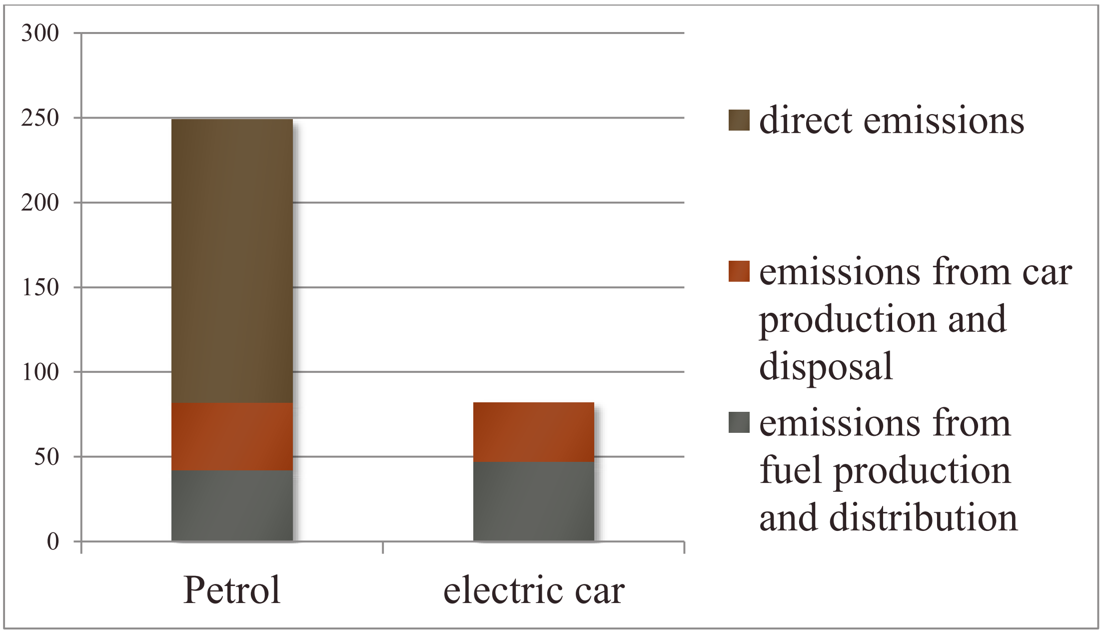

FIGURE 1: GREEENHOUSE GAS EMISSIONS GASOLINE-DRIVEN CAR VS. ELECTRIC CAR (PÖTSCHER ET AL., 2014)

This means that a tremendous reduction of emissions would be the consequence of the introduction of electric mobility in Austria. However, the authorities are still lacking behind from pioneers like Norway or the Netherlands where more than 20% of new car sales are electric ones (New York Times, 2015). In fact, Norway recently published its transport plan until 2029, where it says that it wants to ban diesel and petrol cars after 2025 (Nasjonal Transportplaner, 2016). Furthermore, sales figures show that the trend towards electric cars has set in globally, showing yearly growth rates of 60% (Thiel et al., 2015).

As a consequence of this change, a reduction of air pollution and emission reductions can be expected. Nevertheless, for an overall scientific and sustainable assessment of the environmental performance of electric cars, it is necessary to do a comprehensive study including not only energy resources, but also materials resources along the whole lifecycle of a car (Henßler et al., 2016). Writing about resources lead to the necessity to mention that 50% of the resources that have ever been consumed by human kind, have been consumed during the last 25 years. It does not wonder that traffic plays a major part in that development. It is clear that the immense growth of oil demand is mainly responsible for that. However, also the car fleet becomes always bigger. In Austria, the number of cars in use has doubled during the last three decades. Referring back to electro mobility leads to the question what impact do electric cars have on the development of material consumption?

Since this area of research has not been investigated in depth so far, this thesis wants to raise more awareness for this issue.

1.2 State of the art

In order to reduce resource consumption, recycling and reuse efforts are key and have to be improved. As a result, there have recently been some changes in the recycling and reuse policy of the European Union. In fact, the legislation has become more stringent. Since Austria is part of the European Union, the authorities are required to implement stricter rules for reuse and recycling as well. In the European Union, end-of-life vehicles generate between 8 and 9 million tonnes of waste every year (EUR-Lex, 2015). Therefore, the EU set several regulatory measures to secure a high degree of reuse and recycling which are valid since 2015. The main points of the directive 2000/53/EC are stated below (Eur-Lex, 2015):

- ELV have to be reused or recycled to a degree of 85% by their weight
- ELV have to be reused or recovered to a degree of 95% by their weight
- New vehicles must not include heavy metals like lead, mercury, cadmium and hexavalent chromium
- Main attention is on recycling, reuse and recovery
- Not more than 5% of the weight of a car are allowed to be disposed of on a landfill,
- A maximum of 10% of the weight of a car are allowed to be burned as shredder residue in an incineration
- Passenger car vehicles and small trucks are affected by the legislation

What research has been done in the area of resource consumption of electric cars and conventional cars? There are studies which focused on the comparison of gasoline and plug-in hybrid cars as well as a study by the Environmental Agency Austria, which compared electric cars and conventional cars in their material composition. What is new in this thesis will be stated below.

1.3 Goals of the research and research questions

The need for material efficient production and high recycling rates becomes always more important, also in connection to the climate goals as it was stated under 1.1. In order to achieve that goals, information about the use of materials, the used technologies and goods are crucial. The core of this thesis is to show the consequences for the demand on materials/goods after the introduction of a new technology – namely electro mobility! The main goal is to compare the resource footprint of traditional mobility and electro mobility in a model region (Austria).

In order to get useful results, the two baseline scenarios, traditional and electro mobility, shall be analysed and compared:

1. Scenario 1 (status quo): Due to limited time and capacity for this master thesis, the current car fleet of Austria shall be simplified by assuming that Austrians drive only petrol cars.
2. For the 2nd scenario we assume that Austrians drive only with electric cars (Austria's car fleet 100% electro).

The analysis of the good/material flows will be done based on four "Material Flow Analyses" (Baccini and Brunner, 2012) for the two scenarios mentioned above. This is done in order to be able to compare the different material inputs, outputs, stocks and flows for the two scenarios of our model region Austria. Before we can apply the model, the two following questions shall lead us to the answering of the two main research questions:

- What material flow system describes the traditional (petrol-driven) and electric mobility?

- Which data do I need to quantify those systems?

The country where the model shall be applied and where the research shall be done is Austria, because it is the perfect country for electro mobility due to its high degree of renewable energies. The resource analysis shall create a holistic view of the environmental performance of electric cars. In order to be able to focus on the main points the following research questions were chosen:

> "What are the most important differences for the material input, output and stock, comparing traditional mobility and electro mobility?"
>
> "How does the material consumption per capita change if electric mobility is introduced in the model region Austria?"

The main purpose of the thesis is to answer this questions in the 3rd chapter. All the things which are going to be dealt with are aiming at answering the question from a holistic point of view.

1.4 Structure

After this introductory chapter, the thesis is mainly composed of 2 parts. Firstly, in the 2nd chapter, the basic MFA is introduced and the different processes, stocks and flows are described. This is done in order to show how to illustrate traditional and electro mobility in a material flow system. Then, the data, which is crucial in order to quantify the various MFAs, is presented, and limitations are portrayed. Subsequently, in chapter 3, the two different scenarios are illustrated through 4 MFAs. This aims at answering the two research questions that were mentioned above. At the end, some critical views regarding the results are raised. Finally, the 4th chapter provides the conclusion with the summary of the findings.

The appendices include background information relating to the composition of gasoline cars and electric cars respectively.

2. Methodology

2.1 Material Flow Analysis

In order to be able to illustrate the life cycle of a car and to analyse the material inputs, outputs and stocks, the Material Flow Analysis (Baccini and Brunner, 2012) is used with the help of the STAN software (STAN, 2016), which was developed in order to do MFAs on a large-scale basis.

In the beginning, the system boundary was designed for this MFA. It shows the life cycle of a car in Austria from the moment when it is registered to the stage when the residues are disposed of as “Automotive Shredder Residue” (ASR) on a landfill or burned in a waste-to-energy plant. Since the scheme, meaning the different processes and flows, are the same for all the MFAs performed in the following two chapters, they are described here below only once. In the next subchapter 2.2, the data is presented and limitations are stated.

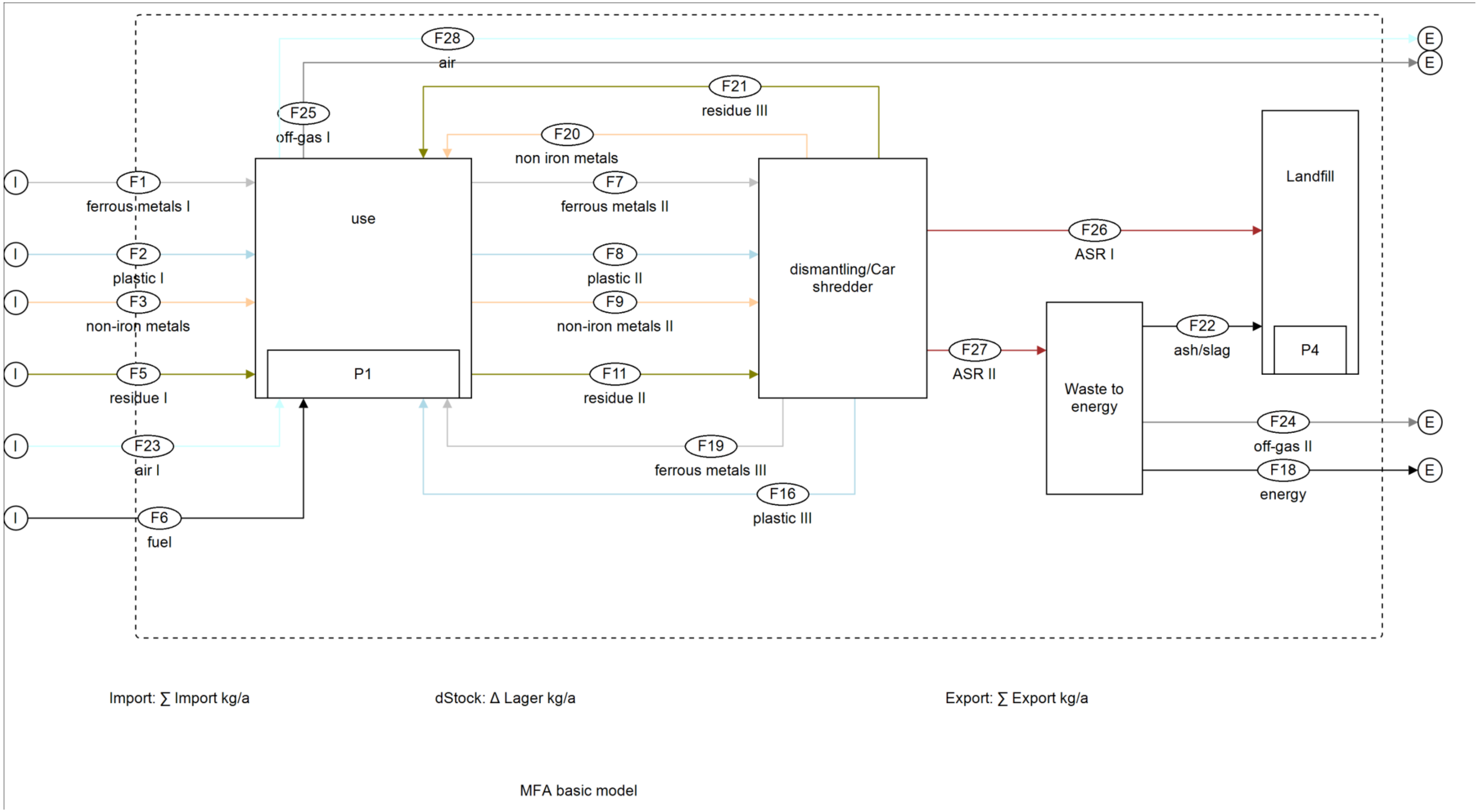

FIGURE 2: THE BASIC MFA

2.1.1 Processes, stocks

Production/use (P1)

This process describes the use phase of a car in Austria, meaning the time period from the registering to the deregistering stage. It has a stock which describes the amount of material that is contained in the current car fleet of Austria. The *imports,* which enter the system and then *use* (*P1)* as inflows*,* reflect the 3 most important materials of a car, the remaining residual materials, the combustion air and the fuel:

- *(F1) ferrous metals I*
- *(F2) plastic I*
- *(F3) non iron metals I*
- *(F4) residue I*
- *(F5) fuel I*
- *(F23) air*

Furthermore, there are the recycling/reuse inputs from the dismantling/shredder process, which are *(F16) plastic II, (F19) ferrous metals II, (F20) non-iron metals II, (F21) residue II*. It is assumed that the recycled materials are used again in the use phase in Austria. The process is not called use/production because it would make the whole MFA too complicated for this thesis, for instance the off-gas calculation.

Moreover, the outputs from the process *(P1) use* are amounts of materials which are contented in the end of life vehicles – *(F7) ferrous metals II, (F8) plastic II, (F9) non-iron metals II and (F11) residue II.* Additionally, the remaining output from (*P1)* is the *off-gas I (F25)* which is emitted during the use phase of a car. (F28) air, is the remaining combustion air that leaves the exhaust pipe.

Dismantling/car shredder (P2)

In general, old cars come through 3 different ways into the recycling stage. 80/85 % go to end of life vehicle distributors, scrap merchants collect 10 to 15 % and 5% is delivered directly to shredder companies. The first step is the drainage, where the car is cleaned from all service fluids. As a next step, the tires, catalysts and the battery is removed. After that step, the car has approximately 60% of its original weight. Afterwards, the shell of a car as well as the cooler and the powertrain go to the shredder (Vermeulen et. al, 2011). The input into this process stems from (*F1) ferrous metals II,* *(F8) plastic II, (F9) non-iron metals II and (F11) residue* and describes the material amount which comes from end of life vehicles.

The shredder process generates these 3 different groups of materials:

- Ferrous metals (iron, steel) – (65-70% by mass)
- Non-iron metals (aluminium, copper, lead, magnesium, zinc, nickel) - (65% by mass)
- ASR (plastics, glass, rubber, foam, textiles) – (20-25% by mass)

The different materials are sorted through different mechanical steps. The so-called air clarifier generates a "shredder light fraction" (SFR) mainly consistent of plastic, paper, textiles and leather. This accounts up to approximately 15-22% of a car. After the air clarifier comes a magnet which separates the steel and iron fraction from the rest of the materials. The share of this content is 70 to 75%. The residue is called shredder heavy fraction and contains 40-45% non-iron metals and 50 to 60% non-metals like wood, rubber and plastic. Another separation step separates the metals from the non-metals. The metals can be reused or recycled and leave the process with flows *ferrous metals (F19)* and *non-iron metals (F20)*. (Vermeulen et al., 2012)

The remaining output of the shredder stage leave the process through *ASR I (F26)* and *ASR II (F27).*

Waste to energy (P3)

The *waste to energy process (P3)* transfers the inflow *(F27) ASR II* to the outflow (*F22) ash/slag*, to the export *(F24) off-gas II* and to the outflow *(F18) energy I*. The energy flow will be 0, because we cannot describe energy as a mass flow. This is the case because ASR is composed of very heterogeneous material and therefore difficult to recycle and to recover mechanically. The process *(P3) waste-to-energy* is an economical and environmental alternative to *landfilling (P4)*. In Austria, 80,42 % of ASR is incinerated. As it was mentioned under 1.2, since 2015, the share of ASR from which energy is recovered must not exceed 10% of the original vehicle weight (EU-Directive 2000/53/EC). Therefore, the amount of ASR which is burned in Austria has decreased during the last years, from 8500t in 2011 to 6500t in 2013 (Eurostat, 2016). Actually, ASR can be burned in grate furnaces, rotary kilns or fluidized beds, where the

ASR is usually mixed with municipal waste before it gets into the furnace. Furthermore, ASR could also be burned in cement kilns, however, for that, the fuel has to be upgraded which makes it less common. (Van Caneghem et al., 2011)

Landfill(P4)

The process *(P4) landfill* gets inflows *(F26) ASR I and (F22) ash*. The former is the amount of ASR which is directly landfilled per year in Austria. The latter represents the ash which is landfilled after burning of *ASR II (F27).* Since there is neither an outflow nor an export a stock arises in this process. The stock contains the "Shredder Light Fraction" (SLF) and other materials arising from shredding. (Eurostat, 2016). These are composed of organic substances like plastics and elastomers, natural products such as wood, leather and fibres and inorganic materials including dust and glass for instance. (European Commission, 2016). Overall, an average of 19,58% of ASR goes to the *landfill P4* in Austria. Traditionally, the amount of ASR has been landfilled to a degree of 100%. The EU-Directive 2000/53/EC states that only 5% of a vehicles total weight shall be landfilled.

2.1.2 Flows

Import Ferrous metals (F1)

The import of *ferrous metals I (F1)* comprises different kinds of steel and cast iron which are part of a car. Whereas this fraction was higher in the past, the trend goes towards lighter materials and manufacturers use less steel and avoid cast iron if possible (Renault, 2016). Furthermore, due to high pressure that vehicles have to become lighter in order to reduce fuel use and emissions, higher-strength steel gets more important. This kind of steel is thinner, therefore lighter, and also easier formable (Panich et. al, 2014). The import *ferrous metals I (F1)* enters the process *use (P1)*, where it stays until the car becomes an end-of-life vehicle.

Import plastic I (F2)

The import flow *plastic I (F2)* includes all kinds of plastics which are used in a car. The use of plastic becomes always more important, because it is light and mouldable. These two features are crucial due to increasing efforts to reduce weight for fuel and emission decrease as we heard before. The main plastics that are included in this flow are polypropylene - PP (26%), Polyamid - PA (15%) and polyurethane - PUR (15%). They are mainly part of the interior (49%), exterior (20%), tank (20%) and in the electrics/lights (11%) (Schelker and Geisslehardt, 2008). After entering the system boundary, the flow goes to the process *use (P1)* where it remains until the car gets an ELV.

Import non-iron metals I (F3)

The third most important components of a car are *non-iron metals (F3)*. As *(F2) plastic*, it gains of importance due to its lightness in comparison to ferrous metals. If one takes a closer look to the composition of this flow, it can be seen that aluminium is by far the most important component (approximately 50%). Other crucial metals are copper (electrics) and lead (battery) (Appendix II). There are of course many more metals in use, however, the quantity per car is very small. Like the other import flows, flow *non-iron metals I (F3)* enters the process *use (P1)*, too.

Import residue I (F5):

The import flow *residue I (F5)* includes all the materials of a car which can not be classified under one of the other import flows mentioned before. The most significant constituents are glass, rubber, service fluids, textiles and wood. This part accounts up to 15% of the weight of a car. As the demand for sustainable and environmentally friendly materials increases, components like wood or textile get more important. The BMW i3, an electric car, uses for example no cast iron and only a bit of steel, instead carbon fibre is used for the whole shell of the car (BMW, 2016). An immense change from ferrous metals to residue would be the consequence. However, traditional car makers like Renault say that carbon is too expensive and not as usable and secure as steel. If there is a small scratch in the carbon shell, the whole shell has to be exchanged as there are no replaceable components available as for steel (Hellwig, 2016). The import flow *residue I (F5)* enters the process *use (P1).*

Import fuel (F6)

The import flow *fuel (F6)* describes the fuel type which is used for the two scenarios. On the one hand, for traditional mobility it was mentioned (1.3) that it is assumed that Austria's car fleet comprises only gasoline cars. In the MFA Scenario1, the fuel is therefore gasoline which is consumed per year for the current car fleet in Austria. On the other, illustrating electric mobility in the MFA Scenario 2 leads to the fact that the fuel is energy (electricity). As energy is not a mass flow it cannot be depicted in this model and exhibits therefore the value 0. The import *fuel (F6)* enters the process *use (P1)* as it is necessary to run a car.

Import air (F23)

During the burning of gasoline in the motor, air is sucked from outside. The amount of air that is needed is illustrated through this flow. It enters the system boundary, since the atmosphere was not included, and enters the process *use (P1)* as it is used during running a car.

Flow *ferrous-metals II (F7)*

This flow represents an outflow as well as an inflow. Firstly, it is an outflow from process *use (P1)*, meaning the sum of ferrous metals included deregistered end-of-live vehicles in Austria. Secondly, it is an inflow of the process *dismantling/car shredder (P2)*, as it is assumed that the amount of deregistered end-of-life vehicles go through the dismantling and shredder process.

Flow *plastic II (F8)*

This is the amount of plastic which leaves process *use (P1)* as outflow, and enters process *dismantling/car shredder (P2)* as inflow. According to the previous flow, this is the amount of plastic which is part deregistered end-of-life cars in Austria.

Flow *non-iron metals II (F9)*

The output *non-iron metals II (F9)* from the *use phase (P1)* depicts the amount of non-iron metals which is content deregistered end-of-life vehicles in Austria. Additionally, this flow is also an input into the process *dismantling/car shredder (P2)*, since the cars are disassembled by different companies.

Flow *residue II (F11)*

All the other components that leave the use stage *(P1)* as deregistered end-of-life vehicles are comprised in this flow. Simultaneously, this output is also an inflow into the process *dismantling/car shredder (P2)* and represents the residue material which has to be treated by recycling/shredder companies.

Export off-gas I (F25)

The *off-gas I flow (F25)* describes the CO2-equivalent emissions during the use phase of a car in Austria. It shows an average value of emissions generated by street traffic of the years 2013 and 2014. This is the reason why the flow leaves process *use (P1)* and it leaves the system *boundary Austria* as an export, since the atmosphere is not included in the system. In particular, there is a huge problem due to the missing sink for CO2-emissions, which led to the problem of global warming (Baccini and Brunner, 2012).

Export air (F28)

This is the remaining amount of air which was used by the engine, however, which does not leave the exhaust pipe as pollution (amount of CO2). It leaves the system boundary as it is emitted into the atmosphere.

Flow ferrous metals III (F19)

This flow shows the recycling/reuse flow of ferrous metals. In particular, during the process *dismantling/car shredder (P2)* the ferrous metals are removed in the dismantling stage and also after the car shredder the ferrous metals are separated from the other materials. Therefore, the metals arrive at the use phase at different times. Due to lack of time for this master thesis, it is assumed that they enter the use phase at the same time again. Furthermore, actually some of them are reused, some of them are recycled and enter the production phase. For further matter of simplification, we assume that they enter the process *use (P1)* again. The recycling rate for ferrous metals in passenger cars is nearly 100% nowadays (Gruden, 2008).

Flow plastic III (F16)

It can be seen that flow *plastic III (F16)* leaves process *dismantling/car shredder (P2)* and enters *use (P1)*. So this is the amount of plastic which arises after (*P2)* and is recycled and later reused in the use phase of a car. The same simplifications are valid as for the previous flow *(F16)*. The recycling rate is on average only 11%. What makes it really difficult to recycle plastics is that they are contaminated with different substances such as oil. In addition, it is often not economically feasible to recycle plastic, because the market price of some plastics (for example PUR) is very low. The main obstacles for recycling is the lack of market for recyclables, the missing infrastructure and a knowledge gap between car producers, recycling companies and customers. (Miller et al., 2014)

Flow non-iron metals III (F20)

The share of non-iron metals in a car is also recycled to a very high degree. The literature reflects an average recycling rate of 90% per cent. If the reuse and recovery rate also of ASR is added, the value is close to 100% which lead to the fact that 0% of non-iron metals are neither disposed of nor incinerated. In fact, as seen under flow *non-iron metals II (F9)*, aluminium is the most important metal in this group. So the recycling rate of the whole column is dependent on the one of aluminium. As aluminium is immensely energy intensive in its production, the recycling rate has been constantly growing (Jochem et al., 2004). Like all the other recycling flows, this flow goes from the process *dismantling/car shredder (P2)* to *use (P1).*

Flow residue III (F21)

The remaining recycling/reuse/recovery flow is the one of all the other materials which are not part of one of the other material groups. As mentioned before, the most important materials are glass, textiles, service fluids and rubber. Since it is very hard to establish all the recycling/reuse/recovery rates of all the materials and to add them up, the difference of the amount of materials of *ASR I (P26)* and *ASR II (F27)*, and the sum of the remaining recycling flows *(F19), (F16), (F20)* were compared. This leads to a recycling rate of around 95%. The flow leaves process *dismantling/car shredder (P2)* and ends in *use (P1).*

Flow ASR I (F26)

After the process *dismantling/car shredder (P2)*, there is an outflow of *ASR I (P26)*. As already explained under *(P2)* the product that is generated in a shredder and separated from ferrous and non-iron metals, which are also shredder products, is called automotive shredder residue (ASR). In Europe, ASR is classified as hazardous waste. Furthermore, ASR accounts for 20-25% by mass. According to Nourreddine (2007) ASR is a mix of plastic (19–31%), rubber (20%), textiles, fibre materials (10–42%) and wood (2–5%). This fraction is contaminated with metals (8%), oils (5%), and other also hazardous substances (about 10%), for instance PCB, cadmium and lead. The flow ASR I (P26) depicts the amount of ASR which goes directly to the *landfill (P4).* In Austria, an average of 19,58% of ASR were landfilled between 2011 and 2013. According due to European law, the share of the material, which is landfilled, must no exceed 5% of the mass of a car (2000/53/EC).

Flow ASR II (F27)

The content of the material of flow *ASR II (F27)* is the same as *ASR I (F26)* and it is an outflow from process *dismantling/car shredder (P2)* as well. However, it is an inflow into process *waste-to-energy (P3).* The material is often mixed with municipal waste and then burned in a furnace where energy is generated out of the gas flow (Vermeulen et al., 2011).

Flow ash/slag (F22)

During the burning of ASR, ash and slag is generated which is landfilled afterwards. This flow describes exactly this process, namely the outflow of the *waste-to-energy (P3)* plant and its inflow into the *landfill (P4).* The average ash content of ASR is 42%. (Van Caneghem et al., 2010)

Flow energy (F18)

This is the amount of energy which is generated through the burning of ASR. Since an energy flow is not a mass flow, its value is 0 in our mass flow system.

Export off-gas (F24)

This export flow illustrates the flue gas which is generated from burning ASR. The main components of the flue gas are CO2, NOx, SO2, HCl, some non-iron metals, mercury and cadmium. There are also furans and dioxins in the flue-gas, however, for those substances is no current data available. This flow leaves the system boundary as the atmosphere was not included in the system. (Vermeulen et al., 2012)

After the description of all the processes and flows, the main data for the MFAs in the 3rd chapter is presented and limitation factors are indicated.

2.2 Data/resources/ uncertainty

The data for the composition of gasoline cars and electric cars come from several different sources. As there was enough data for gasoline cars, it was rather hard to get data for electric cars. In fact, several European automobile manufacturers and experts were contacted and they did not provide any specific data on the composition of cars, as this falls under their secrecy policy. However, through different studies and professors it was possible to get information on which this thesis is based now. The following data are the basis for the whole work. The specific tables where this data is based on can be found in the appendices (Appendix II). In addition, important data about the Austrian car market as well as data for the waste management phase (w-t-energy, landfill) is depicted.

2.2.1 Material composition of gasoline and electric cars

First of all, it is very important to distinguish between two types of e-cars. On the one hand, the conventional car with a combustion engine was taken, such as the Renault Kangoo or the VW Golf and they were transformed into an electric version. In fact, those cars are completely identical except for the powertrain. On the other, there are electric cars that were designed as such starting from the development stage. For instance, most prominent in this category are Renault Zoe, Nissan Leaf or Tesla.

In order to establish the weight basis for the two MFA scenarios, electric mobility and conventional mobility, the two different e-car categories were compared with their gasoline driven counterparts. The results are interesting, showing that the Renault Kangoo electro is with 1501 kg heavier than the conventional one with 1355 kg. The main reason for that is the battery in the e-car which weighs 250kg. According to a technician of Renault, the battery is composed of around 40% ferrous metals, approximately 40% aluminium and 20% copper. Lithium which is often discussed as a critical material in the media accounts for only about 1% of the battery. (Hellwig, 2016)

How does the weight differ for a car which was exclusively constructed as an electric one? The Renault Zoe is such a car and is compared here with the Renault Cloe 4, because they are of the same size. Once again, the electric car is the heavier one with 1503kg, whereas the gasoline version of the Cloe 4 weighs only 1279kg (Renault, 2016).

The same applies if a high-class e-car such as the Tesla Model S is compared with a comparable Audi A6 (Hellwig, 2016). The Audi A6 weighs between 1650 and 2000kg, depending on its equipment, which is in any case lighter than the Tesla Model S with 2100kg.

The fact that the electric cars are heavier than their gasoline counterparts requires us to set a higher base weight for e-cars in the following MFAs. This might change in the future, however, with the current data available this is the state of the art which is illustrated. The findings which were presented above are based on an interview with a Renault technician (Hellwig, 2016).

The subsequent table shows all data of the material composition of cars on which the MFAs for gasoline cars are based on. In fact, 5 different sources were taken and the average content of the various material groups were calculated. Then, the uncertainty level was established, meaning the standard error which is calculated from the standard deviation (Strasser and Böhm, 2007). The sources from which the data was taken can be found in the appendices (Appendix II).

TABLE 1: DATA BASIS FOR MATERIAL COMPOSITION OF GASOLINE CARS

Total weight (kg)	1413	1059	1010	1341,1	1000	average	Standard error	Share in kg
Ferrous (%)	59,69	74,64	65,45	74,33	57,80	66,00	3,20	768,90
Plastic (%)	15,99	8,70	9,00	13,53	7,80	11,00	1,45	128,15
Non-iron (%)	7,50	6,30	10,25	4,65	10,30	8,00	0,98	93,2
Residue (%)	16,82	10,36	15,30	7,49	24,10	15,00	2,67	174,75

The next table illustrates the data basis for the material composition of electric cars. However, as it was already mentioned in the introductory words of this chapter, we have fewer sources for electric cars due to secrecy reasons. The figures are based on aggregated data which is a further limitation. In fact, specific data for the composition of electric cars will only be available when the first electric cars will enter the end-of-life vehicles stage on a large scale basis. The sources of the figures can be found again in the appendices (Appendix II)

.

TABLE 2: DATA BASIS FOR MATERIAL COMPOSITION OF ELECTRIC CARS

Total weight (kg)	1199,5	1425,6	913	average	Standard error	Share in kg
Ferrous (%)	50,19	58,59	53,54	54,00	1,99	636,66
Plastic (%)	12,50	13,53	12,40	13,00	0,32	153,27
Non-iron (%)	26,68	23,45	22,33	24,00	1,07	282,96
Residue (%)	10,63	4,43	11,73	9,00	1,86	106,11

2.2.2 Austrian car market

The following data is only applied in the MFAs 3 and 4 (figure 5 and 6), as for the first two MFAs only one unit of each car was compared. The number of vehicles currently rolling on Austrian streets is important to establish the current stock of the *use (P1)* process. The current car fleet in Austria (February 2016) comprises the following cars. Only the most important cars for this thesis are indicated (Statistik Austria, 2016).

TABLE 3: CAR FLEET AUSTRIA 2016

Fuel type	February 2016	Share in %
Gasoline	2.018.918	42,5
Electro	5.535	0,1
Diesel	2.708.045	57,0
Total	**4.753.812**	**100,0 (residue 0,4)**

As it was stated in the introduction of the thesis, the 1st scenario assumes that 100% of the car fleet are gasoline cars, meaning 4.753.812. In contrast to the second scenario that assumes a car fleet of 4.753.812 electric cars.

Moreover, two further figures are crucial for establishing the MFAs. This is the annual number of newly registered cars as well as the number of deregistered end-of-life vehicles per year. These figures allow us to describe the imports of material into the system as well as the number of cars which enter process *dismantling/use (P2)*. In Austria, during the last 3 years an average annual value of 415.626 cars were newly registered (Statistik Austria, 2016). In addition, between 2006 and 2008, around 257.432 cars were deregistered, whereby 186.334 were exported to other countries (mostly Eastern Europe and Africa). This huge amount of exported cars was not considered in the MFAs. However, it shall be mentioned here, because of the significance of the numbers. (Schneider et al., 2016).

TABLE 4: OVERVIEW OVER END-OF-LIFE VEHICLES IN AUSTRIA

type	Quantity	Share in %
Deregistered passenger cars	257.432	100
Commercial export of used cars	40.059	15,5
Deregistered cars but not reported as ELV	146.275	61
ELV arisings	**69.431**	**23,5**

As a further step, the annual gasoline consumption in Austria is shown. The import flow *gasoline (F6)* (see figure 5) was calculated from available data from the chamber of commerce Austria (WKO, 2016), from the agency for oil industry in Austria and from newspaper articles (Salzburger Nachrichten, 2015). According to this data the consumption for gasoline was the following:

TABLE 5: AVERAGE VALUES OF GASOLINE AND DIESEL CONSUMPTION/YEAR IN AUSTRIA

2014	8.100.000.000 kg
2013	7.978.500.000 kg
2011	7.250.000.000 kg
average	7.776.166.667 kg

According to the source, the share of the traffic consumption is 77,5% which leads to the assumption that 6.026.529.167 kg gasoline were consumed. The simplification hereby is that it we assume 100% gasoline usage instead of diesel and gasoline. The standard error was calculated from the results as well – 167.948.090kg. If this amount is divided by the population the use of gasoline per capita and year amounts to 710,47kg.

Last but not least, it has to be mentioned that the MFA values in subchapter 3.2 will be based on per capita and year figures. The population that was taken as norm factor is 8.482.491, as this has been the average population in Austria from 2012-2014 (Statistik Austria, 2016).

2.2.3 Waste management

This part focuses on the processes dismantling/car shredder (P2), waste-to-energy (P3) and landfill (P4). The necessary data which is needed in order to establish the MFAs are presented below. This data is crucial for all four MFAs that are performed.

Dismantling car/shredder (P2)

This process transfers the different input materials either back to the *use (P1)* as recycling material and reuse parts, or to a landfill and a waste-to-energy plant as *flows ASR I (F26) and ASR II (F27)* respectively. Therefore, transfer coefficients were defined, in order to state the percentage to which the materials go each way. The transfer coefficients are the following:

TABLE 6: TRANSFER COEFFICIENTS FOR RECYCLING/REUSE RATE IN %

	Ferrous metals III (F19)	Plastic III (F16)	Non-iron metals III (F20)	Residue III (F21)	ASR I (F26)	ASR II (F27)
Ferrous metals II(7)	100	0	0	0	0	0
Plastic II (F8)	0	11	0	0	17,43	71,57
Non-iron metals II (F9)	0	0	100	0	0	0
Residue II (F11)	0	0	0	95,30	0,92	3,78

The literature indicated that ferrous metals have a recycling rate on average of 95% and non-ferrous metals on average of 90% in the area of car recycling (Jochem et. al, 2004). Comparing these values with the amount of those metals in the ASR, leads to the assumption that the remaining percentage is reused back in car production or somewhere else. Therefore, the reuse/recycling rate exhibits 100% for both. If it comes to plastic, the data in the literature states an average recycling rate of 11%. Therefore, it is indicated above in the transfer coefficient table. The remaining value for residue was calculated. The sum of the plastic that goes further to ASRI and ASR II was subtracted from the sum of all ASR which is landfilled or incinerated in Austria per year on average. This amounts to 682.733.000 kg per year, of which 19,58% is landfilled and the rest incinerated (values for ASRI and ASRII in the table). The resulting amount led to a recycling/reuse rate of 95,3% for residue material (Schelker and Geisselhardt, 2008).

Waste-to-energy (P3)

This process transfers the inflow ASRII (F27) to different outflows. Establishing to what degree the inflow is transported to the two outflows, required us to calculate transfer coefficients on the basis of a study that shows an average ash content of 42%.

Since there was no data available for slag, it is assumed that 58% leave the stack as off-gas. (Vermeulen et al., 2011).

TABLE 7: TRANSFER COEFFICIENTS FOR THE WASTE INCINERATOR IN %

	Energy (F18)	Ash/slag (F22)	Off-gas II (F24)
ASR II (F27)	0	42	58

After knowing the data which was illustrated above, the 4 MFAs were performed. On the basis of these MFAs the research questions are answered.

3. Results and Discussion

This chapter provides the results of the research which leads to the answering of the research questions that were defined in chapter 1.

- What are the most important differences for the material input, output and stock?

- How does the material consumption per capita change if electric mobility is introduced in the model region Austria?

3.1 What are the most important differences for material input, output and stock of the two scenarios?

In order to better illustrate the material composition of cars, the first two MFAs exclude fuel, off-gas or combustion air. The result is that it can be seen what flows will change most drastically in the future and what flows remain the same.

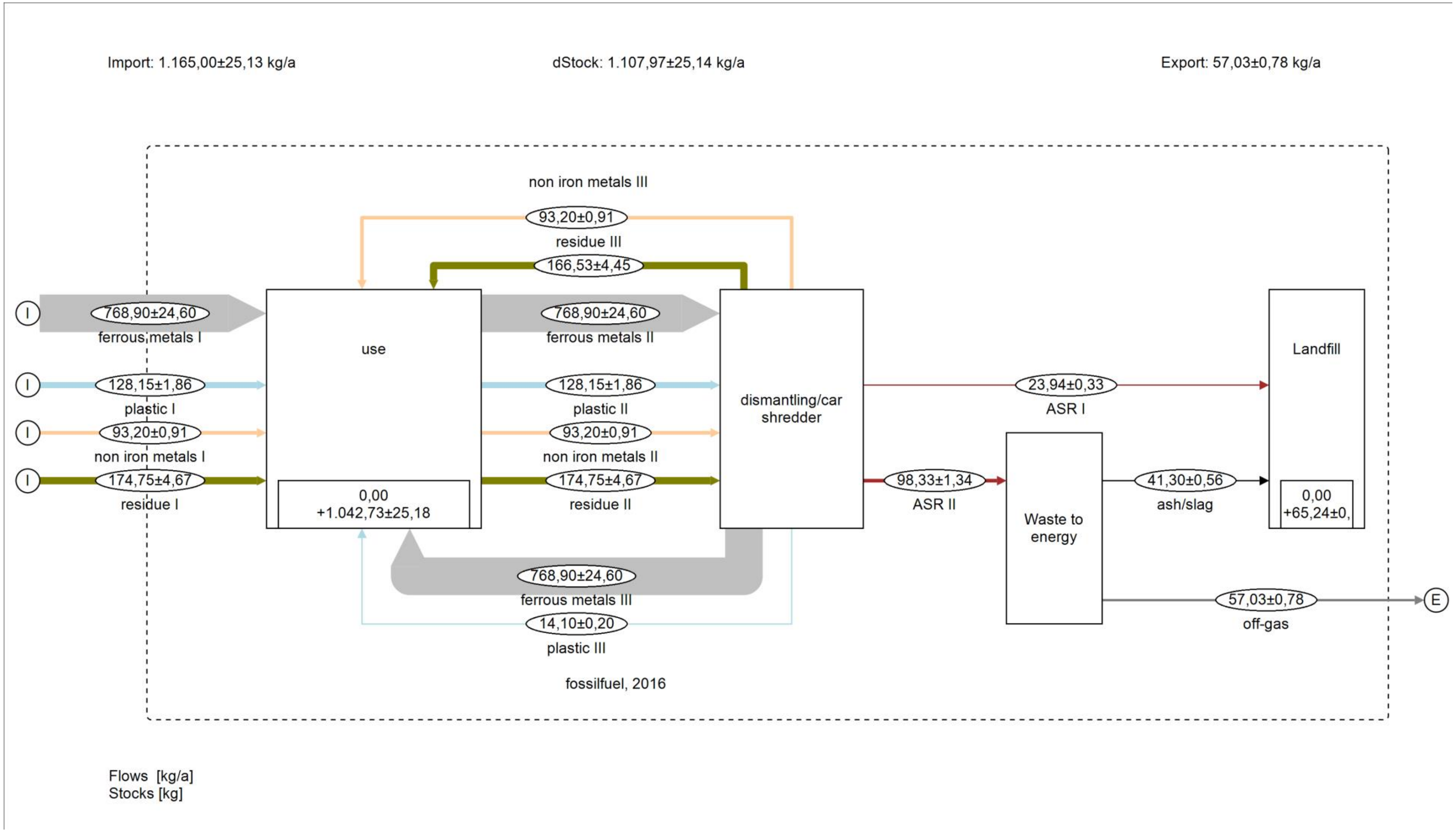

FIGURE 3: MFA MATERIAL DEMAND OF 1 GASOLINE CAR

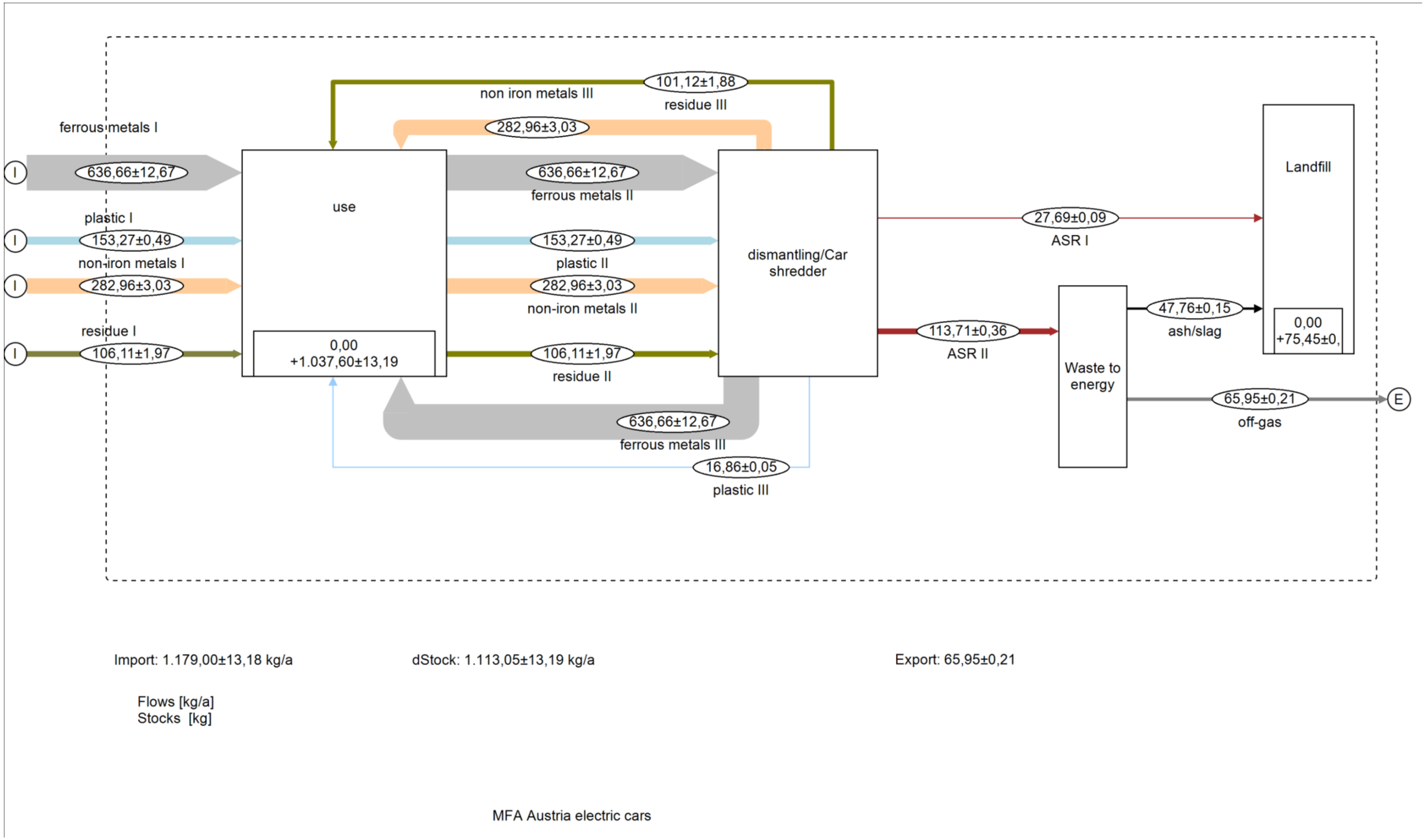

FIGURE 4: MFA MATERIAL DEMAND OF 1 ELECTRIC CAR

3.1.1 Change in stocks

The stock changes arise in the process use (P1) and landfill (P4). The former one is the sum of the material which is recycled or reused. Although the gasoline car is lighter, the stock arising is bigger (1042,73kg/car) than for the electric vehicle. This means that the recycling/reuse rate is higher with 89,5%, in comparison to 88% for electric cars. On the contrary, the stock arising in the landfill is higher for electric mobility, because more plastic is used and plastic has only a low recycling/reuse rate. Therefore, more material is disposed of or incinerated (75,45kg/car) as for a gasoline car (65,24kg/car).

3.1.2 Change in inputs, outputs

Ferrous metals I + II (F1+F7)

It can be seen that the ferrous metals flow is for both cars the main source of materials. However, the one for the gasoline car (768,90kg) is bigger than its counterpart in figure 4 (636,66kg). The main reason for that is the heavy battery (approximately 250-350kg/car) which has to be used in the electric car. As a result, car manufacturers use less *ferrous metals (F1)* and replace them with *plastic (F2)* and *non-iron metals (F1)*. For instance, doors and smaller parts of the shell are made-of aluminium or plastic instead of steel (Hellwig, 2016).

Plastic I + II (F2+F8)

As mentioned above, plastic is used in electric cars to replace heavy materials like steel and cast iron. In addition, they are used in the battery and to cover electric wires for example (further details under 2.1.2). As a result, the demand for plastic will increase from 128,15 kg/car to 153,27 kg/car if electric mobility is introduced.

Non-iron metals I+II (F3+F9)

What one can immediately observe is that *non-iron metals I (F1)* is by far more used in the production of an electric car than for a gasoline car. In fact, 93,20kg of non-iron metals are part of a gasoline car and 282,96kg of an electric car. That is an increase of more than 300%. As it was already mentioned in the flow description under 2.1.2, the main material in this group is aluminium. According to a representative of the headquarters of Renault in Paris, there are already turbulences on the aluminium markets, as its demand increases (Girard, 2016). In particular, not only the demand for aluminium will rise, but also the one for copper which is the second most used metal in this group. This metal is mainly used for electronics and wires which are more required for the electric car. In addition, the battery of an electric car is also reason for an increase of non-iron metals, because its main components are aluminium and copper after steel.

Residue I + II (F5+F11)

Within this group of materials, the demand will decrease if a society switches to electric mobility. The amount of materials will shrink from 174,75kg/car to 106,11kg/car. The main components of this group of materials are glass, rubber and service fluids. Whereas the consumption for glass will remain the same, an electric car contains less rubber and far less service fluids. In general, the trend goes towards simplification of materials and in the designing phase of a car, engineers take already into account that the reuse and recycling rate have to be high for the various materials in the future. (Van Caneghem et al., 2010)

Ferrous metals III (F19) and non-ferrous metals III (F20)

The literature states an average recycling rate of 95% for ferrous metals and 90% for non-ferrous metals. However, as the material which is landfilled and burned in Austria, *ASR I (F26)* and *ASR II (F27)*, does not contain ferrous and non-ferrous metals (Eurostat, 2016) it is assumed that 100% go back to the use process. Either in the way of recycling, or through reuse, meaning that some parts of the car are removed and assembled again in another one. Furthermore, as it was explained under 2.1.2 *dismantling/car shredder (P2)*, the shredder residue is again separated and the metals are used again in car manufacturing or somewhere else.

Plastic (F16)

The part of plastic which is recycled or reused is rather low. The average value is 11% which means that only 14,10kg of the 128,15kg are recycled or reused in a gasoline car and 16,86kg of the 153,27kg in the electric car. The rest goes as ASR to the landfill or the incinerator. The reasons for that are stated under 2.1.2 *plastic III (F16)*.

Residue (F21)

The reuse and recycling rate was stated with 95% for the residue material (see 2.2.3). The main reason for that is glass and textiles for example, which can be easily used again. In fact, 166,53kg of the residues of a conventional car are reused or recycled and 101,12kg of the residue materials in an electric car. This indicates that a wider variety of materials is used in the conventional car. Furthermore, more residue material is burned or landfilled which leads to the fact that the ASR is composed of more diverse materials.

ASR I (F26)

The material which is directly landfilled after the shredder process amounts to 27,69kg/electric car and 23,94kg/gasoline car. The difference is not that big, however, if we speak of millions of cars this difference will be significant. The main components of shredder residue can be read under 2.1.2 *ASR I (F26)*. As already mentioned under the stock change *landfill (P4)*, the higher fraction of plastic in an electric car leads to more ASR which is disposed of.

ASR II (F27)

This material is the fraction that goes into a waste incinerator, where energy is generated from the shredder residue. However, this residue is always mixed with other waste, either with municipal waste or sludge from a waste water treatment plant. One electric car provides 113,71kg of shredder residue which is burned in an incinerator, whereas a gasoline car generates 98,33kg of fuel. This numbers are valid for the waste management scheme of Austria. Consequently, there will be more energy generated if a society switches to electric mobility.

Ash/slag (F22)

The ash/slag ratio was calculated with 42% which amounts to 47,76kg for one unit of the electric car and 41,30kg for one unit of the conventional one. This amounts are disposed of on a landfill. This is the second reason why more landfilled material arises if a society switches to electric mobility.

Off-gas (F24)

The rest of the material is emitted into the atmosphere as flue-gas. Hence, this flow leaves the system boundary as it was not included in the system. The burning of shredder residue from one electric car creates 65,95kg off-gas and the one generated from one gasoline a car 57,03kg. This leads to the assumption that more flue-gas cleaning systems have to handle higher quantities, which contain as stated under 2.1.2, poisonous substances like hydrogen chloride, cadmium or dioxins.

3.1.3 Change in import, export and stock overall

Looking at the MFAs shows that the overall material input in order to produce one electric car is higher (1179kg) than for one gasoline car (1165kg). The reason for that is the battery which is heavy (250-350kg). This was already demonstrated under 2.2.1. Furthermore, the changing stock for the electric mobility scenario is only slightly higher, because there is more landfill material (P4), however, less recycling material used in (P1). Finally, if the exports are compared, it can be stated that electric mobility generates more emissions from the burning of ASR. This is the case because of the higher plastic content in an electric car. The two figures show 57,03kg/car of off-gas for gasoline cars and 65,95kg/car for electric cars as shown above.

After showing the differences of material composition for one unit of an electric car and one unit of a gasoline car, the holistic scenarios are drawn in the following subchapter.

3.2 Holistic scenarios: Traditional mobility vs. electro mobility (in kg/c.y)

A realistic scenario of the status quo would be a mix of petrol and diesel cars. However, due to limited time and resources, this master thesis assumes that the status quo comprises only petrol driven cars. All possible aspects are included in this MFA, meaning material resources, fuel, combustion air and off-gas along the whole life cycle of a car. In particular, this includes the use phase, the recycling and dismantling phase, and the disposal or incineration of the remaining material. What is more, the numbers in the two following MFAs take into account all the cars which are newly registered per year, which are currently registered overall and which are annually deregistered. Furthermore, the numbers were calculated on a per capita/year basis in order to be able to compare the results with other studies.

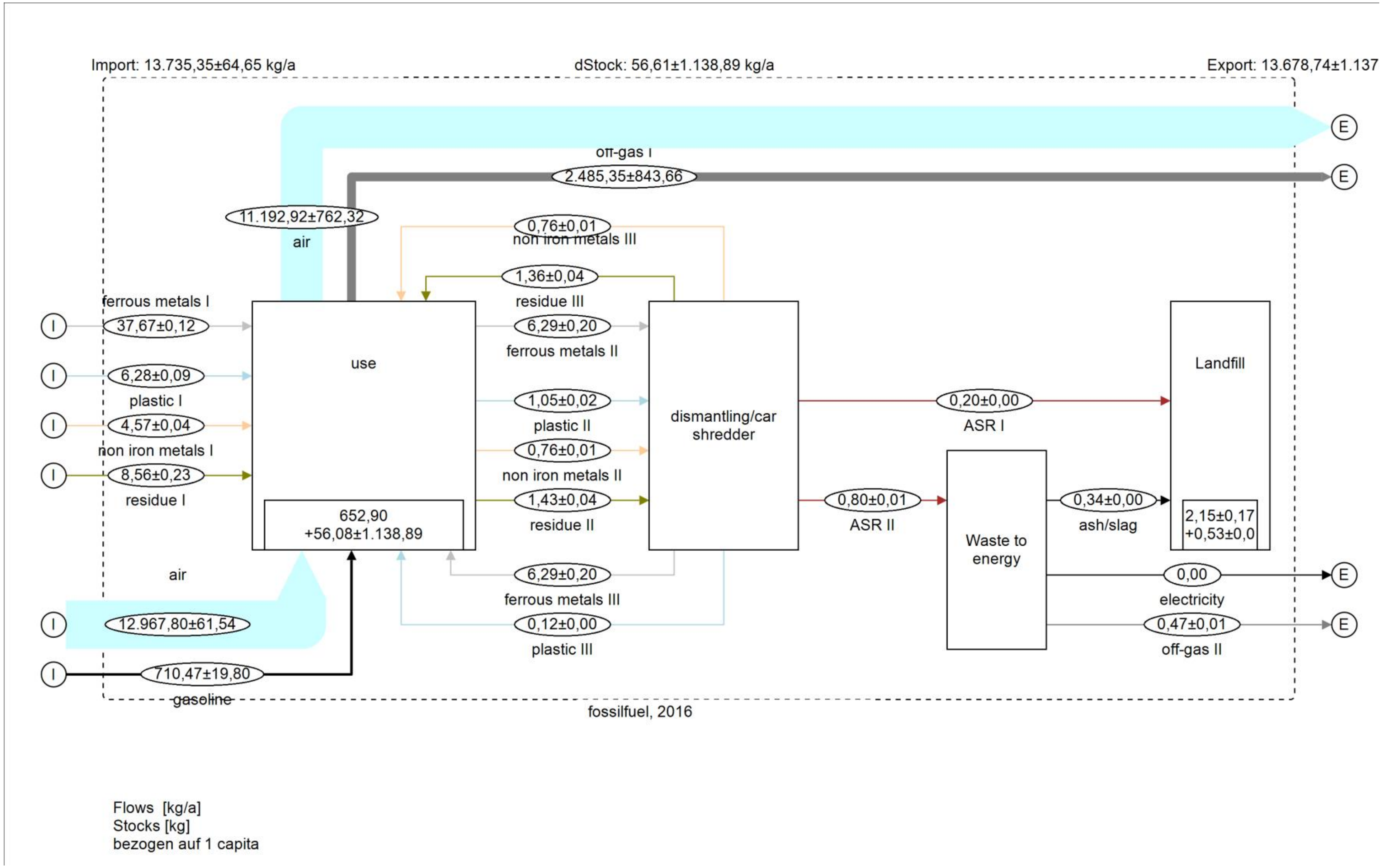

FIGURE 5: HOLISTIC MFA CONVENTIONAL MOBILITY BASED ON GASOLINE

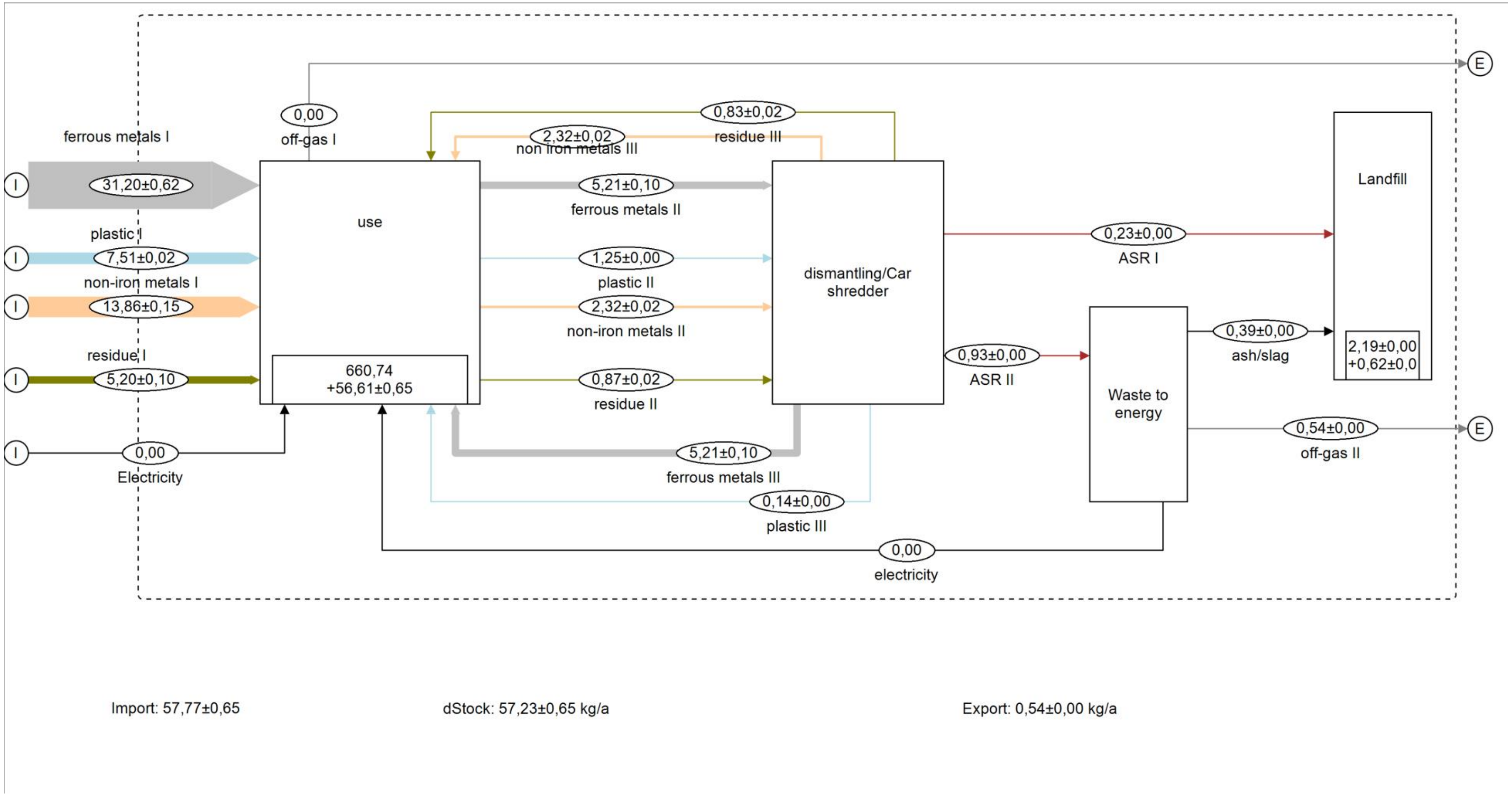

FIGURE 6: HOLISTIC MFA BASED ON ELECTRIC MOBILITY

3.2.1 What are the most important stocks / changing stocks (in kg/c.y)

Use (P1)

The process *use (P1)* has a stock of 652,90 kg/c.y, which reflects the sum of all materials of the current car fleet in Austria. In contrast, electric mobility shows a stock of 660,74kg/c.y, which demonstrates the higher material input for the 4.753.812 passenger vehicles in Austria (mainly due to the battery). The changing stock shows almost the same figures (56,08kg/c.y for status quo vs. 56.61kg/c.y for electro). It contains the recycled/and reused materials and the newly registered cars that are more than the end-of-life vehicles which leave the system.

Landfill (P4)

Due to its higher material consumption more residue material arises in the landfill if there is a switch to electric mobility. In fact, 0,62kg/c.y in comparison to 0,53kg/cap.y in the status quo scenario. A current stock could not be calculated, because of lacking data.

3.2.2 What are the most important differences for material input, output?

Material imports into the system (F1, F2, F3, F5, F6, F23)

Moreover, in the case of conventional mobility, the main imports into the system and inflows into process *use (P1)* stems from combustion air (12.967,80kg/c.y) and gasoline (710,47kg/c.a). The other imports/inflows are negligible. Furthermore, the outflows from the use phase of a gasoline car are air (11192,92kg/c.a) and off-gas (2485,35kg/c.a). If we compare this with the second MFA for electric mobility, it is clearly illustrated that the material inflows represent the most important inflows into the process. Since no combustion air is needed it also cannot pollute the environment. Consequently, the human footprint on the environment is immensely bigger for conventional mobility than for electric mobility. This is the case, because the most significant import flows are ferrous metals (31,20kg/c.a), non-iron metals (13,86kg/cap.a), plastic (7,51kg/c.a) and residue material (5,2kg/cap.a), meaning the materials for the production of a car.

Import flow electricity for electric cars (F6)

The import flow fuel (F6) is for electric cars in comparison to gasoline cars an energy flow. As an energy flow cannot be expressed as a mass flow, this flow is 0. As it was mentioned in the introduction, the current electricity mix of Austria shows that 76% of electricity is produced by renewable energies. As a result, there is not that much pollution in the production of electricity. As a lack of time, this aspect was not included in the MFA. However, it was indicated in the introduction that the same amount of emissions are expected for the production and disposal as well as from the production and transport of the fuel of electric and gasoline cars (with the electricity mix in Austria).

End-of-life vehicle material (F7, F8, F9, F11)

The MFA for traditional mobility shows that out of the material which enters the use phase as part of all newly registered cars per year in Austria (57,8kg/c.y), 9,53kg/c.y leave the use phase and enter the dismantling/car shredder stage. This is the amount of material which is contained in all ELV that arise in Austria. The ELV that are exported and sold somewhere else are not included. The main components as already indicated ferrous metals and plastic. The introduction of e-mobility in Austria would change the following. The material consumption in the end-of-live vehicle phase would slightly increase up to 9,65kg/c.y. This due to the higher weight as it was already indicated.

Taking a closer look at the different materials shows the following: The material flows per car were taken and multiplied with the number of ELV arisings in Austria per year. This amount (69.431) is taken from the table under 2.2.2. Then, the results are again divided by the norm factor (Austrian population). Consequently, we get 6,29kg/c.y ferrous metals (F7), 1,05kg/c.y plastic (F8), 0,76kg/c.y non-iron metals (F9) and residue material (F11) of 1,43kg/c.y which enter the dismantling/car shredder (P2) process (traditional mobility). In comparison, regarding e-mobility, the amounts for ferrous metals and residue material shrank (5,21kg/c.y and 0,87kg/c.y). Whereas the figures for plastic and non-iron metals rose (1,25kg/c.y and 2,32kg/c.y).

Car recycling/reuse flows (F19, F16, F20, F21)

The recycling/reuse flows for the different materials were calculated from the STAN software (STAN, 2016). The degree to what the flows are recycled/reused can be seen in the transfer coefficient table under 2.2.3. In fact, ferrous metals and non-iron metals are recycled and reused to 100%, plastic to a degree of 11% and the residue material to 95%. The result for gasoline cars is 6,29kg/c.y of ferrous metals and 0,76kg/c.y of non-iron metals which are reused and recycled. And 0,12kg/c.y of plastic as well as 1,36kg/c.y of residue material. On the contrary, concerning e-cars, there are recycling/reuse flows of 5,21kg/cap.y ferrous metals, 0,14kg/cap.y of plastic, 2,32kg/cap.y for non-iron metals and 0,83kg/cap.y for the residue material.

ASR I + II (A26 +A27)

Traditional mobility produces remaining material (ASR) after separation (0,23kg/cap.y) which is directly landfilled and (0.93kg/cap.y) which go to the incinerator. The values were established as already mentioned under 2.2.3. In comparison to the flows from the gasoline car there is more material incinerated and more material landfilled in the case of electro mobility (0,8kg/cap.y and 0.20kg/cap.y).

Ash (F26)

The number for this flow were calculated from the assumption that ASR has an average ash content of 42% (Vermeulen et. al, 2011). As now further numbers for slag were found, the rest was taken as off-gas in the next flow. This means that 42% of the inflow (0,8kg/cap.y), are landfilled as ash after incineration of the ASR. This accounts up to 0,39kg/cap.y for electric cars. Consequently, more ash is landfilled than for conventional mobility (0,34kg/cap.y).

Export Off-gas II (F24)

The remaining off-gas flow for electric cars was taken as transfer coefficient of 0,58 and calculated an amount of 0,54kg/cap.y flue-gas which leaves the system as before. The resulting emission are higher than for gasoline cars (0,47kg/cap.y).

3.2.3How does the material consumption per capita change if electric mobility is introduced in the model region Austria?

Last but not least, the remaining research question is answered on the basis of the two MFAs of the holistic scenario above (figure 5 and 6). An introduction of electro mobility in Austria would change the total material consumption drastically.

The material flow through the system (Austria) (in kg/c.y) would become significantly smaller if the whole society switched to electric cars. In fact, the input decreases from 13.730kg/c.y to 58kg/c.y. Whereas the input for traditional mobility consists mainly of air (94%) and gasoline (5%) raw materials are negligible (>1%), the input for electro mobility is only the materials: 54% ferrous metals, 24% non-iron metals, 13% plastic and 9% residuals.

The same result is got for the output, which would immensely decrease if e-mobility is introduced. In particular, from 13680kg/c.y to 0,5kg/c.y. The output of traditional mobility contains air (82%) and pollution (18%) mainly due to combustion, whereas the output for e-mobility is only made up of pollution from the waste incinerator.

In the case of the stock, the introduction of e-mobility would slightly increase it from 56,2kg/c.y to 57kg/c.y.

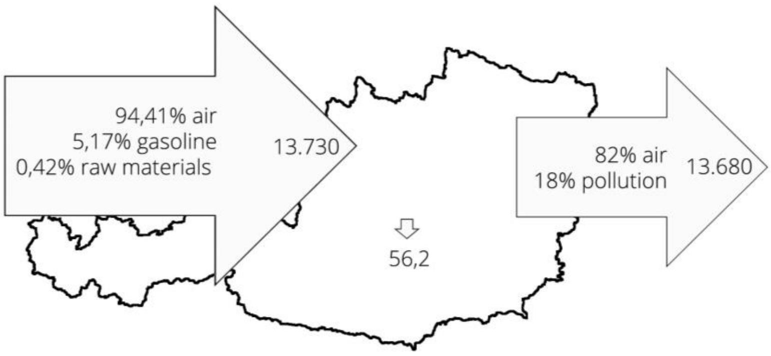

FIGURE 7: MATERIAL FLOW OF CONVENTIONAL MOBILITY THROUGH AUSTRIA (IN KG/C.Y)

FIGURE 8: MATERIAL FLOW OF ELECTRIC MOBILITY THROUGH AUSTRIA (IN KG/C.Y)

3.3 Critical view on the results

The holistic MFA (including also fuel, combustion air, off-gas) shows that the material consumption per capita in Austria would change drastically if the society switches to 100% electric cars. The material input into the system is 240 times higher for gasoline cars than for electric cars and the outputs even 25.000 times. However, the stock arising is slightly higher for electro mobility (1%).

If we take a closer look to the materials, as it was done in the MFAs in figure 3 and 4, it was mentioned that the change to electric mobility will increase the demand for non-iron metals, such as aluminium, and plastics. However, there is a drawback in the case of aluminium, meaning it is very energy intensive. It needs 5 times as more energy in the production than steel for example. So if we increase the share of aluminium in the modern electric car, higher energy demand and therefore more emissions in the production phase will be the result. (Gruden, 2008)

What can be also mentioned is that due to a higher amount of plastic in electric cars, more waste is generated which has to be landfilled or burned and then landfilled. Furthermore, more off-gas is generated due to higher amounts which are going to be landfilled. It would be interesting to know if bioplastics provided an alternative to their conventional counterparts in reducing landfilled material.

At the end it can be said, that it depends on many factors how the material consumption changes per capita. The thesis showed that it will change, the trend goes towards light metals and plastic in order to even out the heavy batteries. If less material is used in the future, will depend on the development of the batteries. At the moment, all the compared cars show that the electric vehicles are the heavier ones.

4. Summary and Recommendations

This master thesis aimed at raising awareness for the introduction of electric mobility from a resource perspective. In the first part of the thesis, the basic problem was introduced to the reader and the goals of the thesis and the research questions were presented.

As further step, it was tried two describe traditional and electric mobility. In particular, the basic MFA was designed and the processes, flows and stocks were described. Then, the data was collected and explained in order to quantify the various MFAs. The current developments in car manufacturing were introduced and basic numbers for the Austrian car market were shown, because these date is crucial for understanding the MFAs that followed in chapter 3.

Subsequently, the results of the two scenarios, namely traditional mobility (gasoline cars) and electro mobility were indicated. Therefore, it was decided to perform 4 MFAs, two for each scenario. The first two MFAs focused on the material composition of one electric car as well as one gasoline car. The material that arose, was followed along the whole life-cycle of the car. So it was able to state how much material of one car goes to the different flows and stocks. Based on this two MFAs we were able two answer the first main research question, namely

- What are the most important differences for the material input, output and stock?

The results show that the main differences lie in the usage of non-iron metals and plastic. Due to the higher weight of electric cars, because of the battery, engineers try to compensate that with using more plastic and non-iron metals such as aluminium. As a result, less ferrous metals are needed. However, aluminium and plastic mean also less security, because ferrous metals as steel are enormously robust materials. What could be not shown in the first two MFAs is the huge amount of gasoline which is needed to run a car. This amount significantly increases the material consumption per capita both of which was shown in the 3rd and 4th MFA (figure 5 and 6).

In the second part of the 3rd chapter the two other MFAs were performed. Based on those, it was able to answer the second research question:

- How does the material consumption per capita change if electric mobility is introduced in the model region Austria?

The material consumption per capita in Austria changes significantly if electro mobility is introduced. In fact, the material input for traditional mobility is 13.735,35kg/c.y, of which 94,41% is air, 5,17% is gasoline and 0,42% are materials. The outputs are 13.678,74kg/c.y, of which 81,83% are air and 18,17% is pollution described as off-gas. The slight difference is the material which arises in the system as a stock of 56,23kg/c.a.

On the contrary, electro mobility would only account for material inputs of 57,77kg/c.y, of which 54% are ferrous metals, 24% is non-iron metals (mainly aluminium.) , 13% is plastic and 9% are residuals (textiles, rubber, glass). The output of the system amounts only for 0,54kg/c.y, of which 100% is off-gas from the incinerator. The stock that arises in the system is 57,23kg/c.y and is therefore slightly bigger than the one for traditional mobility. The reason for that is the higher weight for electric cars mainly due to their heavy batteries. This leads to the application of more plastic instead of ferrous metals, and plastic is mainly landfilled as ASR which further increases the stock of the region.

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Appendices

Appendix I: EV and CV comparison from an energy input perspective

It can be clearly stated that the electric car produces much less greenhouse gases mainly due to the missing use phase emissions. This emission reduction could be further strengthened if Austria enlarged its share of renewable energies (grey column). What is missing in the figure is the contribution of emissions from the waste management phase. It is expected that the introduction electric cars will transfer emissions to the production and to the waste management phase. Whereas the disposal and production acquire only 5% of the whole energy input along the lifecycle of a gasoline car, it is 26% for the electric car of which a huge amount is needed for the battery and the engine (Aguirre et. al, 2012).

As a next step, promoting electric cars will also lead to less energy input during the whole life cycle phase of a car. A study from California shows that the energy input is 40% higher for a gasoline car as for an electric car, assuming that California's electricity mix is based on 22 % renewable energies (RE). In Austria, we have 76% RE, which means the potential for reduction is even much higher. It means actually more than 4 times as less energy input as for a gasoline car (Aguirre et. al, 2016).

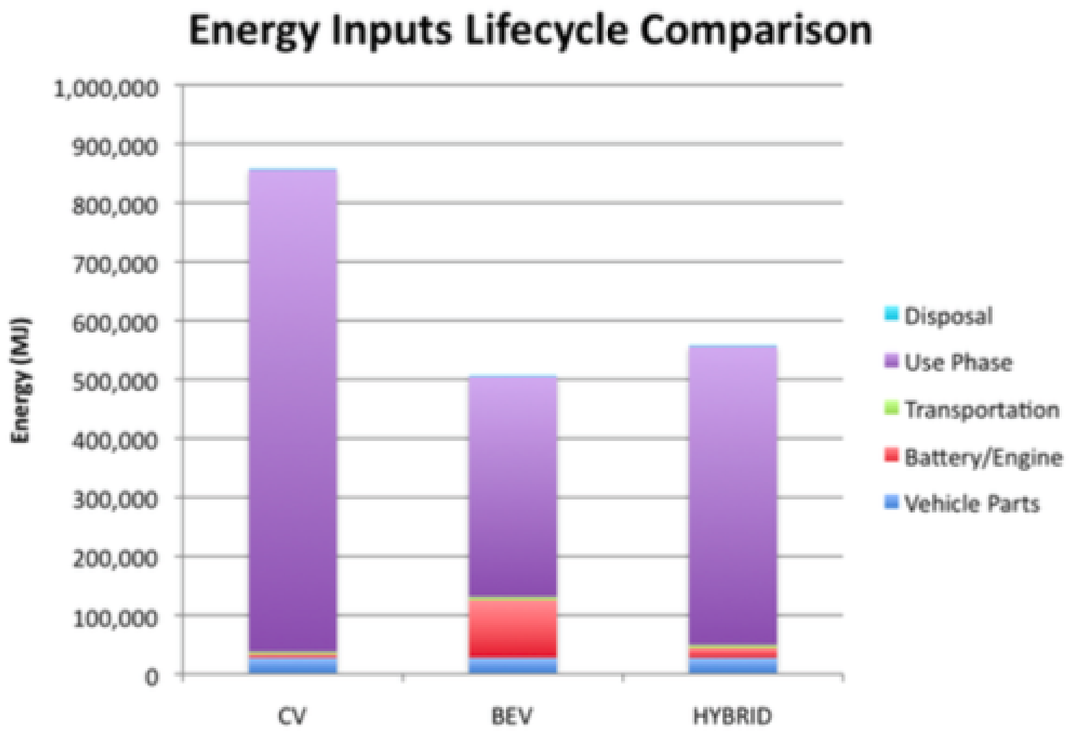

Figure I-1: Energy inputs comparison EV, CV, hybrid (Aguirre et. al, 2012)

If we take a closer look onto the figures, the energy input for a gasoline car stems to a degree of 95% from the use phase and the rest from disposal and production of the coachwork and powertrain, other factors are negligible. For an electric car, the production of the coachwork and powertrain account for the same energy input. However, the battery plays a more important role with 19% of the whole energy input. Furthermore, 74% of the energy is needed in the use phase assuming RE to a degree of 22% renewables. If a lot of renewable energies are used, this amount can be reduced substantially and the battery and the car production become suddenly the most energy intensive factors of the life cycle of a car. (Aguirre et. al, 2012)

(Walter Kille, 2014):

"While electric vehicles have the potential to reduce global warming, the authors state, improving their environmental profile requires engagement around reducing vehicle production supply chain impacts and promoting clean electricity sources in decision making regarding electricity infrastructure."

Appendix II: Data basis for the material composition of electric and gasoline cars respectively

The tables below show all the data that has been used in order to establish the tables in chapter 2. They indicate the material composition of conventional cars and electric cars. Due to secrecy reason, it was hard to get data for electric cars.

Table II-1:(Pötscher et. al, 2012)

It is very important to mention here that the battery which is key for the electric car was not included in the study. I added the weight of the battery based on the assumption of an engineer of Renault (Hellwig, 2016) who guessed that the main components are aluminium copper and steel. We assume a weight of 250kg and the share of the mentioned metals is 40% for steel, 40 % for aluminium and 20% for copper. This means100kg of steel, 100 kg of aluminium and 50 kg of copper.

	Engine		Battery		Coachwork		Total		
	EV	PC	EV	PC	EV	PC	EV	PC	
Steel (Metal-steel mix)	32	150	100		450	603	582	753	1/1
Plastics (LDPE)					150	226	150	226	2/2
Cast iron (metal/FE mix)	20	90					20	90	/3
Fuel, oil, grease	5	40			20	30	25	70	/4
Rubber (EPDM)					40	62	40	62	/5
Aluminium (Al/metal mix)			100		50	60	150	60	3/6
Non-ferrous metals					40	40	40	40	/7
Glass (stones/sand)					25	37	25	37	/8
Electronics, wires (copper/metal mix)	60	10	50		20	20	130	30	4/9
Insulating materials (PUR-hard foam)					14	20	14	20	/10
Lead (lead-metal mix)			20	20			20	20	/11
Lacquer	3,5	5					3,5	5	/12
	120,5	295	270	20	809	1098	1199,5	1413	

Table II-1: Material Composition cars (Umweltbundesamt, 2015)

		Base Vehicle		Engine / Emotor		Powertrain		total	
		EV	PV	EV	PV	EV	PV	EV	PV
1/1	Steel 56,38/65,70	770,7	770,7	5,5	29,8	27,6	80,6	803,8	881,1
5/3	Iron 8,63	18,2	18,2	10,8	97,5	2,4		31,4	115,7
2/4	Aluminium 14,47/2,95	21,8	21,8	55,7		128,8	17,7	206,3	39,5
4/8	Copper 8,82	15,8	15,8	38,9		71	6,5	125,7	22,3
10/10	Non fe	0,6	0,6	1,7				2,3	0,6
3/2	Plastic 11,28/13,53	149,7	149,7	s	1,2	8	30,6	160,8	181,5
6/6	Glass	30,4	30,4					30,4	30,4
8/7	Rubber	24,7	24,7		0,6			24,7	25,3
9/9	Paint	11,8	11,8	2,9				14,7	11,8
7/5	Other	24,5	24,5	0,2	8,4	0,8		25,5	32,9
	Total weight	1068,2	1068,2	118,8	137,5	238,6	135,4	1425,6	1341,1

EV> 1 steel 2 aluminium 3 copper 4 plastic 5 other

PV> 1 steel 2 plastic 3 iron 4 aluminium 5 other

Table II-2:(Hawkins et. al, 2013)

		Base	Engine /	transmission	battery	total

		Vehicle	Emotor			
		EV	EV	EV	EV	
1/1	Steel	455 65	24,5 49	9,36 52		488,86 53,54
5/3	Iron 8,63					
2/4	Aluminium 14,47/2,95	35 5	13 26	8,64 48	82,65 57	139,29 15,26
4/8	Copper 8,82		9,5 19		55,1 wires, electrics 38	64,6 7,07
10/10	Non ferrous					
3/2	Plastic 11,28/13,53	105 15	1 2		7,25 5	113,25 12,4
6/6	Glass					
8/7	Rubber					
9/9	Paint					
7/5	Other	105 15	4 8			113 12,38
	Total weight	700	50	18	145	913

Table II-3: Composition of an electric car

Total weight	1059 (Golf A 4 petrol) (2000)
Ferrous	790,483 73,7
Plastic and textiles	184,266 17,4
Aluminum	41,301 3,9
Non ferrous	25,416 2,4
Glass	23,298 2,2
Fluids	4,236 0,4

Table II-4: Material Composition of a VW Golf A4

In 2000 an average car was composed of 59% steel, 28 % plastic, 8% Non iron metals, 5% aluminium. The total weight is 1120kg (Spielmann and Althaus, 2006).

The following figures were taken from a publication by Gruden (2008):

- 535 kg steel (1996)   52,97%
- 91 kg plastic 9%
- 126 kg cast iron   12,48%
- 53 kg non-iron metals   5,28%
- 205 kg rest (total 1010kg) 3

The following data stems from a publication about automotive shredder residue: (Vermeulen et al., 2011)

Ferrous metal 57,5%

Plastics 7,5%

non – Ferrous metal 9,9%

Tyres 3.5% Glass 2.9% Fluids 2.1% Rubber 1.6% Other 1.5% Process polymers 1.1% Electrical/electronics 0.7% Carpet 0.4%. battery 1.1%.

Total weight: 1000

Appendix III: Process list

The 4 following tables are the process lists for the 4 MFAs that were performed.

First process list →Figure 3

Second process list → Figure 4

Third process list → Figure 5

4th process list → Figure 6

First process list →Figure 3

Prozessname: dismantling/car shredder						
Input						
P2	F7	ferrous metals II	S1,use	P2,dismantling/car shredder	768,90±24,60	768,90±24,60
P2	F8	plastic II	S1,use	P2,dismantling/car shredder	128,15±1,86	128,15±1,86
P2	F9	non iron metals II	S1,use	P2,dismantling/car shredder	93,20±0,91	93,20±0,91
P2	F11	residue II	S1,use	P2,dismantling/car shredder	174,75±4,67	174,75±4,67
Output						
P2	F26	ASR I	P2,dismantling/car shredder	P4,Landfill		23,94±0,33
P2	F27	ASR II	P2,dismantling/car shredder	P3,Waste to energy		98,33±1,34
P2	F19	ferrous metals III	P2,dismantling/car shredder	S1,use		768,90±24,60
P2	F16	plastic III	P2,dismantling/car shredder	S1,use		14,10±0,20
P2	F20	residue III	P2,dismantling/car shredder	S1,use		166,53±4,45
P2	F21	non iron metals III	P2,dismantling/car shredder	S1,use		93,20±0,91
Prozessname: Landfill						
Input						
P4	F22	ash/slag	P3,Waste to energy	P4,Landfill		41,30±0,56
P4	F26	ASR I	P2,dismantling/car shredder	P4,Landfill		23,94±0,33
Prozessname: use						
Input						
S1	F2	plastic I		S1,use	128,15±1,86	128,15±1,86
S1	F3	non iron metals I		S1,use	93,20±0,91	93,20±0,91
S1	F5	residue I		S1,use	174,75±4,67	174,75±4,67

S1	F19	ferrous metals III	P2,dismantling/car shredder	S1,use		768,90±24,60
S1	F16	plastic III	P2,dismantling/car shredder	S1,use		14,10±0,20
S1	F20	residue III	P2,dismantling/car shredder	S1,use		166,53±4,45
S1	F21	non iron metals III	P2,dismantling/car shredder	S1,use		93,20±0,91
S1	F1	ferrous metals I		S1,use	768,90±24,60	768,90±24,60
Output						
S1	F7	ferrous metals II	S1,use	P2,dismantling/car shredder	768,90±24,60	768,90±24,60
S1	F8	plastic II	S1,use	P2,dismantling/car shredder	128,15±1,86	128,15±1,86
S1	F9	non iron metals II	S1,use	P2,dismantling/car shredder	93,20±0,91	93,20±0,91
S1	F11	residue II	S1,use	P2,dismantling/car shredder	174,75±4,67	174,75±4,67
Prozessname: Waste to energy						
Input						
P3	F27	ASR II	P2,dismantling/car shredder	P3,Waste to energy		98,33±1,34
Output						
P3	F24	off-gas	P3,Waste to energy			57,03±0,78
P3	F22	ash/slag	P3,Waste to energy	P4,Landfill		41,30±0,56

Second process list → Figure 4

Prozess	Fluss	Flussname	Herkunftsprozess	Zielprozess	Massenfluss [kg/a]	Massenfluss (berechnet) [kg/a]
Prozessname: dismantling/Car shredder						
Input						
P2	F7	ferrous metals II	P1,use	P2,dismantling/Car shredder	636,66±12,67	636,66±12,67
P2	F8	plastic II	P1,use	P2,dismantling/Car shredder	153,27±0,49	153,27±0,49
P2	F9	non-iron metals II	P1,use	P2,dismantling/Car	282,96±3,03	282,96±3,03

				shredder		
P2	F11	residue II	P1,use	P2,dismantling/Car shredder	106,11±1,97	106,11±1,97
Output						
P2	F19	ferrous metals III	P2,dismantling/Car shredder	P1,use		636,66±12,67
P2	F20	non iron metals III	P2,dismantling/Car shredder	P1,use		282,96±3,03
P2	F21	residue III	P2,dismantling/Car shredder	P1,use		101,12±1,88
P2	F16	plastic III	P2,dismantling/Car shredder	P1,use		16,86±0,05
P2	F26	ASR I	P2,dismantling/Car shredder	P4,Landfill		27,69±0,09
P2	F27	ASR II	P2,dismantling/Car shredder	P3,Waste to energy		113,71±0,36
Prozessname: Landfill						
Input						
P4	F22	ash/slag	P3,Waste to energy	P4,Landfill		47,76±0,15
P4	F26	ASR I	P2,dismantling/Car shredder	P4,Landfill		27,69±0,09
Prozessname: use						
Input						
P1	F16	plastic III	P2,dismantling/Car shredder	P1,use		16,86±0,05
P1	F19	ferrous metals III	P2,dismantling/Car shredder	P1,use		636,66±12,67
P1	F20	non iron metals III	P2,dismantling/Car shredder	P1,use		282,96±3,03
P1	F21	residue III	P2,dismantling/Car shredder	P1,use		101,12±1,88
P1	F2	plastic I		P1,use	153,27±0,49	153,27±0,49
P1	F3	non-iron metals I		P1,use	282,96±3,03	282,96±3,03
P1	F5	residue I		P1,use	106,11±1,97	106,11±1,97
P1	F1	ferrous metals I		P1,use	636,66±12,67	636,66±12,67
Output						

P1	F11	residue II	P1,use	P2,dismantling/Car shredder	106,11±1,97	106,11±1,97
P1	F9	non-iron metals II	P1,use	P2,dismantling/Car shredder	282,96±3,03	282,96±3,03
P1	F8	plastic II	P1,use	P2,dismantling/Car shredder	153,27±0,49	153,27±0,49
P1	F7	ferrous metals II	P1,use	P2,dismantling/Car shredder	636,66±12,67	636,66±12,67
Prozessname: Waste to energy						
Input						
P3	F27	ASR II	P2,dismantling/Car shredder	P3,Waste to energy		113,71±0,36
Output						
P3	F22	ash/slag	P3,Waste to energy	P4,Landfill		47,76±0,15
P3	F24	off-gas	P3,Waste to energy			65,95±0,21

Third process list → Figure 5

Prozess	Fluss	Flussname	Herkunftsprozess	Zielprozess	Massenfluss [kg/a]	Massenfluss (berechnet) [kg/a]
Prozessname: dismantling/car shredder						
Input						
P2	F7	ferrous metals II	S1,use	P2,dismantling/car shredder	6,29±0,20	6,29±0,20
P2	F8	plastic II	S1,use	P2,dismantling/car shredder	1,05±0,02	1,05±0,02
P2	F9	non iron metals II	S1,use	P2,dismantling/car shredder	0,76±0,01	0,76±0,01
P2	F11	residue II	S1,use	P2,dismantling/car shredder	1,43±0,04	1,43±0,04
Output						
P2	F26	ASR I	P2,dismantling/car shredder	P4,Landfill		0,20±0,00
P2	F27	ASR II	P2,dismantling/car shredder	P3,Waste to energy		0,80±0,01
P2	F19	ferrous metals III	P2,dismantling/car shredder	S1,use		6,29±0,20

P2	F16	plastic III	P2,dismantling/car shredder	S1,use		0,12±0,00
P2	F21	residue III	P2,dismantling/car shredder	S1,use		1,36±0,04
P2	F20	non iron metals III	P2,dismantling/car shredder	S1,use		0,76±0,01
Prozessname: Landfill						
Input						
P4	F22	ash/slag	P3,Waste to energy	P4,Landfill		0,34±0,00
P4	F26	ASR I	P2,dismantling/car shredder	P4,Landfill		0,20±0,00
Prozessname: use						
Input						
S1	F6	gasoline		S1,use	710,47±19,80	710,47±19,80
S1	F2	plastic I		S1,use	6,28±0,09	6,28±0,09
S1	F3	non iron metals I		S1,use	4,57±0,04	4,57±0,04
S1	F5	residue I		S1,use	8,56±0,23	8,56±0,23
S1	F19	ferrous metals III	P2,dismantling/car shredder	S1,use		6,29±0,20
S1	F16	plastic III	P2,dismantling/car shredder	S1,use		0,12±0,00
S1	F21	residue III	P2,dismantling/car shredder	S1,use		1,36±0,04
S1	F20	non iron metals III	P2,dismantling/car shredder	S1,use		0,76±0,01
S1	F1	ferrous metals I		S1,use	37,67±0,12	37,67±0,12
S1	F23	air		S1,use	12.967,80±61,54	12.967,80±61,54
Output						
S1	F7	ferrous metals II	S1,use	P2,dismantling/car shredder	6,29±0,20	6,29±0,20
S1	F8	plastic II	S1,use	P2,dismantling/car shredder	1,05±0,02	1,05±0,02
S1	F9	non iron metals II	S1,use	P2,dismantling/car shredder	0,76±0,01	0,76±0,01
S1	F11	residue II	S1,use	P2,dismantling/car shredder	1,43±0,04	1,43±0,04

S1	F25	off-gas I	S1,use		2.485,35±843,66	2.485,35±843,66
S1	F28	air	S1,use		11.192,92±762,32	11.192,92±762,32
Prozessname: Waste to energy						
Input						
P3	F27	ASR II	P2,dismantling/car shredder	P3,Waste to energy		0,80±0,01
Output						
P3	F18	electricity	P3,Waste to energy		0,00	0,00
P3	F24	off-gas II	P3,Waste to energy			0,47±0,01
P3	F22	ash/slag	P3,Waste to energy	P4,Landfill		0,34±0,00

4th process list → Figure 6

Prozess	Fluss	Flussname	Herkunftsprozess	Zielprozess	Massenfluss [kg/a]	Massenfluss (berechnet) [kg/a]
Prozessname: dismantling/Car shredder						
Input						
P2	F7	ferrous metals II	P1,use	P2,dismantling/Car shredder	5,21±0,10	5,21±0,10
P2	F8	plastic II	P1,use	P2,dismantling/Car shredder	1,25±0,00	1,25±0,00
P2	F9	non-iron metals II	P1,use	P2,dismantling/Car shredder	2,32±0,02	2,32±0,02
P2	F11	residue II	P1,use	P2,dismantling/Car shredder	0,87±0,02	0,87±0,02
Output						
P2	F19	ferrous metals III	P2,dismantling/Car shredder	P1,use		5,21±0,10
P2	F20	non iron metals III	P2,dismantling/Car shredder	P1,use		2,32±0,02
P2	F21	residue III	P2,dismantling/Car shredder	P1,use		0,83±0,02
P2	F16	plastic III	P2,dismantling/Car shredder	P1,use		0,14±0,00

	P2	F26	ASR I	P2,dismantling/Car shredder	P4,Landfill		0,23±0,00
	P2	F27	ASR II	P2,dismantling/Car shredder	P3,Waste to energy		0,93±0,00
Prozessname: Landfill							
Input							
	P4	F22	ash/slag	P3,Waste to energy	P4,Landfill		0,39±0,00
	P4	F26	ASR I	P2,dismantling/Car shredder	P4,Landfill		0,23±0,00
Prozessname: use							
Input							
	P1	F6	Electricity		P1,use	0,00	0,00
	P1	F16	plastic III	P2,dismantling/Car shredder	P1,use		0,14±0,00
	P1	F18	electricity	P3,Waste to energy	P1,use	0,00	0,00
	P1	F19	ferrous metals III	P2,dismantling/Car shredder	P1,use		5,21±0,10
	P1	F20	non iron metals III	P2,dismantling/Car shredder	P1,use		2,32±0,02
	P1	F21	residue III	P2,dismantling/Car shredder	P1,use		0,83±0,02
	P1	F2	plastic I		P1,use	7,51±0,02	7,51±0,02
	P1	F3	non-iron metals I		P1,use	13,86±0,15	13,86±0,15
	P1	F5	residue I		P1,use	5,20±0,10	5,20±0,10
	P1	F1	ferrous metals I		P1,use	31,20±0,62	31,20±0,62
Output							
	P1	F11	residue II	P1,use	P2,dismantling/Car shredder	0,87±0,02	0,87±0,02
	P1	F9	non-iron metals II	P1,use	P2,dismantling/Car shredder	2,32±0,02	2,32±0,02
	P1	F8	plastic II	P1,use	P2,dismantling/Car shredder	1,25±0,00	1,25±0,00
	P1	F7	ferrous metals II	P1,use	P2,dismantling/Car shredder	5,21±0,10	5,21±0,10
	P1	F25	off-gas I	P1,use		0,00	0,00
Prozessname: Waste to energy							

Input						
P3	F27	ASR II	P2,dismantling/Car shredder	P3,Waste to energy		0,93±0,00
Output						
P3	F18	electricity	P3,Waste to energy	P1,use	0,00	0,00
P3	F22	ash/slag	P3,Waste to energy	P4,Landfill		0,39±0,00
P3	F24	off-gas II	P3,Waste to energy			0,54±0,00