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End-of-life vehicle recycling in the European Union: Analysing changing material flows of end-of-life steel, aluminum, copper and plastics due to the transition toward zero-emission vehicles

A Master's Thesis submitted for the degree of
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Affidavit

I, **ANDREA GUTSCHI, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "END-OF-LIFE VEHICLE RECYCLING IN THE EUROPEAN UNION: ANALYSING CHANGING MATERIAL FLOWS OF END-OF-LIFE STEEL, ALUMINUM, COPPER AND PLASTICS DUE TO THE TRANSITION TOWARD ZERO-EMISSION VEHICLES", 115 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

The European Commission plans to ban petrol and diesel vehicles by 2035 and several European Union (EU) countries have already adopted final dates for the sales or registrations of internal combustion engine vehicles (ICEV). The development goes beyond national and supranational strategies and is clear: electricity as fuel becomes increasingly popular and conventional fuel types are continuously losing market share. However, all vehicles eventually become waste. It is estimated that the waste produced by end-of-life vehicles (ELVs) in the EU amounts to 8 to 9 million tons yearly. A revision of the EU Directive 2000/53/EC is expected for the fourth quarter of 2022 as changes in vehicle design, especially the increasing share of plastics, electronics, carbon fibers as well as batteries and rare materials in electric vehicles (EVs), have been recognized. By means of a literature review, expert input, and material flow analysis (MFA), this thesis aims to answer the following questions: What should the 2022 revision of the EU ELV Directive include against the background of changing driving technologies? How will the transition toward EVs change the material flow of ELVs in general, and of ELV steel, aluminum, copper, and plastics in particular? Where are the main gaps between the current ELV recycling scheme and an ELV recycling scheme focused on EVs? Is the EU ELV recycling industry ready for the large-scale introduction of EVs? Overall, the amount of recyclable material is expected to increase by about 19% by 2045, when EVs make up the main share of ELVs in the EU. This is mainly due to the increase of the average vehicle weight. It is further assumed that there will be less steel per car – either because lighter steel is used or because steel is replaced by materials like aluminum and plastics. The amount of aluminum, on the contrary, will most likely increase. The assumed increase in this thesis was 25% per vehicle. An almost 6-fold increase, however, is expected for copper, mainly due to the material being used in batteries and electric components. The amount of plastics used per vehicle is expected to increase by about three quarters. Recycling ELVs today deals with challenges from recycling automotive shredding residue (ASR) to recovering copper that will only intensify with changing driving technologies. Overall, more material and more heterogenous material needs to be treated and recycled by 2045.

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List of Abbreviations

ABS	Acrylonitrile-butadiene-styrene
AC	Air conditioner
ACEA	European Automobile Manufacturers Association
AHSS	Advanced high-strength steel
ANN	Artificial neural network
ASR	Automotive shredding residue
BAT	Best available techniques
BEV	Battery electric vehicle
BFR	Brominated flame retardant
CAR	Center for Automotive Research
CEO	Chief Executive Officer
cm^3	Cubic centimeter
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
EAF	Electric arc furnace
EEA	European Environmental Agency
EEB	European Environmental Bureau
ELV	End-of-life vehicle
EPDM	Ethylene-propylene-diene-monomer
EOL	End-of-life
EPR	Extended Producer Responsibility
EU	European Union
EuRIC	European Recycling Industries’ Confederation
EV	Electric vehicle
FC	Fuel cells
FCEV	Fuel cell electric vehicle
HEV	Hybrid electric vehicle
HSS	High-strength steel
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IDIS	International Dismantling Information System
kg	Kilogram

kW	Kilowatt
kWh	Kilowatt-hours
LCA	Life Cycle Assessment
LIBS	Laser-induced breakdown spectroscopy
m^3	Cubic meter
MF	Material flow
MFA	Material flow analysis
MPP	Metal-plated plastics
NOES	Non-oriented electrical steel
PE	Polyethylene
PHEV	Plug-in hybrid electric vehicles
PC	Polycarbonate
PCB	Polychlorinated biphenyl
POP	Persistent organic pollutants
PP	Polypropylene
PS	Polystyrene
PST	Post shredder technology
PVC	Polyvinyl chloride
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
TPE	Thermoplastic elastomer
TPV	Thermoplastic vulcanizate
UHSS	Ultra-high-strength steel
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States
VOC	Volatile organic compound
WFD	Waste Framework Directive

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1. Introduction

About a quarter of the EU's total greenhouse gas emissions stem from the transport sector, and the need to reduce passenger cars' environmental impact has long been recognized. The EU aims for them to emit 15% less by 2025, and 37.5% less by 2030 (EEA, 2021). In July 2021, the European Commission suggested that not only should the EU reach a higher emission reduction of 55% by 2030, but also a 100% reduction for sold cars by 2035 – which is an effective ban on petrol or diesel vehicles (Carey & Steitz, 2021). This would go beyond the European Commission's 2020 "Sustainable and Smart Mobility Strategy," which foresees that by 2030, the number of zero-emission cars reaches 30 million as a milestone to a basically 100% zero-emission fleet by 2050 (European Commission, 2020).

At the 2021 UN Climate Change Conference in Glasgow (COP26), 14 EU countries signed a declaration that 2040 shall be the final date of possible registrations for internal combustion engine (ICE) cars. There were also some cities, car manufacturers like Mercedes, Ford, and Volvo, and some investors who signed the document (GOV.UK, 2022). As of June 2021, 17 countries worldwide had adopted final dates for the sales or registrations of ICE cars, ranging from 2025 (Norway) to 2050 (Costa Rica). Seven of them were EU countries: Sweden (2030), Netherlands (2030), Ireland (2030), Slovenia (2030), Denmark (2035), France (2040), and Spain (2040). As of then, only battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) shall be newly registered in those countries. In Slovenia, also plug-in hybrid electric vehicles (PHEVs) will be allowed (Wappelhorst, 2021). A 2021 survey by *Transport & Environment* found that 63% of European citizens from 15 different cities are in favor of a ban as early as 2030 (Abnett, 2021), the year when Austria wants to ban new registrations of ICE cars, too. This goal is not legally binding, however (Autovista24, 2021).

Compared to an overall reduction of individual transport, encouraging a transition toward alternative fuels is a more practical approach, especially since a negative trend of private car ownership seems far away. According to a 2022 report by the European Automobile Manufacturers' Association (ACEA), there were 246.3 million cars on EU roads in 2020 - a growth of 1.2% from the previous year and the equivalent of 560 passenger cars per

1,000 inhabitants (ACEA, 2022a). Figure 1 shows that the years 2016-2020 have indeed been marked by a steady growth.

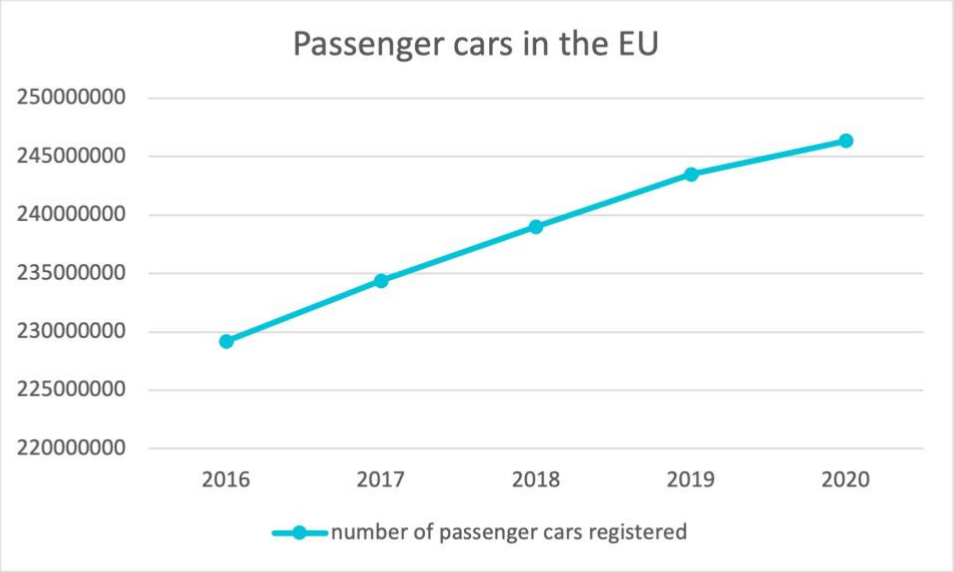


Figure 1: Number of passenger cars in the EU [based on (ACEA, 2022a)]

However, in 2020, only 5.5% of those were not powered by diesel or gasoline: 0.5%, 0.6%, and 1.2% were the percentages of BEVs, PHEVs, and hybrid electric vehicles (HEVs), respectively. Natural gas and liquified petrol gas supplied 0.5% and 2.5% of the EU's car fleet, respectively. The rest (0.2%) was listed as unknown or other fuel types (e.g., FCEVs) (ACEA, 2022a). But the development is clear: electricity as fuel becomes increasingly popular, as also Figure 2 shows. The first quarter of 2022 alone saw an increase in HEVs from 20.9% to 25.1% of all passenger car sales in the EU and BEVs represented 10% of new car sales, which is almost double the amount of their share in the previous year's period. Conventional fuel types are continuously losing market share, representing 52.8% of all sold vehicles in the EU today (ACEA, 2022c). According to Walter Kletzmayr, CEO of the Austrian ARGE-Shredder GmbH, electromobility grew by 75% from 2020 to 2021 in terms of new registrations in Austria, where already more than 2% of cars in use are EVs. However, the hybrid technology is for him only a short- to medium-term trend, that is completely inferior to BEVs when it comes to their overall energy footprint (Kletzmayr, 2022).

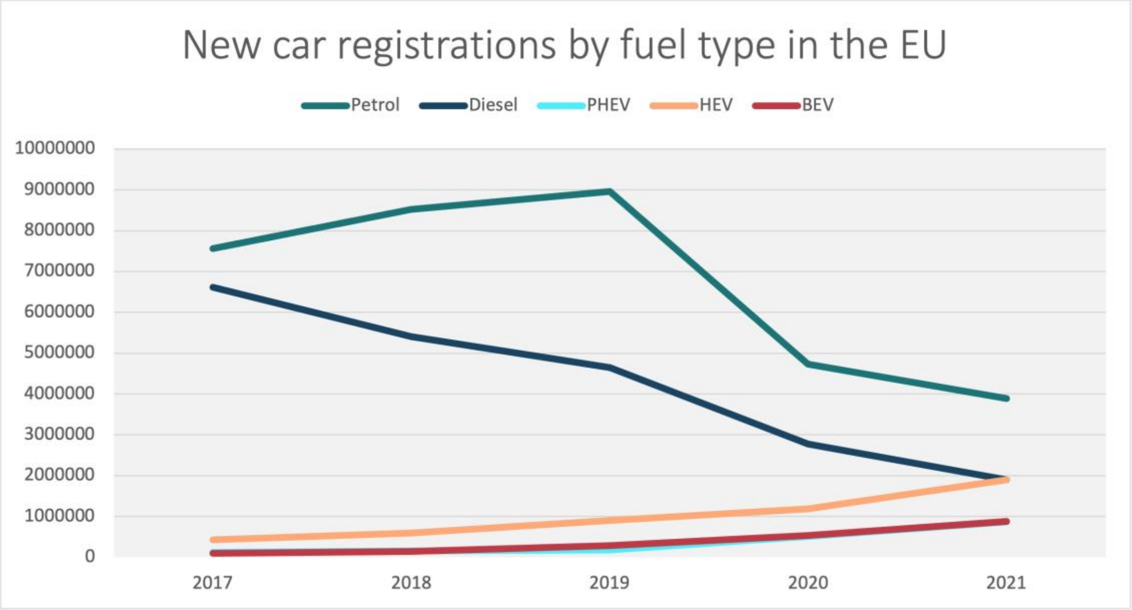


Figure 2: New car registrations by fuel type in the EU [based on (ACEA, 2022b) (ACEA, 2020b) (ACEA, 2019)]

Regardless of their propulsion technology, all these vehicles eventually become waste, or end-of-life vehicles (ELVs). In the EU, the average lifetime lies between 15 and 22 years (European Commission, 2021). For the ACEA, this relatively long lifespan compared to other products is proof of the industry's success in creating durable and reparable products (ACEA, 2020a). One of the industry's characteristics is that cars have one of the highest recycling rates of all products, although they can change their owner up to four times during their lifetime (Auto Express, 2022). But to ensure traffic safety means to avoid using end-of-life (EOL) cars on streets (Sakai, et al., 2014).

An ELV is defined as a deregistered car that is further being treated as waste (dismantling, shredding, disposal). Member states of the EU and of the European Economic Area/the European Free Trade Association have to report their ELV numbers in accordance with the Commission Decision 2005/293/EC on monitoring rules (Eurostat, 2022) as required by Article 9 of the ELV Directive 2000/53/EC (European Union, 2000). While those numbers have to be reported yearly, efforts in implementing the Directive have to be reported every three years (European Commission, 2021). The generation of ELVs depends on the general economic circumstances of a country, its accident rates, and the reliability of in-use vehicles. The flow of materials resulting from ELVs is determined by

ELV generation, ELV treatment infrastructure, and ELV material composition (Staudinger & Keoleian, 2001). It is estimated that the waste produced by ELV in the EU amounts to 8 to 9 million tons annually (European Union, 2000).

In its 2020 paper, the European Commission also briefly mentioned the need to revise Directive 2000/53/EC to reduce "the overall environmental footprint of the production and dismantling of cars" (European Commission, 2020). Currently, the Directive foresees that at least 95% of a vehicle's weight is recovered and reused, while at least 85% shall be recycled. This numbers were to be adopted by each member state as of 2015 the latest (European Union, 2000). A revision of the Directive is expected in the fourth quarter of 2022 after public consultations took place between July and October 2021 (European Commission, n.d.).

A car is highly complex. About 15,000 parts are installed and a wide range of materials is used. In terms of weight, cast iron and steel make about 68% of an average passenger car, non-ferrous metals make 8%, plastics make 9%, gum makes 5%, glass makes 3%, fluids make 2%, textiles make 1%, and other parts are responsible for 4% (Janjić, Bukvić, & Stojanović, 2016). Sawyer points out that car parts can be calculated from different aggregation levels having 1,000, 100, or only 2 parts, whereas the third would be the mere separation into a metallic and a non-metallic part (Sawyer, 1974).

ELV recycling involves the same principles as recycling in general: materials may be re-used as recyclables, i.e., again employed in the production process, or non-recyclables, i.e., used to generate energy. Primary recycling refers to the same material being used to produce new products, whereas with secondary recycling, material is processed to be used for purposes different than its original use (Janjić, Bukvić, & Stojanović, 2016). In general, the global automotive industry is characterized by the use of a lot of (virtual) water, the use of toxic materials, natural resource depletion, energy-intensive processes, pollution in wastewater, and illegal dumping of ELV (Janjić, Bukvić, & Stojanović, 2016). But circularity is one of its main concerns.

New car designs and increased computerization require to think about the ELV stage of those vehicles, too (Sakai, et al., 2014). This thesis focuses on the changing requirements for the EU's recycling scheme driven by the increased electrification of cars. As such, it excludes the topic of battery recycling, which is being under intense discussion and approaches to recycle EVs's lithium-ion batteries are being studied (Harper, et al., 2019). However, the aim of this thesis is to compare selected materials – namely steel, aluminum, copper, and plastics - ELV recycling is concerned with today with their respective future flows. Due to their unpredictability, socioeconomic effects are to a large part excluded as well. It is, however, assumed that the trends of the past years concerning sales and vehicle in stock will continue. A return to conventional fuels is not expected, and it is assumed that the stock of vehicles will continue to grow, albeit with a decreasing rate of new registrations as it was the case in the period 2018-2021 (ACEA, 2022d).

2. Objectives & Research Questions

The previous Chapter has shown that a technology transition in the passenger car sector is well under way. However, besides the battery in EVs, changing requirements for recyclers due to such a transition is often ignored, albeit we are talking about millions of tons of recyclable material each year.

This thesis focuses on regulated ELV recycling in the EU, which is bound to rules set by legislation, as opposed to unregulated systems prevailing in countries such as India (Krishna Mohan & Amit, 2020). Accordingly, one focus of the thesis will be an assessment of current EU legislation, in particular the Directive 2000/53/EC, and the analysis of proposals for its update, which is expected for the end of 2022 (European Commission, n.d.). The goal is to summarize the main points the Commission wants and needs to address in this revision. Both the literature review and the material flow analysis, the thesis' methodological approaches, as well as interviews with industry experts will help to answer the following research questions:

1. **What should the 2022 revision of the EU ELV Directive include against the background of changing driving technologies?**

This thesis is thereby focusing on four material groups: steel, aluminum, plastics, and copper. A discussion of each of these material's potentials in the future will lead to the answer of the second research question:

2. **How will the transition toward EVs change the material flow of ELVs in general, and of ELV steel, aluminum, copper, and plastics in particular?**

Answering this second question allows to look at the problem on a more general level and answer the third research question:

3. **Where are the main gaps between the current ELV recycling scheme and an ELV recycling scheme focused on EVs?**

Finally, the findings will come down to one central question:

4. **Is the EU ELV recycling industry ready for the large-scale introduction of EVs?**

To answer these four questions, the methodology described in Chapter 3 is applied.

3. Methodology

3.1. Literature Review

A thorough literature review lies at the center of this thesis. Challenges of current ELV recycling practices were researched and the present and future potentials of steel, aluminum, copper, and plastics recycling were derived from existing studies and papers. The literature review allowed to collect both quantitative and qualitative data that could subsequently be used for the discussion within the other two methodologies. Regarding quantitative data, Eurostat and the ACEA were very valuable sources. The literature review also showed that, although practices have been established for decades, ELV recycling really is of topical interest. Excluding interviews and sources for pure data, more than a third of this thesis' sources stem from the last three years – 13.5% from 2022, 10.1% from 2021, and 13.5% from 2020. For Chapter 4.1.4, dealing with the revision of the EU Directive 2000/53/EC, the Commission Staff Document from 2021 and position papers such as the ones by the European Environmental Bureau (EEB), the European Automobile Manufacturers' Association (ACEA), and European Aluminum were important sources.

3.2. Material Flow Analysis

A material flow analysis (MFA) helps to calculate and visualize the journey of different products, materials, or substances. This thesis makes use of MFAs to compare two different ELV recycling systems: the current one, using numbers dating from 2019, and a hypothetical one as of 2045 - 15 years after 2030, when a dominating share of new car registrations is assumed to be EVs. An MFA is done for ELVs in general, and for the four material groups separately. The chosen software to generate the MFA diagrams is STAN 2.7.

3.3. Expert Input

In May 2022, a conversation via Zoom was held with Ing. Walter Kletzmayr from *Arge-Shredder GmbH,* a consortium of six Austrian shredder companies. The focus of this conversation was on the upcoming revision of the EU ELV Directive, but also included insights into technological challenges shredders face with the large-scale introduction of EVs. Similarly, first-hand information was collected via E-mail conversations with Auto Metzker in 2022, an Austrian car recycling company that exists since 1936 (Auto Metzker, n.d.). In total, 12 questions were answered by Josef Metzker and colleagues.

Input from both experts was used to support certain claims and data from the literature review and provided thought-provoking impulses throughout the thesis.

4. Results & Discussion

4.1. Literature Review

The following sub-chapters describe the main results of the conducted literature review as described in Chapter 3.1.

4.1.1. State-of-the-Art ELV Recycling

State-of-the-art ELV treatment focuses on metals, in particular iron and steel, and precious metals (Li, et al., 2020). Indeed, the steel and the aluminum industry can be considered the two largest scrap customers (Brahmst, 2006). Retrieving iron as secondary resource has been a particular focus in the last decades (Sakai, et al., 2014). In theory, metals can be recycled infinitely without losing their quality. However, the addition of alloys and mixing of different metals leads to secondary metals with poorer quality properties, especially when separation is incomplete. Consequently, car recycling is considered to be of open-loop nature. Indeed, only around a third of ferrous components in a car are secondary materials (Nakamura, et al., 2012). In our interview, Kletzmayr also stated that it is a very open system since the shredder output cannot be identified. In Austria, only about 10 to 15 % of it is from cars, the rest comes from other sources such as electrical EOL equipment (Kletzmayr, 2022). However, ELV supply chains may also be considered closed-loop chains when materials move in a circular flow (Krishna Mohan & Amit, 2020).

The combination of different metals and their alloys also makes their recycling so complex (Ohno, et al., 2015). Furthermore, some of the about 60 metals used in a car are critical ones. Those are not only used in electronic components, but also in aluminum and steel alloys (Ortego, Valero, Valero, & Iglesias, 2018).

Metals are lost after shredding either quantitively - due to landfilling or in the slag resulting from smelting – or qualitatively - caused by the dissolution of contaminants in molten metals (Amini, Remmerswaal, Castro, & Reuter, 2007). The latter case is the mixing of two species, which impairs the original functionality of either species (Nakamura, et al., 2012). The necessary dilution of contaminated metals with high-purity material should the maximum allowable content be exceeded, depletes the metal's resources (Amini, Remmerswaal, Castro, & Reuter, 2007). The resulting dilution losses can be quantified using the exergy of the primary material used to dilute the metal. Nakamura et al. found that eliminating dilution losses, quality losses of disassembled steel scrap, and, to a lower extent, quality losses of shredded steel scrap could save 87% of pig iron production on a single-car level. Consequently, up to 38% of CO_2 can be saved. Conversely, ignoring dilution and quality losses overestimates the CO_2 reduction potential of scrap recycling. Improved sorting and design as well as an easier identification of chemical properties could help reduce the losses (Nakamura, et al., 2012).

One could argue that the automotive sector is both the main sink and source of scrap (Løvik, Modaresi, & Müller, 2014). The next Chapter will describe what the state-of-the-art recycling process currently looks like. To be valid for the EU as whole, a very general description as shown in Figure 3 is given. The thesis focuses on four material groups: besides the metals steel, aluminum, and copper, it also addresses plastics.

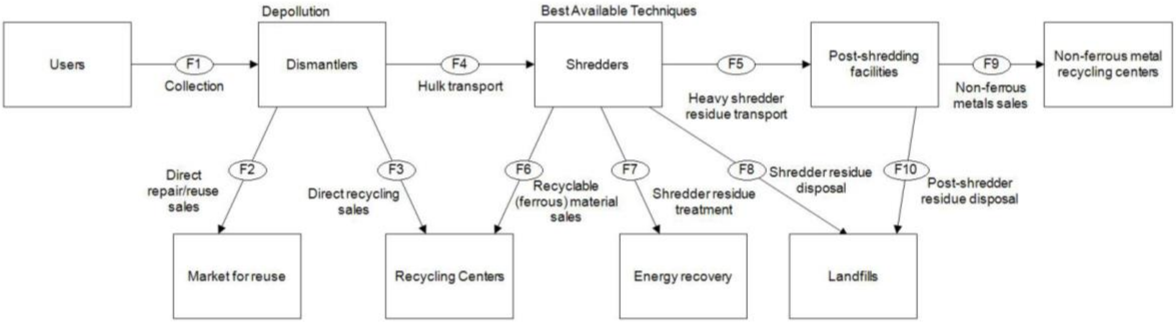


Figure 3: ELV treatment process

4.1.1.1. ELV Recycling Procedure in the EU

A typical recycling scheme of ELV involves the following parties: users, collectors, treatment companies, shredders, and post-shredding facilities (Ortego, Valero, Valero, & Iglesias, 2018). In the EU, there are about 14,000 authorized treatment facilities, where depollution and dismantling have to take place, as well as 350 shredding facilities (European Commission, 2021).

Recycling starts with dismantlers collecting ELV, dismantling them, and selling parts for a revenue. Parts may be reused, repaired, remanufactured, or scrapped (Krishna Mohan & Amit, 2020). Oil is going to energy recovery (Ortego, Valero, Valero, & Iglesias, 2018). Annex I of the EU ELV Directive prescribes that depollution has to take place. This includes removing batteries, neutralizing explosive parts such as air bags, collecting and storing oils, fluids, and fuel as well as removing mercury-containing components as far as possible (European Union, 2000). This step of removing hazardous components is part of this first step of the recycling process, dismantling, which reduces the vehicle's weight to up to 70% of its original weight (Sakai, et al., 2014). But it is not necessarily the very first step: in accordance with the 3Rs (reduce, reuse, recycle), parts that may still be useful for other cars are harvested even before depollution takes place (Auto Express, 2022). Vehicles or parts may be exported, too (Krishna Mohan & Amit, 2020).

A post-dismantling vehicle is a hulk. Hulks are transported to shredders where they are crushed (Krishna Mohan & Amit, 2020). Shredders can process entirely dismantled car bodies in a mill, producing fist-size primary steel items by cutting. Ferrous and non-ferrous materials are separated by magnets (Sawyer, 1974). In the EU, shredders have to work based on the best available techniques-principle (BAT) (European Commission, 2021). The 2000-horsepower type of shredder, a hammermill, is used frequently (Simic & Dimitrijevic, 2012). The shredded steel scrap falls under the EU specification "E40" when 95% of the pieces are smaller than 200 millimetre and no piece exceeds 1 centimetre. E40 must be prepared to be directly chargeable and must be free of moisture, cast iron, tin cans, or other material from incineration, copper, lead, steriles, and tin (EFR, 2007). In theory, the outcome of shredders should be free of hazardous substances. In reality, however, impurities often occur (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020). The resulting metallic and non-metallic components are separated by physical or chemical processes and sold to specific recycling centers (Krishna Mohan & Amit, 2020).

Shredding the hulks allows for a recovery rate of up to 80%. The products are approximately 70% magnetic metals (iron and steel), approximately 23% light materials such as PVC, paints, ceramics, or glass, about 6% mixed non-magnetic metals (aluminum), and less than 1% iron that contains copper (0.2-0.3%) and can be recycled (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020).

Magnetic separation is used to remove ferrous metals from the shredded volume (Ohno, et al., 2015). Heavy plastics and non-ferrous metals that remain after magnetic separation are often split by a so-called heavy media process, a flotation method that works well for copper and aluminum. For plastics, however, flotation is not so efficient. Instead, special firms take them up, separate them – there are approximately 40 different plastic types and polymers used in a car -, and produce pellets out of it. However, most of the plastics recovered from vehicles are downcycled, or not recycled at all (Auto Express, 2022).

Besides metals, what is left from the vehicles is dubbed automotive shredder residue (ASR). It represents 20% to 25% of the average weight of an ELV, or about 200 kg (Simic & Dimitrijevic, 2012). Theoretically, approximately half of ASR is plastics, about 13% is rubber, and about 20% is glass. The rest consists of other materials, mostly textiles or carpets. But in reality, dirt, moisture, and metal residues further affect its composition, representing up to 35% of its weight. Toxic components such as lead, arsenic, chromium, cadmium, or polychlorinated biphenyls (PCBs) may also be found in ASR (Staudinger & Keoleian, 2001). Besides possible contamination, the physical heterogeneity of it and a lack of secondary markets that leads to expensive additional processing tend to hinder complete recovery of ASR (Simic & Dimitrijevic, 2012). Shredders are responsible to send it to landfill sites or to energy recovery (Krishna Mohan & Amit, 2020). Although techniques to recycle ASR are rather demanding due to its calorific value and ash content, recycling ASR has become a need to meet recycling targets that are difficult to reach by recycling metals only (Sakai, et al., 2014).

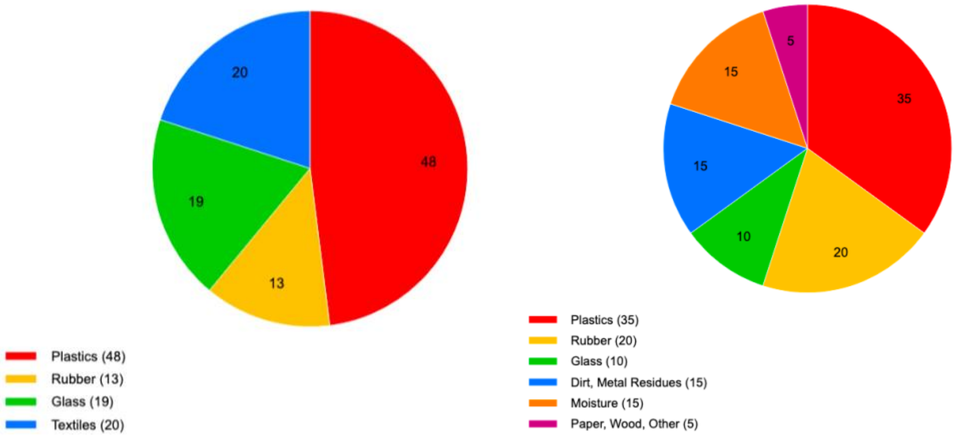


Figure 4: ASR composition – theoretical (left) and in reality (right) [based on (Staudinger & Keoleian, 2001)]

In the UK, a landfill tax of over 95 pounds per ton incentivized scrappers to recycle every material and reduced the share of light materials such as plastics, fabrics, foams, and rubbers being landfilled. Instead, they are converted into gas to produce electricity and power households (Auto Express, 2022). What is more, ASR can be introduced into a gasifier without any pre-treatment (Simic & Dimitrijevic, 2012). However, a 2011 study by Simic and Dimitrijevic showed that increasing the cost for landfilling does not automatically reduce the amount of disposed ASR in the EU (Simic & Dimitrijevic, 2012). Evidently, banning landfilling completely has a larger effect. A study by Cardamone et al., for example, showed that banning landfilling for ELV plastics and instead treating them in thermal recovery overall improves the environmental performance of ELV recovery in terms of carcinogens, respiratory inorganics, non-renewable energy, and non-carcinogens. Only global warming as a performance indicator will be negatively influenced owing to increased thermal treatment (Cardamone, Ardolino, & Arena, 2022).

Air classifiers at shredders generate "light" ASR, the non-ferrous, non-metallic stream. The "heavy" shredder residue constitutes the rejected, contaminated stream when non-ferrous metals are further processed (Staudinger & Keoleian, 2001). While light ASR, also called fluff, is taken care of by shredders, the heavy fraction is treated in post shredding technology (PST) facilities that use eddy-current and density separation to separate non-ferrous metals and sell them to recycling centers – mainly copper, zinc, and aluminum (Ortego, Valero, Valero, & Iglesias, 2018). Building PST facilities may be incentivized by EU recycling targets, national landfill bans, or economic benefits from the sales recovered metals (Cardamone, Ardolino, & Arena, 2022).

Shredding and post-shredding outputs are delivered to smelters, where aluminum or steel is produced. Shredding including post-shredding is designed to mainly recycle aluminum, steel, zinc, and copper alloys. Magnesium is part of the aluminum cycle as secondary alloy (Ortego, Valero, Valero, & Iglesias, 2018). Batteries containing lead, but also air bags or fuel tanks, are being treated separately due to their toxicity and potential damaging effect on shredders (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020).

Some manufacturing brands have established their own scrap schemes and encourage owners to return cars with authorized dealers – often incentivized by a discount on a new car. This way, scrapping via official systems is more likely and the brand's responsibility to ensure legal recycling is easier to track. Unofficial scrapping, on the other hand, is encouraged by low steel prices and the subsequent export of ELVs – among other factors. In the UK, there is at least a cash ban for selling scrap, albeit enforcement is lacking (Auto Express, 2022).

4.1.1.2. Success and Challenges

By reusing old car components, dismantlers set a good example already (Allwood, 2012) as, just like other socioeconomic players, they should follow the 3Rs principle (Sakai, et al., 2014). Saving raw material and energy as well as protecting the environment and creating jobs are among the more strategic goals of recycling (Janjić, Bukvić, & Stojanović, 2016). Increased employment results from bureaucratic work, but also from the different facilities that treat ELVs as shown in Figure 3. While the existence of a legal framework in the EU has successfully promoted ELV management, there are still some problems that need to be tackled, including proper information on dismantling already during the design stage, the collection of obsolete cars and the prevention of illegally dumping or using them, the treatment of hazardous substances, component recycling, and material separation during shredding and post-shredding (Sakai, et al., 2014). Accordingly, besides low dismantling rates and illegal dumping, costly recycling of materials such as plastic and rubber as well large quantities of toxic waste are among the symptoms of a malfunctioning recycling industry (Janjić, Bukvić, & Stojanović, 2016). Even if an ELV may be recycled legally, waste that is generated along the treatment stream – especially fluids such as brake fluids or oil filters - may not be classified and disposed of properly (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020).

In a 2001 report prepared by the University of Michigan, Staudinger & Keoleian emphasize that the environmental burden of ELVs depends on the materials they contain. A direct burden would be the generation of ASR, or tires. Indirectly, emissions associated with supplementary activities such as the removal of fluids or the smelting of steel cause environmental burdens, too. Mercury release either during shredding from switches containing mercury or during the melting in electric arc furnaces (EAFs) may be of concern, as well (Staudinger & Keoleian, 2001). The use of mercury, as well as lead, cadmium, and hexavalent chromium, in cars themselves is banned by Article 4 of Directive 2000/53/EC (European Union, 2000). Nevertheless, blast furnaces, required to produce steel for the automotive sector, were still responsible for 13% of mercury emissions in the EU in 2017 (Kogut, Tuz, & Burmistrz, 2021).

The recycling of ASR is a big challenge of ELV recycling. Techniques to recycle ASR are rather demanding due to its calorific value and ash content. In the EU, there are two approaches to have a larger share of ASR being recycled: intensifying dismantling or collecting materials after shredding (PST) (Sakai, et al., 2014). In most countries in the EU, all non-metal shredder residues are typically sent to disposal after metals have been recovered and no PST plants are operated to collect them separately, whether integrated into shredding facilities or outside (Cardamone, Ardolino, & Arena, 2022). However, Sakai et al. argue that also in PST systems, plastics usually end up in thermal recovery and glass in disposal sites. Better dismantling would thus have a more positive impact on the recycling rates of glass and plastics. While ASR's hazardousness typically increases recycling cost, intensified dismantling would decrease it. Developing techniques to dechlorinate ASR has been made necessary by the waste incineration Directive 2000/76/EC. Persistent organic pollutants (POPs) are also of concern, both in ASR recycling and treatment. It is important to note that ASR also contains valuable (depleted) resources such as silicon, potassium, and calcium (Sakai, et al., 2014).

Staudinger & Keoleian, in 2001, concluded that ASR management is challenging, but that eco-design, in-house management of ELVs by manufacturers, and the increasing value inherent to ELVs are possibilities to tackle this challenge (Staudinger & Keoleian, 2001).

Interestingly, Ortego et al. conclude that while the disassembly of electric parts containing metals, the disassembly of gearbox and engine parts containing steel alloys, special shredding systems that generate different scrap types out of aluminum or steel alloys, information systems for treatment facilities allowing proper disassembly, and recycling critical metals in ASR are important, eco-design to ease disassembly in the first place is the most important measure (Ortego, Valero, Valero, & Iglesias, 2018). Although it may compete with safety, comfort, or profitability, easy disassembly of ELVs should be considered already in the construction stage (Janjić, Bukvić, & Stojanović, 2016). The time it takes to disassembly the vehicle is influenced by how the vehicle is constructed, and how much individual components are connected (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020). Sakai et al. also emphasize the importance of eco-design as well as of sharing dismantling information throughout the supply chain (Sakai, et al., 2014). Since a car contains more than 15,000 different parts, a ranking according to the value of the material in the respective part would help achieve a more ecological car design (Ortego, Valero, Valero, & Iglesias, 2018).

Today's recycling facilities are primarily designed for the separation of ferrous from non-ferrous material, i.e., steel from aluminum, zinc, or copper. In this process, alloying elements are lost either as part of ASR that is eventually landfilled or due to downcycling when being sent to smelters in the last stage. Ortego et al. quantify downcycling as the amount of additional virgin metal needed to manufacture a car when the starting material is ELV scrap. When the downcycling of a specific vehicle part has a small negative value, metals are recycled to a high functional degree. In their case study using a 1,270kg-heavy SEAT Leon II model, 32.8kg, or 4.5%, of its 780kg-heavy metal part are not functionally recycled (i.e., the downcycling value). The highest loss is attributable to aluminum due to its high rarity value and its bad recyclability as alloy in steel. Indeed, 0.75% is the average content of aluminum in steel used in the SEAT model which has a lot of ultra-high strength steel parts containing up to 2% of aluminum (Ortego, Valero, Valero, & Iglesias, 2018). Impurities are the main reasons for why metals cannot be recycled endlessly. For plastics, chemical degradation is to blame. Goals of recycling must be to retain the quality during production, use, and recycling and to employ high-quality material only when needed (Ekvall, Fråne, Hallgren, & Holmgren, 2014).

Table 1 summarizes the main successes and challenges of state-of-the-art vehicle recycling.

Table 1: Main successes and challenges of state-of-the-art ELV recycling

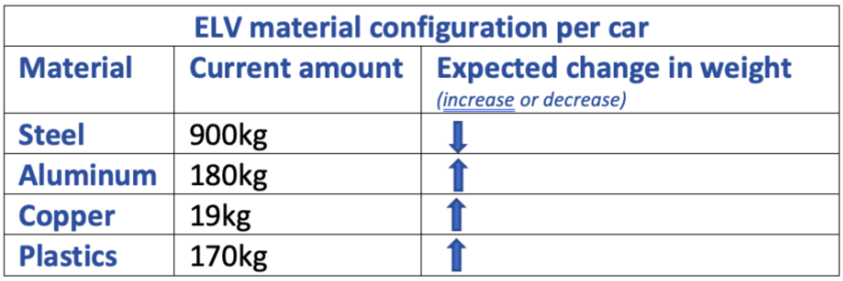
State-of-the-art ELV Recycling	
Successes	**Challenges**
Reusing parts from dismantling	Recycling of ASR
High recycling rates / saving raw material	Toxic waste
Saving energy	Downcycling
Creating jobs	

The next sub-chapters look at the development of three metals (steel, aluminum, copper) and of plastics to conclude how the material demand and, consequently, ELV recycling will change for these material groups when a shift toward electric fleets manifests itself as of 2030.

4.1.2. ELV material changes

The way how cars are designed has been changing during the last decades; iron alloys have been replaced by aluminum alloys in wheels or cylinders, plastics has been increasingly used for the interior, and the electrification of cars increased the demand of metals, for example rare earth metals as well as metals such as cobalt, manganese, lithium, and nickel to produce batteries (Ortego, Valero, Valero, & Iglesias, 2018). Table 2 gives an overview of the amounts of ELV steel, aluminum, copper, and plastics that are currently generated from ICE cars in the European Union as well as their expected development in the next decades due to increased electric chargeable cars. The next Chapter will dive into each of these material groups to show where their main potentials now and in the future lie.

Table 2: ELV material configuration per car



ELV material configuration per car		
Material	**Current amount**	**Expected change in weight** *(increase or decrease)*
Steel	900kg	⬇
Aluminum	180kg	⬆
Copper	19kg	⬆
Plastics	170kg	⬆

4.1.2.1. Steel

Steel is the main material used in cars. Globally, 93 million tons of iron and steel are used per year to produce light trucks and cars (Ekvall, Fråne, Hallgren, & Holmgren, 2014). In 2019, the average weight of steel used in a vehicle was 900kg. 40% of it is found in high-strength applications such as doors, closures, and the body structure. 23% and 12% are used in the drive train and the suspension, respectively, and the rest is in steering systems, wheels, fuel tanks, braking systems, and tires. 60% of the total body structure is made from advanced high-strength steel (AHSS), which can reduce the total weight by up to 10% (World Steel Association, n.d.). An Austrian recycler states that about 70% of the used parts he is selling are of steel alloys and hardly any part is 100% steel[1].

Recycling steel has a great leverage effect in reducing the automotive industry's environmental impact: 1 ton of recycled steel reduces the demand of the raw materials iron ore, coal, and limestone by 1,100 kg, 630 kg, and 55 kg, respectively. Furthermore, it saves 642 kWh of energy, 1.8 barrels of oil, and 2.3m^3 of landfill area. Overall, recycling steel reduces energy demand by 74% and virgin material demand by 90%, uses less water (40%), and produces less water and air pollution (76% and 86%, respectively) and almost no mining waste. Steel is suitable for recycling because its physical properties do not change, no matter how often the recycling process is repeated. It can therefore be used for the same purpose as originally intended (primary recycling). Besides being employed again in vehicles, it may also be used for office supplies, electrical equipment, cans, or construction material for buildings, roads, infrastructure, and railways (Bureau of International Recycling, n.d.(a)).

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"When you take a building down, the steel girder is totally reusable. All you need to do is unbolt it and clean it, because steel doesn't degrade with use. Re-use means we can avoid all the energy of melting, casting and re-rolling old steel." (Allwood, 2012, p. 51)

Although, in principle, the recyclability of steel is the same, steel from ELVs is still kind of a different story than EOL steel coming from buildings. By looking at ELV steel, this thesis focuses on obsolete, or post-consumer, scrap. This excludes unavoidable by-products in steelmaking or steel fabricating which is reintroduced into the steel mill (Sawyer, 1974).

Steel from shredders is going to the foundry. Subject to international standards, the scrap steel is a billion-euros market (Auto Express, 2022). Nakamura et al. found that ELV steel scrap is mainly used in construction, while pig iron, i.e., scrap resulting from steel production, is used for machinery such as cars. The latter goes to basic oxygen furnaces which produce high-quality products. The quality needs of the construction sector are lower, hence EAF products made from old scrap are used (Nakamura, et al., 2012).

Already in 1974, Sawyer defined three elements that must be in balance in order for automobile scrap being technically feasibly reused as ferrous material in the steel industry:

"The desired product mix and related specifications for each product
The level of impurity removal undertaken in the scrapping process
The quantity of dilution provided by the steelmaker"
(Sawyer, 1974, p. 29)

The mixing of alloys and the closely related problem with impurities are the biggest concerns in steel scrap recycling. Currently, parts that cannot be removed such as airbags or AC coolants, parts that can be reused such as the engine, and parts containing copper such as wire harnesses are removed (copper reduces steel materials' workability). The rest is shredded. Magnetic separation is used to remove ferrous metals from the shredded volume, which are recycled to be used as iron source for the production of steel via EAFs (Ohno, et al., 2015). Approximately 10% of an ELV's ferrous parts enter the production of a new vehicle. Of the other 90%, some parts are reused as second-hand components, but most goes to other products, e.g., buildings. It is precisely for this majority that a quality loss occurs. Tin and copper are the most undesirable contaminants in iron and steel, especially since the melting in basic oxygen furnaces or EAF does not remove them (Nakamura, et al., 2012). Stainless steel also leads to relatively high concentrations of molybdenum, nickel, and chromium in ELV scrap (Ohno, et al., 2015).

Except for chromium, impurities such as copper, nickel, molybdenum, and tin are fully transferred from scrap inputs to steel outputs. The end product must thus be blended with pure iron or steel to be used as steel for car bodies again (Sawyer, 1974), leading to downcycling.

Steel that is formed into rolls of thin sheets and then into complex forms should be low in alloying metals (Sawyer, 1974), but alloys are very much used: in the vehicle frame as high-tensile steel or in exhaust parts as stainless steel, for example. The problem is that different car parts have different concentrations of alloying elements; when being mixed, higher concentrations in certain parts will be diluted with lower concentrations in others. For example, manganese is relatively highly concentrated in the suspension compared to other parts. The vehicle body and brakes have rather low alloy concentrations. When these are mixed with highly concentrated parts, however, scrap quality is impaired. Some alloying elements, such as chromium or manganese, oxidized rapidly and generate slag. Others such as molybdenum or nickel remain in the molten product and have to be diluted with primary iron to fulfill quality criteria (Ohno, et al., 2015).

Ohno et al. suggest sorting scrap into three categories, as shown in Table 3, to reduce alloy dilution and iron contamination: suspension parts with high manganese concentrations, exhaust parts with high molybdenum, nickel, and chromium concentrations, and the rest. The first type of scrap could be used for spring steel, the second one for austenitic stainless steel, and the less-contaminated third category can be used as an iron source in steel production. This sorting into these categories is an easy implementable process since ELV recycling companies wouldn’t need a lot of knowledge about the materials’ composition or invest a lot into their existing facilities. The key lies in switching from recycling that aims for using steel scrap as an iron source to focusing on the content of alloying elements in it. Similarly, scrap trading would need to switch from pricing based on scrap's shape to pricing based on its alloy content. This is especially pressing as current designs in the car manufacturing industry tends to increase the amount of alloying elements (Ohno, et al., 2015).

Table 3: Steel scrap categorization [(based on (Ohno, et al., 2015)]

Steel scrap categorization		
Type	**Impurities**	**Use**
Scrap from suspension parts	High: manganese	Spring steel
Scrap from exhaust parts	High: molybdenum, nickel, chromium	Austenitic stainless steel
Scrap from parts other than from the suspension or exhaust system	Low	Iron source

Besides AHSS, high-strength steel (HSS) and ultra-high-strength steel (UHSS) have been dominantly used by vehicle manufacturers in the last decades. Using AHSS instead of aluminum might even be more climate-friendly, according to certain LCAs. Steel grades are still evolving and there are various reasons for their use in EVs, such as using non-oriented electrical steel (NOES) for motors, which improves range (American Iron and Steel Institute, 2021). Electrical steel is magnetically soft, thin, and tough. A study conducted for voestalpine claimed that it is this kind of steel used in electric motors that moves the vehicle. An EV contains 40 to 100kg of it. Indeed, producing lighter steel has been a focus of the industry in the past (Steiniger, 2019). Especially Tesla's shift from aluminum to steel for its Model 3 has silenced some voices claiming aluminum will be dominant. For HEVs, however, it is very likely that aluminum will remain the preferred material (Onstad, 2018). In 2009, the Öko-Institut did not expect a huge difference between the share of steel in ICEVs and in BEVs with 1.115kg and 1.105kg of steel, respectively (Öko-Institut e.V., 2009a).

4.1.2.2. Aluminum

Aluminum is so widely used because of its versatility, light weight, high formability and corrosion resistance (Hatayama, Daigo, Yasunari, & Adachi, 2009). Just like steel, it has a great potential for recycling: it can be easily used for its intended purpose (primary recycling). Thanks to its strength and flexibility, it is ideal for the construction sector (roof, window frames, building structure) and the transportation sector (from bicycles, to cars and trucks, to trains and airplanes). However, most of it is used for cans and foil. Instead of copper, aluminum has also been used in high-voltage transmission lines since 1945 (Bureau of International Recycling, n.d.(b)).

As aluminum is a fully recyclable material that retains its properties (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020), the recycling of the material from cars has long been recognized as an important step to reach global climate goals. This is an important development since about 1.1% of global CO_2-eq are caused by its production. Today, more than 20% of the global aluminum demand is met by post-consumer scrap. However, while recycling has both environmental and economic advantages – aluminum production is a very energy-intensive process -, each recycling cycle reduces the material's quality due to the different alloys used that limit potential applications of recycled aluminum. In order to properly assess aluminum's material flow (MF), it would thus be necessary to apply dynamic models that take the qualitative changes of each type into account (Løvik, Modaresi, & Müller, 2014). In other words: cascading dominates in aluminum recycling (Hatayama, Daigo, Matsuno, & Adachi, 2012). What is key for efficient recycling of aluminum in cars is the cooperation between the automotive industry, primary and secondary aluminum suppliers, and ELV dismantlers (Løvik, Modaresi, & Müller, 2014).

As mentioned in Chapter 4.1.1.1, metals are separated using magnetic and eddy-current, but also sink-float techniques, which do not allow to identify different kinds of alloys. Hatayama et al. could show that recovering alloys individually leads to a higher usage rate of scrap and thus a lower primary material requirement compared to the current practice of alloys being smelted collectively (Hatayama, Daigo, Matsuno, & Adachi, 2012).

The typical alloying elements used for aluminum are silicon, iron, copper, manganese, magnesium, and zinc. When aluminum is recycled, these elements are reused, and new ones are added. When there is too much of those alloys, primary aluminum is added to achieve dilution. Hatayama et al. looked at the aluminum MF in Japan, the US, Europe, and China – together consuming about 80% of the world's aluminum – to evaluate chemical differences along the aluminum recycling flow. They found that it is especially silicon, iron, copper, and manganese that impair the material's quality. But since scrap is a mixture of several alloys, a separation into different alloy types is difficult (Hatayama, Daigo, Yasunari, & Adachi, 2009).

Cast alloys with a high copper content act as a bottom sink since they absorb scrap from other alloys but can themselves not be used for different alloys (Løvik, Modaresi, & Müller, 2014). Since the production of cast alloy can tolerate other elements quite well, it is getting most of the scrap from EOL products, leading, once again, to a cascading, or downcycling, effect (Hatayama, Daigo, Matsuno, & Adachi, 2012). In contrast, the scrap absorbtion rate is very low for wrought alloys, except for the sub-category dubbed 6xxx. Assuming proper dismantling, 6xxx alloys and cast alloys with low copper content could slow down the downcycling behaviour of the sector. But wrought alloys – which besides 6xxx also include 1xxx and 5xxx – are typically removed from the system with mixed scrap due to insufficient dismantling (Løvik, Modaresi, & Müller, 2014). X-ray analysis, density, and 3D sensing – based on artificial neural networks (ANNs) - are potential techniques to sort wrought alloys out of scrap, so that they can at least be reused for wrought alloy production (Hatayama, Daigo, Matsuno, & Adachi, 2012). A very promising chemical method is laser-induced breakdown spectroscopy (LIBS), which is assumed to successfully identify both wrought and cast alloys in 90% of all cases (Løvik, Modaresi, & Müller, 2014) and may also be combined with ANNs (Campanella, et al., 2017).

In a typical ICE vehicle, most of the chassis and the engine parts are of cast alloys and most of the body and the interior is of wrought alloys (Bell, Davis, Javaid, & Essadiqi, 2003). Aluminum components in HEVs and EVs are different to those of ICE vehicles since the driving systems are different. In EVs, there is no ICE, but a large demand for wrought alloys used in the power-supply box. As far as HEVs are concerned, Hatayama et al. assume that more cast alloys are used as compared to ICEV (Hatayama, Daigo, Matsuno, & Adachi, 2012). Aluminum's use in car manufacturing has been increasing continuously: the share of aluminum per car increased by an average of 75kg between 1998 and 2008. By 2030, up to 10 million tons of it may be used in EVs and HEVs – an increase by a factor of 10 compared to the current amount of aluminum that is used in cars (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020). The Tesla S model, for example, contains about 660kg of aluminum (Onstad, 2018). Hatayama et al. showed that by 2050, vehicles will be responsible for about 25% of both aluminum demand and scrap globally. Around the year 2030, EVs and HEVs will exceed the aluminum demand of ICEs. However, the authors assume ICEs will remain the dominant discard source until the mid-2040s (Hatayama, Daigo, Matsuno, & Adachi, 2012).

In 2019, the aluminum content for a basic “Opel Adam” car was 76.8kg, for a more compact car, the amount is 152.4kg, and a large car has over 440kg. By 2025, this amount is expected to increase by 2.9kg, by 18.3kg, and by 22.2kg, respectively. An increase in the aluminum content is actually expected for all types of cars, independent of their size or propulsion technology. In fact, the overall average content is expected to increase from 179.2kg to 198.8kg between 2019 and 2025. Aluminum in cast, sheet, extrusions, and forged form is expected to increase by approximately 1,8%, 27%, 40,5% and 4,9% respectively. The highest amount will then still be used for the cast with 118.1kg, followed by aluminum sheet with 43.2kg, aluminum extrusions with 26.7kg, and forged aluminum with 10.7kg (Drucker Frontier, 2019).

4.1.2.3. Copper

Copper and copper alloys are used because of their high thermal and electrical conductivity and their resistance to corrosion. The total weight of copper in cars varies a lot depending on the model, but in conventional cars, it is somewhere between 15kg and 29kg. It is used in wirings for electronical parts, which easily reach a length of one kilometer. From the starter motor, to lights, to navigation systems, to windows, to air bags – they all rely on copper (School Science, n.d.). Around 500 components containing leaded copper alone can be found in a car, according to a report by the Öko-Institut (Öko-Institut e.V., 2016).

But recovering copper is not in the focus of ELV treatment today. Although copper prices are high – they are currently rising at unprecedent rates in a speedy recovery from the pandemic (Norland, 2022) -, separately collecting copper is still not economical (Kletzmayr, 2022) (Brahmst, 2006). Ekvall et al. found that reducing the copper content would increase the recycling rate and reduce the minimum requirement of steel form iron ore from 203 to 180 million tons per year globally. 66 instead of 89 million tons of scrap would have to be discarded (Ekvall, Fråne, Hallgren, & Holmgren, 2014). In theory, separating the red metal fraction (copper and copper alloys) and grey metals is quite easy via their specific weights and the use of eddy-current-separations prior to float-sink-plants (Kletzmayr, 2022).

But it is highly unlikely that the copper content in cars will decrease. Instead, it will be necessary to improve the design of wires to make their removal before shredding easier, such as changing the routing of wires to make them more accessible and easier to detach. Increased customization also led to differences in wire harnesses that are not always recognizable for dismantlers, thus decreasing reusability. This is one of the reasons why most copper is passed on to shredders. During shredding, magnetic separation is never perfect and copper from motors may be attached to ferrous streams. Eddy-current separation can subsequently separate the non-ferrous fraction including copper. Afterwards, density techniques are used to separate the copper (Brahmst, 2006). Due to its higher density of almost 9g/cm^3, it can be separated from 2.7g/cm^3-dense aluminum or 1.7g/cm^3-dense magnesium (School Science, n.d.). Together with zin and brass it is part of the heavy part of scrap, which is sold from shredders to other companies further treating it. How the available technologies are used, however, depends on global market prices. A considerable part of ELV copper might still end up in landfills (Brahmst, 2006).

Copper in ELV is first and foremost a contamination problem – and with up to 70 electric motors per vehicle a very common one (Kletzmayr, 2022) - more for the steel than for the aluminum industry, however. This is because aluminum grades can tolerate varying shares of copper in scrap much better than steel (Brahmst, 2006). In Japan, scrap from ELV was found to be a major contributor to copper contamination in iron and steel scrap. Indeed, 0.2% of copper in steel scrap already makes recycling to steel sheets unsuitable. Section steel, however, can be produced – but only if the copper contamination does not exceed 0.3%: otherwise, dilution is necessary, which leads to dilution losses (Nakamura, et al., 2012). As long as steel use is higher than the amount of available scrap, there is enough material to dilute copper concentrations in scrap and copper would not limit the recycling potential. However, when the use decreases, scrap containing copper will have to be either discarded or sent to copper recyclers. Aluminum and zinc do not pose quality issues as they are separated in furnaces (Ekvall, Fråne, Hallgren, & Holmgren, 2014).

Although there is the technical possibility to detect the copper by means of X-ray sorting, this is an extremely expensive system that may be used only for very large plants with an output of more than 150 tons of scrap per hour. The six shredders in Austria are rather small and rely on manual sorting (Kletzmayr, 2022).

The reason why this paper includes the material is that the share of copper in non-ICE vehicles is increasing dramatically, driven by changes in motorization. In fact, the copper content in EVs is estimated to be double the amount of copper you find an ICE vehicle with 38.5kg, 60kg, and 83kg of copper in HEVs, PHEVs, and BEVs, respectively (International Copper Association, 2017). The Öko-Institut e.V. even assumes that BEVs contain about 121kg of copper compared to 19kg that are present in an ICE reference vehicle. An electric motor with the power of 50 kW, for example, contains about 15kg of copper. About 20kg of copper are added when an ICE vehicle is being made fully hybrid. There is no increase in the copper content for FCEVs, however (except for FC-hybrid vehicles) (Öko-Institut e.V., 2009a). The trend of using increasingly sophisticated alloys from ferrous material increased copper contamination in the past, too (Nakamura, et al., 2012).

These expected higher copper contents will be interesting in economic terms (Li, et al., 2020). Importantly, extracting copper from scrap would make ELV recycling more efficient as copper could be re-used for high-quality needs, whereas scrap can be used for construction items that have lower quality requirements (Eminton, 2016).

Leaded copper will be of particular concern. Copper alloys such as bronze and brass typically contain up to 3.5%. of it. However, they are exempt from the ELV Directive's 0.1%-cap on lead in homogenous components and can have a lead content of 4%, but changing this is currently being discussed (see Chapter 4.1.4) (Copper Development Association Inc., 2022).

4.1.2.4. Plastics

In terms of volume, the average percentage of plastics in cars can reach 50% (Vehicle Recycling World, 2022). In terms of weight, about 14.8% of the average European ELV today is mixed plastics - tires, wire sheathings, and battery casings excluded. This percentage is expected to reach up to 20% in new cars (100-200kg), though with different compositions than today, e.g., as housings for electronics. The use of plastics in cars has the clear advantage of making vehicles lighter, which consequently leads to lower emissions (European Commission, 2021). Besides the light-weighting factor, the 20th century saw a significant increase in the use of plastics in passenger cars also because of the material's resistance to rust, the low-cost convenience it brings about and radar wave transmissibility (Emilsson, Dahllöf, & Söderman, 2019). They do not only replace aluminum parts, but also glass, e.g., as polycarbonate (PC) (Plastics Today, 2015). But already today, cars generate about 5% of the EU's total plastic waste (European Commission, 2021). There is thus the dilemma to keep vehicles' weights light and to combat plastic waste at the same time.

In the EU, about 1 million tons of mixed ELV plastics were collected in 2018 (Cardamone, Ardolino, & Arena, 2022). Plastic recycling starts with shredding plastic pieces (to produce pellets), removing metals and other contaminants (typically by using water streams), separating certain types of plastics and mixing the material with virgin material to produce new items (Plastic Collectors, 2020). Larger plastic parts can already be separated in the dismantling stage to be further sold as second-hand items. Most of ELV plastics, however, ends up in ASR and is as such sent to landfills or thermal treatment centers (Cardamone, Ardolino, & Arena, 2022). An Austrian recycler confirms that while some parts may be sold as used parts, most of it is sent to plastic shredder facilities.[2]

The trend to use new difficult-to-recycle plastics such as carbon fiber reinforced plastics further aggravates the situation (European Commission, 2021). For a long time used only for race cars, carbon fiber is today found in door, hoods, and fascias of standard cars. Mixing carbon fiber with polymers makes the material more affordable (Plastics Today, 2015). But greater mixing also means greater effort for recycling. However, Emilsson et al. argue that carbon fiber is interesting mainly for high-end cars – although they admit that the use of light-weight carbon fiber is higher for BEVs than for ICEVs - and will not become relevant for ELV recycling before autonomous driving has arrived in the mass market (Emilsson, Dahllöf, & Söderman, 2019)

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For China, Li et al. calculated that under business-as-usual from 2020 onwards, 4.6 million tons of recyclable plastics from ELV will be available by 2030. However, should a trend to light-weight vehicles occur, the number of recyclable plastics will reach 6.2 million tons. Li et al. even expect the potential of recycling plastics and rubber to surpass that of steel in long-term. This requires improvements in reuse and recycling technologies of dismantlers. Better sorting of plastics before the shredding may lead to a higher value in economic terms, since recycling becomes cheaper and easier (Li, et al., 2020).

A widely used plastic type is polypropylene (PP). The advantage of PP, used for gas cans or bumpers, is its heat and impact resistance (A&C Plastics, Inc., n.d.). A study by Emilsson et al. showed that the share of PP in a car’s top six plastic types is the lowest for diesel cars with 36% and the highest for PHEVs with 49% but remains the most important plastic type for all vehicle categories. While ethylene-propylene-diene-monomer (EPDM) is relevant as a top-six plastics type only for conventional cars, thermoplastic vulcanizate/thermoplastic elastomer (TPV/TPE) and acrylonitrile-butadiene-styrene (ABS) are relevant only for BEVs. Interestingly, the combined weight of plastics and polymers is lowest for BEVs with 122kg, and highest for diesel cars with 185kg. However, this may be due to a sampling problem: the authors could only compare ICEVs weighing more than 1,500 kg with BEVs since no BEVs lighter than 1,250 were found in their area of research, which was the Swedish automobile market (Emilsson, Dahllöf, & Söderman, 2019).

TPV is a grade of TPEs, i.e., polymer-rubber mixtures. TPEs are very elastic and are used in covers for airbags, handles, cables, or wires, for example. The material is also easily recyclable (Scott, n.d.). ABS is also a thermoplastic - contrary to thermoset plastics, these types of materials can be melted more than once without being burnt. This characteristic also makes ABS easy to recycle. ABS is often used for automotive parts because it is quite cheap and can be easily colored, but its rather low melting point of 105 Degree Celsius makes it unusable for parts subject to a lot of heat (Plastic Collectors, 2020). However, the coloring of ABS parts poses a serious problem to recyclers since near-infrared technology, which separates polystyrene (PS) very easily, for example, does not detect black color. And most ABS used in electronics is actually black. Even if electrostatic separation is used, which would be able to detect ABS in pre-concentrated scrap, the problems related to mixtures with different types of plastics and to contaminations with dust, glass, or metal residues remain (Sesotec, 2022).

The recovery options for plastics are municipal waste combustion, cement kilns, syngas production, or blast furnaces (Öko-Institut e.V, 2003). Cardamone et al. also emphasize that recovering plastics from ELVs strongly relies on advanced sorting. Additives such as stabilizers or brominated flame retardants (BFRs), but also volatile organic compounds (VOCs) contaminating scrap make mechanical recycling unfeasible for plastic recovery (Cardamone, Ardolino, & Arena, 2022). They present some innovative processes that could be added to the ELV recycling process following PST. Those include upgrading, CreaSolv®, Pyrolysis, Extruclean, and Modix. In their proposed scheme, all processes are used based on different densities and optics. While currently, recycling rates are obtained mainly during dismantling and reach 2.6%, the proposed scheme would yield a recycling rate of about 50%, especially because PP and PE (polyethylene) could be recovered more efficiently. Instead of 984 kilotons, only 232 kilotons would be combusted or landfilled per year. CreaSolv®, a process using dissolution and precipitation, is mainly responsible for such an improvement (Cardamone, Ardolino, & Arena, 2022).

As far as metal-plated plastics (MPP) are concerned, Xue et al. found that, compared to electrochemical or chemical recycling, which not only basically destroy the plastics but also consume a lot of chemical reagents and produce acid liquid and waste gas, mechanical recycling is more environmentally friendly and technically feasible. Crushing liberates the coatings from the material, which is subsequently separated in magnetic fields. MPP are widely used in the automotive industry and include letterings and badges of manufacturers as well as door handles and grills. Containing 90% ABS or an ABS mixture with polycarbonate, their coatings made out of copper, chromium, and nickel make it easier to transform the plastics into any desired shape. But the recycling process is hardly economically or technologically feasible (Xue, Li, & Zhenmig, 2012, p. 2661).

New standards on both the use of recycled plastics in new cars and relating to the waste management of plastic components ins ELVs are crucial to improve the circularity of automotive plastic parts. Indeed, those seem very near with the upcoming revision of the EU ELV (Vehicle Recycling World, 2022). Some manufacturers have already taken the initiative themselves. In the Renault Zoe model, an electric car, the seats are made of those plastics (Auto Express, 2022) and approximately a quarter of thermoplastics in a BMW model i3 are made from recyclates. Starting from 2025, Volvo wants to have minimum 25% of its plastics to be recycled - in every model (European Commission, 2021). Contrary to most authors, Milojević et al. expect a decline in the use of plastics with increasing obligations for car designers to chose recyclable materials. Especially the difficulty to recycle PVC may lead manufacturers to use alluminium allyos instead (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020). This is, however, not a very popular view.

Table 4 gives an overview of the main types of plastics present in ELVs – today and in the future.

Table 4: Types of plastics in ELVs

Types of plastics in ELVs		
Name	**Relevant**	
	... today (ICEVs)	**...in the future (BEVs)**
Polycarbonate (PC)	X	X
Polystyrene (PS)	X	X
Polyvinyl chlorine (PVC)	X	X
Polypropylene (PP)	X	X
Polyethylene (PE)	X	X
Metal-plated plastics (MPP)	X	X
Ethylene-propylene-diene-monomer (EPDM)	X	
Carbon fiber		X
Thermoplastic vulcanizate/thermoplastic elastomer (TPV/TPE)		X
Acrylonitrile-butadiene-styrene (ABS)		X

4.1.3. ELV Recycling as of 2030

Modern vehicles are environmental-friendly, zero-emission, and intelligently used and shall be produced out of recyclable materials and with renewable energy (Janjić, Bukvić, & Stojanović, 2016). In contrast to motor vehicles with ICEs, HEV, EV, and FC vehicles generally have a greater share of light alloys – aluminum (Al) and magnesium (Mg) – as well as more electric and electronic components. For the recycling industry, the dismantling of batteries (or, in case of FC, the dismantling of FC) containing cadmium

(Cd), nickel (Ni), and other elements will be a new requirement (Janjić, Bukvić, & Stojanović, 2016). Apart from that, Løvik et al. estimate the modus operandi of dismantlers will probably not be much influenced since their primary revenue comes from component sales instead of selling the hulk, which contains most of the aluminum (Løvik, Modaresi, & Müller, 2014). Janjić et al. estimate that the recycling industry will have to adapt to hybrid vehicles by 2030, to electric vehicles by 2035, and to FC cars by 2050 (Janjić, Bukvić, & Stojanović, 2016). The European Commission assumes that ELV management will have to change considerably between 2030 and 2035, owing to the increasing share of BEVs in sold vehicles. The first effect will probably be higher ELV management costs (European Commission, 2021). According to an Austrian car recycler, recycling EVs will not be economically feasible for recyclers under the current legal standards – since guidance on how to do it correctly is missing. While most of an ICEV's parts are recycled today, EV recycling is currently not cost-effective[3].

Sakai et al. assume that the development of EVs and HEVs is likely to require more non-ferrous metals (Sakai, et al., 2014). In contrast, in a study by Li et al., non-ferrous metals and rubber remain at 9% and 5% for both conventional and alternative passenger vehicles, respectively. The steel content differs only slightly, too. According to Li et al., steel makes up 71% and 68% of conventional and alternative passenger vehicles, respectively (Li, et al., 2020). The environmental effects of intensifying plastics recycling depend on their share in the hulk – with an increasing variety of different types of plastics, it will be crucial for the environmental impact of ELV recycling (Soo, Peeters, Compston, Doolan, & Duflou, 2017).

Whether steel is increasingly replaced by aluminum, which is thought to bring about a 40%-reduction in weight, is not definitely answered. The steel industry is working hard on lighter sheets for cars, with high-strength steel already being 20% lighter than conventional steel (Öko-Institut e.V., 2009a).

Furthermore, hazardous substances and rare metals are increasingly needed, which makes the recycling of ASR even more complicated (Sakai, et al., 2014). As far as rare metals

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[3] E-mail correspondence with Josef Metzker from Auto Metzker, 2022

are concerned, magnetic selection might not sufficiently separate them, and new post-shredding techniques may become necessary (Sakai, et al., 2014).

Li et al. discussed a business-as-usual as well as a light-weight case, the latter representing a trend of decreasing weight of vehicles within 2020-2030 by using plastic and aluminum parts instead of steel. A 1%-decrease of iron and steel's share is expected annually starting with 2020. An annual 0.5%-increase, on the other hand, is expected for plastics and non-ferrous metals (Li, et al., 2020). However, BEVs are heavier because their battery's weight starts at about 250kg (Öko-Institut e.V., 2009a). The 480kg-heavy battery in Tesla's most common model, its Model 3, is even the company's lightest design (Enrg.io, 2020). The battery pack is likely to increase the amounts of steel, aluminum, copper, and plastics in a car, while EV motorization needs less aluminum and steel, but more copper, than its ICE counterpart. Overall, EVs need more material and are thus heavier, which is mostly due to battery requirements (Öko-Institut e.V., 2009a). An Austrian recycler claims that the development of ELV recycling is in the wrong direction as the materials used in order to reduce EVs's weight are hardly recyclable[4].

The introduction of EVs eventually requires to re-design or even form a new dismantling plant. In their proposed concept of such a plant, Milojević et al. introduce steps to treat electric motors and to separate magnets to depolarize and reuse them (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020) The changing material composition, such as more recyclable plastics, needs to be considered in improving the design of recycling facilities (Li, et al., 2020).

Li et al. emphasize the need for both policymakers and car producers to understand the ELV population and its recyclable materials (Li, et al., 2020). Julian Allwood argues that the design of metal components can help reduce surplus material and production emissions. Similar to the clothing industry, car manufacturers could calculate the amount of metals they need for maximum efficiency, thus reducing the share of steel and aluminum that does not end up in cars but leaves manufacturing as scrap (Allwood, 2012).

4.1.3.1. Aluminum scrap surplus

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In general, aluminum scrap generation from ELV, buildings, and other sources is increasing rapidly, leading to a lot of scrap that cannot be absorbed, i.e., unrecyclable scrap. In a study by Hatayama et al., the addition of EVs and HEVs leads to an increase of unrecyclable scrap from 2.9 million tons (scenario with ICEs only) to 6.1 million tons by 2030. 2030 is also considered to be the "transition year," where most of ELVs are still ICE vehicles. Consequently, this leads to a decrease of the demand of cast alloy in new vehicles, while scrap keeps delivering used cast alloys. Without scrap sorting, this scrap would be suitable only for the production of cast alloys, and the automotive sector would become a net scrap producer. With scrap sorting, 2.4 million tons of wrought alloy could be collected separately and be used to produce the same kind of wrought alloys, reducing the primary aluminum demand as well as the supply of unrecyclable scrap by 1.9 million tons. This reduction is due to the larger amount of discard, which also increases the amount of unrecyclable scrap. But more scrap also means that sorting can get more effective, thus reducing the impact on primary aluminum sourcing (Hatayama, Daigo, Matsuno, & Adachi, 2012).

In a global model by Løvik et al., there is an aluminum scrap surplus as of 2025. Increased dismantling can delay the surplus to 2033, having a particularly significant effect on 6xxx alloys. Sorting alloys can further delay the surplus to 2047 or 2048, depending on the dismantling level. Thus, sorting alloys in mixed scrap after shredding is more effective than a high dismantling rate. Still, technologies to sort dirty EOL scrap have yet to prove themselves. If the removal of magnesium would not be state-of-the-art, we would already have a scrap surplus, and the increased use of wrought alloys will increase the magnesium concentration in scrap in the future. However, the magnesium removal process (demagging) emits chlorine and magnesium itself is a valuable alloying element. Consequently, the strategy should rather be to redirect magnesium-containing scrap to appropriate application instead of removing it (Løvik, Modaresi, & Müller, 2014). Løvik et al. showed that in the next decades, the increase of magnesium will be accompanied by a decrease of silicon and copper concentrations in scrap – reflecting the typical composition of wrought aluminum, which is expected to penetrate the market. Improved dismantling will support this trend, because wrought aluminum will not benefit as much from dismantling as cast aluminum. When it comes to components that are relevant for safety, e.g., wheels, low impurity levels are required, which makes the exclusionary use of primary metal necessary. Only with thorough testing can scrap be used for such parts, the iron content being especially critical. One possibility would be establishing intermediate reservoirs: Nissan, for example, has recycled wheels in parts of their steering system (Løvik, Modaresi, & Müller, 2014).

Løvik et al. suggest three measures to increase recycling: intensify dismantling before shredding, recycle cast parts for safety-relevant components, and develop automated scrap sorting technologies. What is necessary for these measures to work out is a shift from composition-based to a material-based recycling agreements, leading to new alloy standards (Løvik, Modaresi, & Müller, 2014).

4.1.4. Directive 2000/53/EC

In the EU, Directive 2000/53/EC regulates the treatment of ELVs. It foresees that at least 95% of a vehicle's weight is recovered and reused, while at least 85% shall be recycled. Recycling refers to reprocessing materials for their original or other applications and excludes energy recovery. Reuse refers to using components for its original purpose. Recovery is relevant for parts that cannot be reused, e.g., hazardous materials, and is closely connected to proper disposal (European Union, 2000).

4.1.4.1. Period 2000-2022

In 1999, before the Directive entered into force, there were only 10 EU member states with specific ELV regulations (Austria being one of them) (European Commission, 2021). By 2015 the latest, member states had to transpose the Directive into national law (European Union, 2000). Technically, the targets included in the Directive are to be met by the states, but car importers and manufactures bear the additional recycling costs based on Extended Producer Responsibility (EPR) (Sakai, et al., 2014). However, how EPR is executed differs strongly between EU countries. While some have deposit systems, in Austria, bilateral contracts between manufacturers/importers and car dealers and recyclers regulate how ELVs are collected and who pays for their collection and treatment (Kletzmayr, 2022).

Dismantlers have to recover materials in accordance with the Directive. Manufacturers do not only have to design cars that meet the requirements and organize free-of-charge

ELV disposal, but also inform dismantlers about accurate disassembly techniques. To this end, the International Dismantling Information System (IDIS) was established. It is currently used by 26 car manufacturers. However, EPR as required by Article 8(a) of the Waste Framework Directive (WFD) is not fully met as the Directive lacks a clear obligation for producers to cover ELV treatment costs (European Commission, 2021). According to Kletzmayr, no practitioner would ever use IDIS, although he is convinced that the system and its obligation for manufacturers to provide dismantling information has its right to exist, especially for EVs and HEVs (Kletzmayr, 2022).

Overall, the Directive was quite successful. Based on 2017-data, 15 EU member states met the 95%-target, the average being 94%. The 85% recycling rate was not met only by Finland, Latvia, Italy, and Malta (European Commission, 2021). In 2019, reuse and recycling reached 89.6%, reuse and recovery 95.1% (Eurostat, 2022). It also allowed the EU to become a global innovation driver for post-shredding technologies (ACEA, 2020a). In 2001, Staudinger & Keoleian concluded that the adoption of the EU Directive also pressured the US to manage ELV treatment by legislation. Indeed, the Chairman of the US-based Ford Motor Company, Bill Ford, is quoted as reacting to the introduction of the EU legislation in a very forward-thinking way:

> *"We see it as an opportunity in the US where we are getting into the recycling business. We're presently considering the European market situation. And there will be major changes. Future transportation may not involve owning a car. Instead, you may own the right to transportation. We will make vehicles and either lease or loan them to you. We'll end up owning a vehicle at the end-of-life and have to dispose of it. We will treat it as a technical nutrient, making it into a car or truck again. We're getting ourselves ready for a day when this is truly a cradle-to-cradle. We're not fighting it, we're embracing it."*
>
> (Staudinger & Keoleian, 2001, p. 55)

Such a "Transport-as-a-Service" system is indeed brought forward by some groups such as Tony Seba's *RethinkX* think tank (Arbib & Seba, 2017).

Economically, the implementation of the Directive had the benefit of consolidating dismantlers and recyclers and allowing consumers free-of-charge ELV disposal

(European Commission, 2021), although Simic and Dimitrijevic criticize that the Directive still ignores the independent operations of, on the one hand, dismantler, and, on the other, recycling factories (Simic & Dimitrijevic, 2012).

A comparative study from 2017 showed that while the recycling efficiency is higher in Belgium than in Australia, only half of deregistered cars are treated as ELV in the EU country compared to its overseas counterpart which has a rate of over 80%, the main culprit being exports. However, the stricter ELV regulation as well as post-shredding processes that allow the recovery of plastics and non-ferrous materials in Belgium improve the environmental performance of the country by almost 8 times compared to Australia (Soo, Peeters, Compston, Doolan, & Duflou, 2017).

While there has been a lot of legal discussions in the EU on what requirements passenger cars of the future should meet, leading to several statements and even new legislation, the ELV Directive has not been updated since over 20 years. Article I of Regulation 2019/631, for example, states that by 2030, 35% of all new passenger cars registered in the EU shall be zero- or low-emission cars. For light commercial cars, the percentage shall be 30%. However, when it comes to ELV recycling, the Regulation only briefly mentions battery recycling and re-use as prerequisites for the transition (European Union, 2019).

4.1.4.2. Revision 2022

In March 2021, the European Commission got the ball rolling by publishing a document evaluating the ELV Directive. In this "Staff Working Document," changes in vehicle production in the last 20 years are recognized, especially the increasing share of plastics, electronics, carbon fibers as well as batteries and rare materials in cars. The Commission also assumes that relatively new vehicles will be scrapped in the next years due to the shift to EVs and HEVs (European Commission, 2021). For example, the European Environmental Bureau (EEB) stresses that the definition of "reuse," which is currently restricted to reusing components for their original purpose, should be rethought to not hamper the development of the used-battery market. The EEB also suggests the establishment of an EPR scheme that allows fees paid in the EU to follow the EOL stage of a vehicle, wherever this may be (EEB, 2020). And despite the existence of IDIS, facilities responsible for dismantling, repair, and reuse are still struggling to get full access to information from manufacturers (European Commission, 2021, p. 28). Hence why the EEB brings forward the establishment of “a harmonized chemicals inventory list” (EEB, 2020, p. 4).

Despite its successes, evaluating certain provisions is of high importance. For example, the current version is missing targets for electronic parts containing precious metals such as palladium, silver, and gold as well rare earth metals. While recovering such material is costly for dismantlers, it is also a potential income for them. Meeting the recovery target of 95% will become extremely difficult if electronic parts like these are increasingly used. Similarly, plastic waste from ELV – accounting for 5% of total EU-wide plastic waste – is not addressed. The same goes for other light materials such as fiber reinforced plastics or carbon fiber (European Commission, 2021).

One of the Directive’s biggest failures was that targets for the period after 2015 were not set (as foreseen by Article 7(3)). The aspect of waste prevention, i.e., properly designing vehicles to ease dismantling and recycling, however, has also not been specific enough and its review is difficult. It is not very likely that vehicles currently sold are easier to be treated for recycling than those in 2000. The Directive should also be more precise in its provisions on the removal of components before shredding since this is what increases ELV recovery rates. This affects plastics and copper, in particular, due to the high costs associated with their removal, and, in the case of plastics, the low value of the material (European Commission, 2021). Furthermore, the exemption of copper from the general lead limit of 0.1%, of Annex II, is being discussed and could be amended or rejected with upcoming review (Copper Development Association Inc., 2022). Kletzmayr identifies a more general problem with Annex II, namely the divergence between the EU’s chemicals legislation, called REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), and EU waste legislation. While the former follows a risk-based approach, the latter evaluates substances according to a hazard-based approach. According to EU chemical law, the risk of lead in cables of ELVs being harmful is almost zero (Kletzmayr, 2022).

4.1.4.2.1. Stakeholder views

The Commission's evaluation also included stakeholders' views. For example, more than 40% of the consulted stakeholders emphasized that specific targets for plastics and aluminum (and glass, too) would improve the Directive's implementation (European Commission, 2021). European Aluminum, on the other hand, claims that already about 95% of ELV aluminum is recycled today and that introducing a minimum target of recycled aluminum in cars would simply redirect recycled aluminum from other sectors to the car sector and, thus, would have no effect on overall circularity in the Union (European Aluminum, 2020). The European Automobile Manufacturers Association (ACEA) has a similar opinion, questioning the added value of specific minimum contents as the recycling industry has a holistic approach to vehicle treatment, which made it so successful in the last years. What is more, the technical requirements to measure single materials' recycling rate is not to be underestimated (ACEA, 2020a). For Kletzmayr, specific material recycling rates make sense only if there is a collection rate, which is the case for household items, but not for vehicles (Kletzmayr, 2022).

Defining targets for using recycled materials in new vehicles is also being discussed, especially for plastics, as this would help to meet the EU's circularity goals. The current Directive dictates only a general effort to increase the amount of recycled material in new vehicles. A range of manufacturers, however, has already set internal goals to increase the use of recyclates. Although these voluntary efforts by certain car manufacturers exist, the revision should also set specific targets for the use of recycled material in new cars. This is also important to link the design of new cars with ELV management (European Commission, 2021). Unsurprisingly, the ACEA emphasized that no new obligations should be added by the revision. Regarding plastics, the association thinks that meeting any criteria on the usage of recycled plastics in *new* cars is impossible as long as the economic and technological feasibility is not given (ACEA, 2020a). The European Environmental Bureau (EEB) is in favor of a mandatory rate or recycled materials in new cars and emphasizes that individual companies have set internal goals already; Volvo, for example, aims for 25% of the plastic used in its cars to be recycled, and 501kg of the VW Golf are made of recycled metals (EEB, 2020). The European Recycling Industries' Confederation (EuRIC) suggests concrete percentages for thermoplastics in newly manufactured cars: 25%, 30%, and 35% by 2025, 2030, and 2035, respectively, based on the weight of the total amount of thermoplastics in the car. These targets would also lead to intensified PST and establish a plastics recycling system that is in accordance with the EU's Plastics Strategy (EuRIC, 2019). In this "European Strategy for Plastics in a Circular Economy," the European Commission also states that

> „(…) certain applications in the construction and automotive sectors show good potential for uptake of recycled content (…). In the context of ongoing and upcoming evaluations of EU rules on construction products and on end-of-life vehicles, the Commission will look into specific ways of promoting this." (European Commission, 2018, p. 9)

Another problem is that approximately 35% of deregistered cars in the EU are "of unknown whereabouts" (European Commission, 2021). These close to 4 million cars may be either sold in other members states, kept on private premises, illegally exported to non-EU states, or illegally treated. A stricter regulation on the deregistration processes in the EU is therefore desirable. A related problem is that of shipping used cars, which are, contrary to ELV, not considered 'waste' and therefore do not fall under the EU Regulation on waste shipments. The guidelines on the 'usability' of old cars that exist are not legally binding and leads to a lot of vehicles that lack roadworthiness being exported to African countries. From the perspective of circularity, there is also a material loss involved (European Commission, 2021). A better deregistration management is also demanded from the European Aluminum association (European Aluminum, 2020) and the ACEA, the latter seeing it also as a tool to combat treatment by unauthorized facilities (ACEA, 2020a). An Austrian car recycler also sees the export to non-EU countries as a major problem and mentions that, in Austria, insurance companies often encourage such sales to mitigate losses[5]. For Kletzmayer, the main problem is also the role of insurances that do not sufficiently track what happens to cars that have been deregistered with them. In theory, a document confirming proper recycling should be requested by them, but this rarely happens in reality. There is also a lack of inter-country data linkages, but IT projects such as Cartena-X are being developed and may help remedy the situation (Kletzmayr, 2022). Sakai et al. also found that countries that import used cars to a large extent tend to have an insufficient management of ELV (Sakai, et al., 2014).

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[5] E-mail correspondence with Josef Metzker from Auto Metzker, 2022

20 years ago, Kletzmayr and his former colleague Peter Jung, the founder of *Altauto.at*, established an EU-wide model based on a deposit of about 500 euros to be paid by the buyer. This deposit could then be invested into the shares of manufacturers and interest would be generated. The last owner of a vehicle would then have the incentive to return the vehicle and receive the 500 euros plus interest. This would kill two birds with one stone: an improved practice of deregistered cars and putting EPR into practice, as only with officially deregistered cars manufacturers are able to bear the responsibility. Unfortunately, this model did not convince every manufacturer and, thus, an EU-wide agreement has not been reached (Kletzmayr, 2022).

Regarding hazardous substances, the overall impression was that these have been addressed effectively and sufficiently, although some manufacturers use more lead for circuit boards than allowed, for example (European Commission, 2021). In its position paper from 2020, the ACEA recommends that, given partial overlaps and contradictions, cars' hazardous substances should be entirely regulated within the ELV Directive and be made coherent with other regulations (ACEA, 2020a). The EEB, in its position paper also from 2020, cautions that, currently, the circulation of these materials from old to new products is not prevented (EEB, 2020).

The European Aluminum association emphasized the improving materials' quality is crucial to close the loops in car recycling, which is achieved especially by intensified dismantling, information exchange, and post-shredding techniques. Importantly, recycling critical raw materials such as silicon or magnesium can be improved by focusing on the collection of aluminum alloys containing those. European Aluminum also recommends better material tracking via IDIS, in particular concerning the composition of alloys. Collecting wrought and cast aluminum separately is brought forward by the association, too (European Aluminum, 2020).

According to the European Environmental Bureau (EEB), the current version of the Directive is not strict enough when it comes to targets on reuse and a separate target is recommendable. On the other hand, the recovery target is proposed to be taken out and replaced by a landfilling ban for organic substances. The EEB also brings forward another important point: the need to establish a uniform calculation method for recycling and reuse percentages. Contrary to the WFD, for example, including backfilling in recycling calculations is allowed. The EEB also emphasized the quality-aspect of recycling, seeing material-specific targets as the solution. Obligations to dismantle plastics could be a first step (EEB, 2020). In Austria, such a uniform method has been brought forward since 2004. The proposed recycling rate would not be calculated from the amount of *treated* ELVs in a year, instead of *collected* ELVs. Although a consensus throughout the EU has not been reached, this method is defined by law and used on *Altauto.at*, the Austrian Internet platform for the central collection and management of data from the takeover, treatment, and recycling of ELVs (Kletzmayr, 2022).

Another issue is that the rather narrow scope means that a quarter of all sold vehicles, e.g., certain commercial vehicles, are not covered by the Directive. Stakeholders' views on whether other category should be subject to the same rules as passenger cars are ambivalent (European Commission, 2021).

Finally, the EEB thinks that the transition to zero-emission cars makes eco-design even more pressing – and not only for the battery with the revision of the respective EU Directive, but for all parts of the car (EEB, 2020).

Furthermore, other EU policies and packages, such as the Circular Economy Action Plan, the European Green Deal (European Commission, 2021) or the Plastics Strategy (EuRIC, 2019) also need to be taken into consideration for the revision of the Directive.

5. Material Flow Analysis

The next Chapter will look at the material flows of ELVs in general, and of ELV steel, aluminum, copper, and plastics in particular, at two different points in time: 2019 and 2045. The system boundaries are the same: location-wise, this thesis focuses on the EU. Timewise, it looks at a one-year development (2019 and 2045, respectively). The main underlying assumption of this Chapter is that 2045 is defined as the first year in which ELVs are majorly EVs and, thus, it is this kind of driving technology that dominates how recycling schemes should look like.

Furthermore, the lifetime of conventional and alternative-fuel cars such as EVs is considered to be similar – except for the battery in EVs, which might be replaced more often (Li, et al., 2020). In this thesis, the lifetime is supposed to be 15 years for all types of cars. As far as one of the studied materials is used for batteries, those are part of the respective MFAs, but battery recycling will not be further discussed.

It is also assumed that the composition of ELVs is equal to that of cars being sold that year, which of course ignores changes in the car design over years. However, this assumption is frequently made in similar studies (Ohno, et al., 2015) (Nakamura, et al., 2012), mainly because it is difficult to predict how regulations and consumer demands will change over time (Nakamura, et al., 2012).

Another assumption is that the disposal, recovery, and recycling stocks are being treated within the same year and no stock will be carried over to the next period. Furthermore, parts that are reused without being transformed are not taken into account separately but are part of the "recyclable" stream.

The decision to focus only on the automotive sector of course ignores that scrap from other sectors is also used for cars. Especially in the building sector, current in-use stocks are huge and scrap coming from other sectors may well increase in the future. An absorption of automotive scrap by these sectors is, on the other hand, very unlikely (Løvik, Modaresi, & Müller, 2014).

5.1. MFA ELVs

An ELV is a deregistered car destined for recycling. Their number is calculated by subtracting the number of cars in use at the end of a year from newly registered cars in that year plus the number of cars in use at the end of the year before. The number of deregistered cars is higher than that of ELVs since the former also include (legally and illegally) exported cars, illegally dumped cars, or unregistered cars that remain within private premises. The number of ELVs is determined by the number of deregistered cars and the number of deregistered cars is determined by registration numbers and lifetimes of cars (Sakai, et al., 2014). Population and economic growth rates determine registration numbers based on the so-called Weibull function (Li, et al., 2020) (Sakai, et al., 2014).

For this analysis, however, the numbers are calculated backwards from the latest reported numbers of ELVs in 2019, as published by Eurostat. This number was 6,057,000, the highest number since 2009, when a peak of 7.7 million was reached due to the introduction of subsidized scrapping schemes in several EU countries. Reuse and recycling reached 89.6%, reuse and recovery 95.1%. Taking the registration papers of those close to 6.1 million vehicles as a basis, 6,889,000 tons of ELVs were added in 2019, again the highest number since 2009. This means that the average vehicle weight in the EU in 2019 was about 1,137 kg, or 1.14 tons (Eurostat, 2022).

The number of sold cars (new registrations) in 2019 and the stock at the end of 2019 were taken from statistics provided by the ACEA (ACEA, 2022a) (ACEA, 2022d). Deregistered cars were calculated backwards from the 4,000,000 cars of unknown whereabouts that make up about 35% of all deregistered cars (European Commission, 2021). The number of legal exports of used, deregistered cars to territories outside the EU was equal to the residual value (1,371,571 vehicles) but is consistent with the 1 million used cars that were exported from the EU to Africa alone, the Union's main importer of old vehicles, in 2018. In total, 7.6 million cars that were exported over the period 2015-2018 to territories outside the EU, according to UNEP (UNEP, 2020).

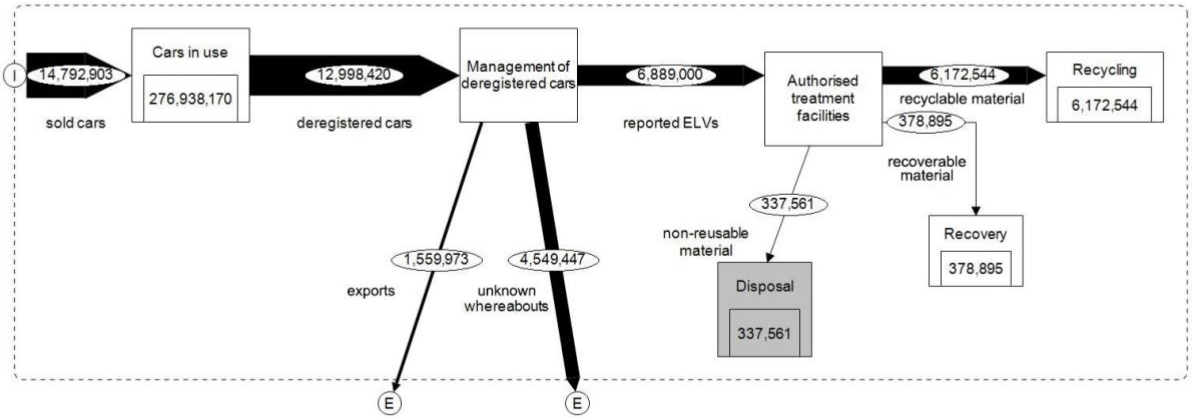

Figure 5: MFA ELVs, 2019 (figures in tons/year)

In order to assess the stock of passenger cars in 2045, the EU population by that time has to be estimated. According to Eurostat, this number is expected to reach its peak in 2044, with 525 million citizens (Eurostat, 2019). The same value is assumed for 2045.

Regarding this population's motorization rate, estimations are difficult because a lot of socioeconomic drivers play into this particular development. Nevertheless, a 2014 study by Shell Germany came up with a motorization rate for Germany of 510 passenger cars per 1,000 inhabitants in 2040, after having reached a peak of 521 cars per 1,000 inhabitants in the mid-2020s (Shell Deutschland, 2014). Assuming the same value for the whole EU in 2045, a decrease is expected as the 2020 EU motorization rate stood at 560 per 1,000 inhabitants (ACEA, 2022e), a trend which is also in line with strategies to reduce individual motorized transport.

Assuming that the stock will not be growing indefinitely, a further assumption for 2045 is applied: the number of new registrations is equal to the number of deregistered cars in a year. The share of official exports and unknown whereabouts is assumed to stay the same as in 2019, leading to 13,983,529 reported ELVs.

For the recycling and recovery rates, it is assumed that the overall rates of 85% and 95% for recycling and recovery, respectively, will remain in place. Given the increasing difficulties with recycling EVs's components compared to ICEVs, it is assumed that the actual rates in 2045 will not be higher.

However, as far as the vehicles' weights are concerned, significant changes are to be expected. As discussed, it is still unknown whether aluminum and plastic parts will increasingly replace steel, or whether lighter steel will dominate the market (Öko-Institut e.V., 2009a) (Li, et al., 2020). Concerning ICE vehicles, incentives for lighter vehicles are emission reductions and fuel economy. Concerning BEVs, increasing the range is a major driver to reduce vehicles' weight. However, with lower costs and higher energy density of batteries, this driver becomes less important. Nevertheless, it will still take some time for these two trends to play out. For studying ELVs' weights in 2045, a scenario with high electrification, but low battery density and high costs for the battery pack is assumed. This scenario would lead to a 37% reduction of the vehicle weight (body in white and closures, see Figure 6) and 12 to 14% of its curb weight according to a study by the Center for Automotive Research (CAR) (Bailo, et al., 2020). Curb weight is the weight including batteries, tires, and liquids (Emilsson, Dahllöf, & Söderman, 2019).

Figure 6 : Body in white and closures [taken from (Sacha Engineering, n.d.)]

The efficiency-to-weight ratio will cause the main difference: while fuel for an ICE that contains 337 kWh weighs up to 30kg, the battery back in a BEV, containing only 100 kWh, weighs up to 540kg - with high-end exceptions such as Tesla's Roadster (833kg battery weight) (Enrg.io, 2020). In order to provide a longer range, the rest of the vehicle must become lighter. Although the battery recycling problem is not in the scope of this work, its weight will be included since it is part of the mass ELV recyclers will have to deal with in the future.

Applying a 14% reduction in curb weight due to the use of lighter materials (aluminum, plastics, high-tensile steel), but adding 500kg of battery pack weight, gives an overall average vehicle weight of 1,478 kg, or 1.48 tons.

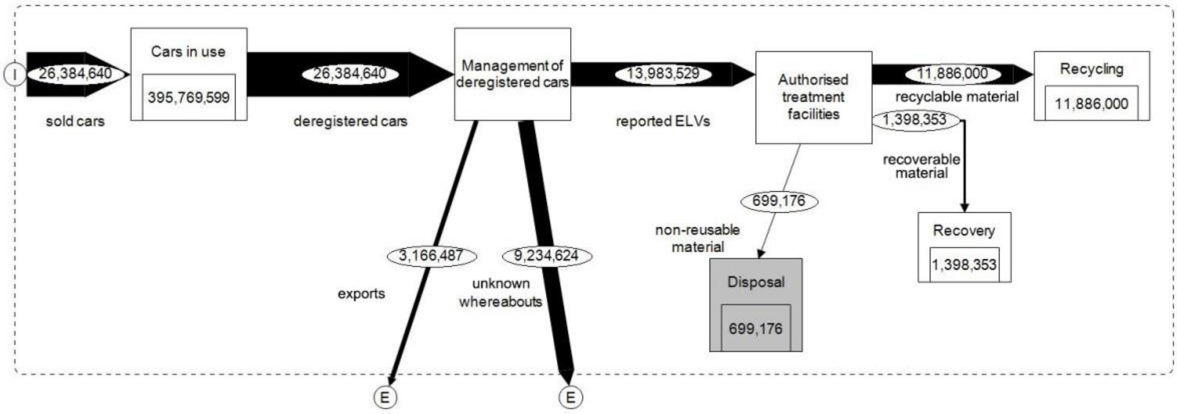

Figure 7: MFA ELVs, 2045

5.2. MFA Steel

The average weight of steel per car of 900kg was taken from 2019 data provided by the World Steel Association (World Steel Association, n.d.). In Figure 8, 900kg are multiplied with the numbers new sales, cars in use, deregistered cars, exported cars, cars of unknown whereabouts, and ELVs from Chapter 4.2.1. (Figure 5).

Already today, about 90% of ELV steel is recycled globally (World Auto Steel, n.d.). EU numbers tend to be higher: according to the Umweltbundesamt, Germany has a ELV metal recycling rate of 97% (Umweltbundesamt, 2014), and in Belgium, the recycling efficiency of ferrous material reaches 99.97% (Soo, Peeters, Compston, Doolan, & Duflou, 2017). Using BAT, a 100% recycling rate is possible. In real life, it lies between 90-98% (Merkisz-Guranowska, 2018). As an EU average, 94% are assumed. The remaining 6% are assumed to be disposed of.

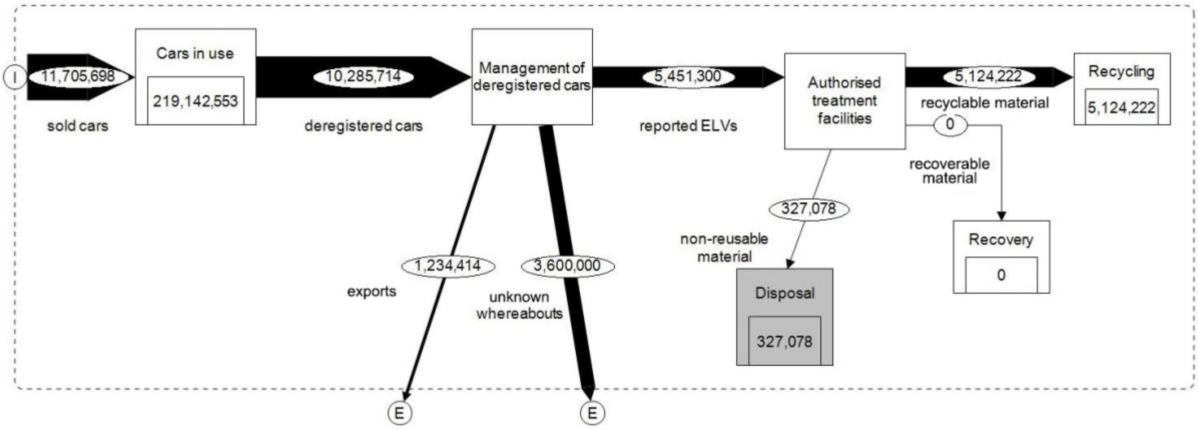

Figure 8: MFA ELV steel, 2019

In 2045, the assumption is that there will be less steel per car – either because lighter steel is used or because steel is replaced by materials like aluminum and plastic. For this MFA, the numbers for ELVs in 2045 are multiplied by 489kg – 50% of the car's weight excluding the 500kg-heavy battery pack. It is assumed that by 2045, it will be possible to recycle 100% of ELV steel.

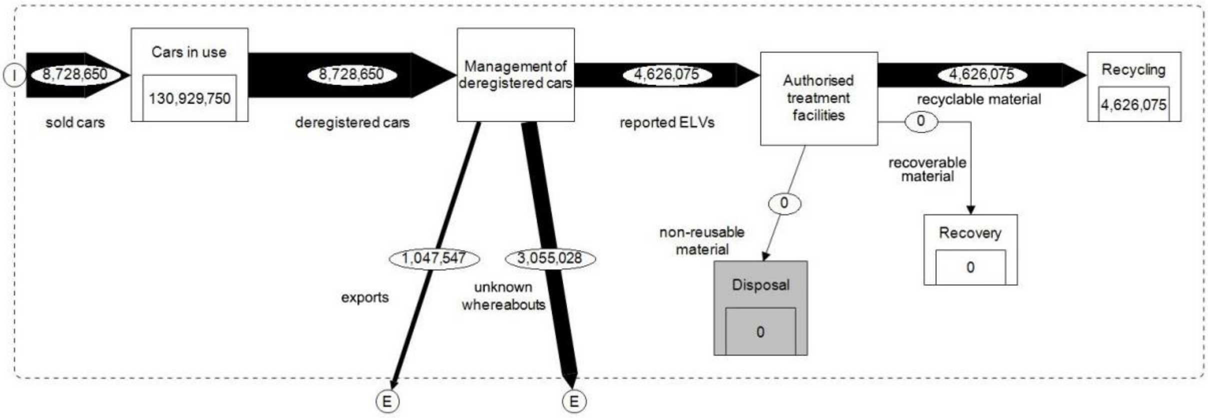

Figure 9: MFA ELV steel, 2045

5.3. MFA Aluminum

In 2019, the average aluminum content per car was about 180kg (Drucker Frontier, 2019). According to European Aluminum, 95% of ELV aluminum is already recycled today (European Aluminum, 2020). Again, it is assumed that the rest is being lost or disposed of.

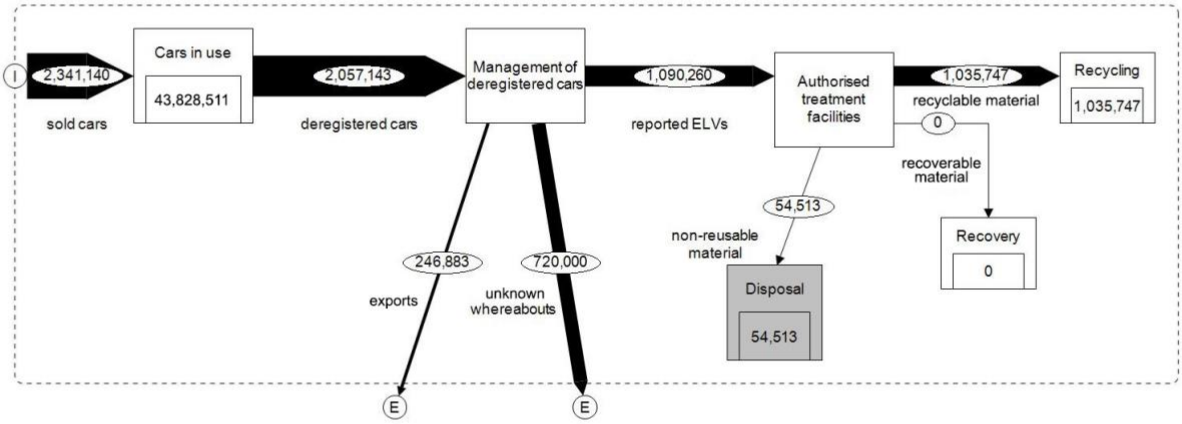

Figure 10: MFA ELV aluminum, 2019

By 2045, it is very likely that the aluminum content per car has increased. Compared to ICE cars, a 25%-increase is assumed (Djukanovic, 2018), which would give 225kg per vehicle. This is to a large part due to high aluminum demands by the batteries (Öko-Institut e.V., 2009a). Furthermore, a 100%- recycling rate by 2045 is assumed.

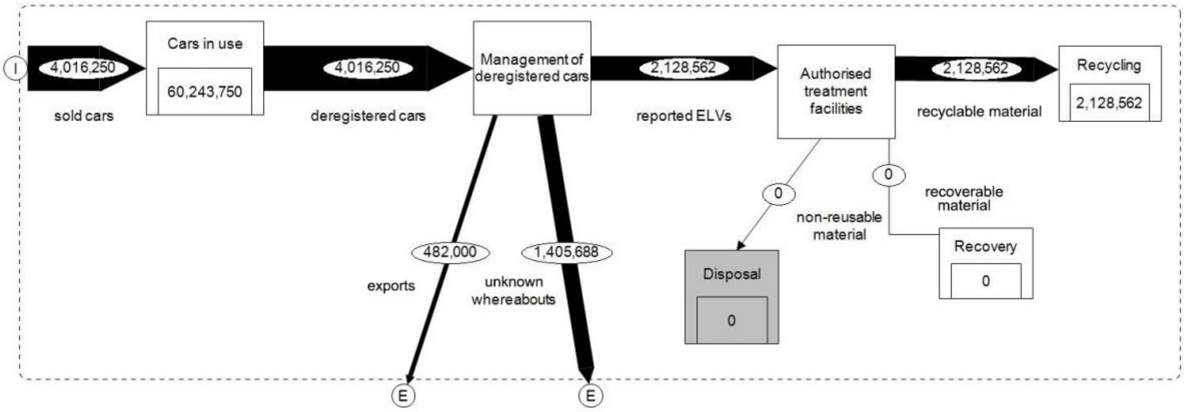

Figure 11: MFA aluminum, 2045

5.4. MFA Copper

According to Öko-Institut e.V., a medium-sized ICEV has 19kg of copper (Öko-Institut e.V., 2009a). Merkisz-Guranowska found that the recovery rate for copper is between 60-80% (Merkisz-Guranowska, 2018). Given the difficulties discussed in Chapter 4.1.2.4, the lower end of this range is applied.

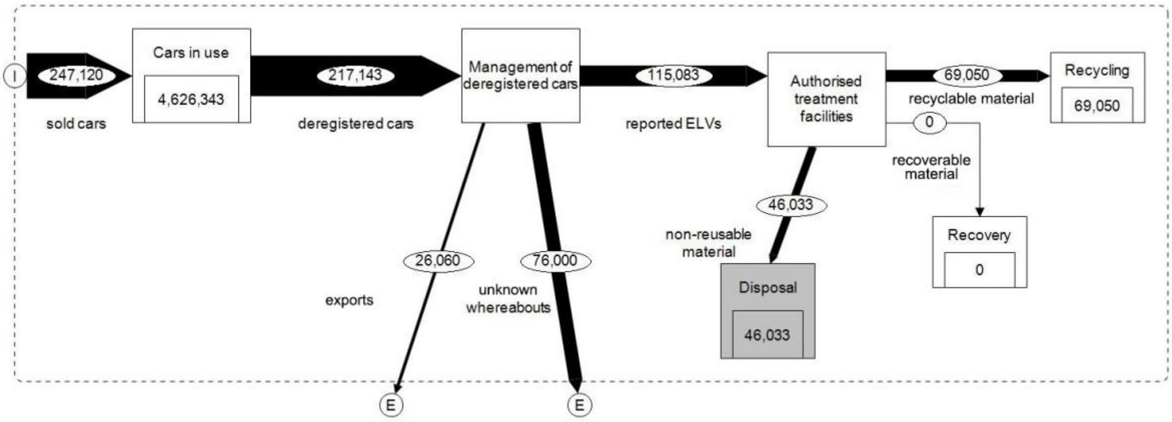

Figure 12: MFA ELV copper, 2019

The Copper Development Association states that the average BEV contains about 83kg of it (Copper Development Association Inc., 2022). By 2045, when ELVs will mainly be BEVs, the recycling rate should reach at least 85%, the rate currently required for the whole car already today.

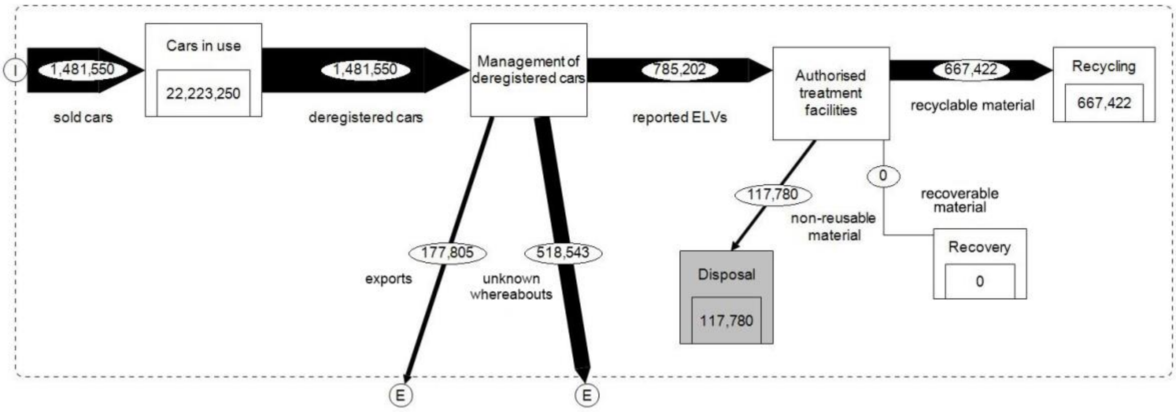

Figure 13: MFA ELV copper, 2045

5.5. MFA Plastics

The plastic content in a car is about 14.8% of its weight (European Commission, 2021), so about 170kg for our 1.14t-heavy reference vehicle. According to Cardamone et al., 2.6% are further processed in recycling facilities, the rest is being landfilled or combusted. In their study, about 55% of total plastics is sent to thermal recovery (Cardamone, Ardolino, & Arena, 2022).

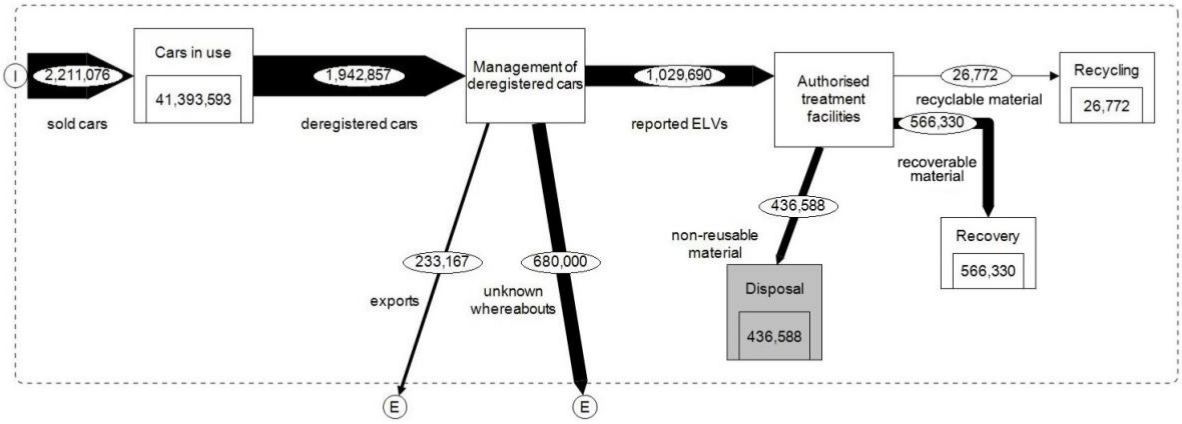

Figure 14: MFA ELV Plastics, 2019

If the future plastic content will reach 20% (European Commission, 2021), the 2045 scenario foresees a plastic content of 296kg per ELV. The proposed plastic treatment processes by Cardamone et al. would lead to a recycling rate of 50.4% and nothing would be landfilled anymore (Cardamone, Ardolino, & Arena, 2022). It is assumed that such a recycling scheme is in place by 2045.

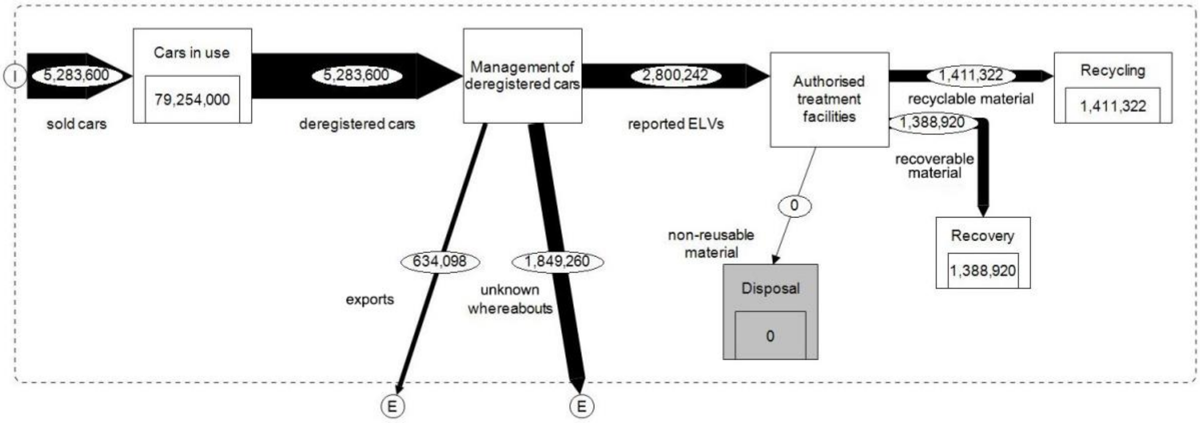

Figure 15: MFA ELV Plastics, 2045

5.6. MFA Summary

As far as the overall ELV MFA is concerned, the amount of recyclable material is expected to increase by about 19% from 6,172,544 to 11,886,000 tons, if EVs make up the main portion of ELVs in the EU in 2045. However, in this scenario, an increase of new car registrations by about 37% was assumed based on projections by Shell Deutschland, which is mainly due to a population increase. This amount also includes the battery pack at its EOL, which is responsible for the weight increase per vehicle as the rest of the vehicle will rather get lighter with the increasing use of other, lighter materials. The composition of the rest of the vehicle will change rather drastically, albeit the exact development is difficult to predict. According to this thesis' MFA, the amount of recyclable ELV steel is expected to decrease by about 11% from 5,124,222 to 4,626,045 tons. The amount of aluminum, on the contrary, will most likely increase. The assumed increase in this thesis was 25% per vehicle, from 180kg to 225kg. A close to 100%-recycling rate of these two metals is realistic given the already high recycling rates today.

An almost 6-fold increase, however, is expected for the amount of copper in new cars, mainly due to the material being used in batteries and electric components. As higher recycling rates will become necessary, the amount of copper going to recycling will most likely even increase by a factor of about 9.7.

The plastics content per vehicle is expected to increase by a factor of about 74%. In 2019, 42% of it were disposed of, 55% went to thermal recovery, and the rest was recycled. In this model, a best-case scenario, the percentages would change to 0%, 49.6%, and 50.4%, respectively. Expecting higher recycling rates in 2045, this means that 1,411,322 tons of plastic need to be recycled in 2045.

6. Conclusion

Currently, ELV recycling in the EU is mainly focused on recovering and recycling metals, especially ferrous metals. However, the use of different alloys and their subsequent mixing makes it difficult for ELV recycling to be of closed-loop nature. Indeed, only around a third of ferrous components in a car are secondary materials (Nakamura, et al., 2012). After shredding, approximately 70% iron and steel, approximately 23% light materials such as PVC, paints, ceramics, or glass, about 6% mixed non-magnetic metals, and less than 1% iron that contains copper is left over and can be recycled (Milojević, Miletić, Stojanović, Milojević, & Miletić, 2020). These percentages will change with the EU-wide transition toward a fully electric fleet, and the heterogeneity of ELV materials will increase. The development of EVs and HEVs is likely to require more non-ferrous metals (Sakai, et al., 2014). The battery pack is likely to increase the amounts of steel, aluminum, copper, and plastics in a car, while EV motorization needs less aluminum and steel, but more copper, than its ICE counterpart. Overall, EVs need more material and are thus heavier, which is mostly due to battery requirements (Öko-Institut e.V., 2009a). The European Commission also recognized changes in vehicle production in the last decades, especially the increasing share of plastics, electronics, carbon fibers as well as batteries and rare materials in cars. Consequently, a revision of Directive 2000/53/EC, which has not been updated since over 20 years (European Commission, 2021), is planned for the fourth quarter of 2022 (European Commission, n.d.). For example, the current version is missing targets for electronic parts containing precious metals such as palladium, silver, and gold as well rare earth metals. Similarly, plastic waste from ELV – accounting for 5% of total EU-wide plastic waste – is not addressed. The same goes for other light materials such as carbon fiber. The aspect of waste prevention, i.e., properly designing vehicles to ease dismantling and recycling, has also not been specific enough. It is not very likely that vehicles that are currently sold are easier to be treated for recycling than those in 2000 (European Commission, 2021). Eco-design is something that needs to be regulated to avoid that manufacturers of zero-emission cars put comfort and profitability over easy disassembly. In the current, metal focused ELV recycling, downcycling and ASR recycling are the main challenges in state-of-the-art ELV recycling. Better dismantling would improve both.

As stated in Chapter 2, the aim of this thesis is to answer the following questions:

1. **What should the 2022 revision of EU ELV Directive include against the background of changing driving technologies?**

Li et al. emphasize the need for both policymakers and car producers to understand the ELV population and its recyclable materials (Li, et al., 2020). According to ELV experts, EV recycling is currently not cost-effective. Legal standards and provisions regarding the treatment of EVs at their EOL stage are necessary. Currently, every EV reaching dismantlers, recyclers, and shredders is still an object of study. But this will change drastically within the next 20 years, making a revision of the core legal document for ELVs, the EU ELV Directive, necessary.

First, the EEB stresses that the definition of "reuse," which is currently restricted to reusing components for their original purpose, should be rethought to not hamper the development of the used-battery market (EEB, 2020). Although the EU Battery Directive will have to provide most of the guidance as to how ELV batteries are to be dealt with, a coherent framework needs to be introduced to the ELV Directive. For example, there are currently no targets for most of the materials contained in ELV batteries.

In the future, ELV copper and plastics need to be treated completely differently. Both the literature review and the MFA showed that a particular focus should be put on copper, as proper separation during the dismantling and the shredding phases is still lacking. Kletzmayr mentioned the options of float-sink-plants combined with prior eddy-current separation as well as copper separation via X-ray (Kletzmayr, 2022). The amount of plastics used per vehicle is expected to increase by about three quarters. However, already today, plastic waste from ELV accounts for 5% of total EU-wide plastic waste and its recycling rate is very low. Additionally, there is a trend to use new difficult-to-recycle plastics such as carbon fiber reinforced plastics (European Commission, 2021). Specific recycling targets for these material groups may remedy the situation, although a rate based on weight is not ideal: for plastics, it is rather about volume than weight. With copper, moreover, one talks about a gram range.

Independent from changing driving technologies, there are large differences in how recovery and recycling rates are calculated in each EU member state. For example, while Germany takes the amount of collected ELVs during one calendar year, Austria applies a more realistic approach of basing its recycling rate on the amount of treated ELVs per year (Kletzmayr, 2022).

It is not only the calculation method that could be harmonized. A harmonized and improved deregistration system is also needed to reduce the number of illegal exports and unknown whereabouts. Approximately 35% of deregistered cars in the EU are "of unknown whereabouts" (European Commission, 2021) and a stricter regulation on the deregistration processes in the EU is desirable.

20 years ago, Walter Kletzmayr and Peter Jung from Austria established an EU-wide model based on a deposit of about 500 euros to be paid by the buyer. This system would allow an improved practice of deregistered cars as well as putting EPR into practice, as only with officially deregistered cars manufacturers are able to bear the responsibility (Kletzmayr, 2022). The EEB also suggests the establishment of an EPR scheme that allows fees paid in the EU to follow the EOL stage of a vehicle, wherever this may be (EEB, 2020).

2. How will the transition toward EVs change the material flow of ELVs in general, and of ELV steel, aluminum, copper, and plastics in particular?

The electrification of cars has a large impact on their material composition and total weight: the 250 to 500kg-heavy batter pack makes it necessary to use lighter material such as AHSS, aluminum, or plastics to keep efficiency levels in an acceptable range. Although steel and aluminum recycling will not change drastically, today's problems related to quality and dilution losses need to be addressed regardless. The discussion whether steel will be replaced by aluminum, as assumed in this thesis, is in reality ongoing. Electrical steel is very much used (Steiniger, 2019), and Tesla's shift from aluminum to steel for its Model 3 (Onstad, 2018) has silenced some voices claiming that aluminum will be dominant. Additionally, the steel industry is working hard on lighter sheets for cars, with high-tensile steel already being 20% lighter than conventional steel (Öko-Institut e.V., 2009a).

The overall ELV material is expected to increase, especially if motorization rates in the EU will remain at a similar level or slightly increase. The amount of recyclable steel is expected to slightly decrease. As a replacement of steel by aluminum as well as more aluminum for additional EV components is assumed, the amount of recyclable aluminum is expected to double.

Aluminum components in HEVs and EVs are different to those of ICE vehicles since the driving systems are different. In EVs, there is no ICE, but a large demand for wrought alloys used in the power-supply box. As far as HEVs are concerned, Hatayama et al. assume that more cast alloys are used as compared to ICEV. Around the year 2030, EVs and HEVs will likely exceed the aluminum demand of ICEs (Hatayama, Daigo, Matsuno, & Adachi, 2012).

Regarding copper, there is an urgent need for action. There will be almost 10 times more copper to be recycled by 2045 compared to 2019, but current recycling schemes rarely recover copper other than in the dismantling stage. In theory, separating the red metal fraction (copper and copper alloys) and grey metals is quite easy via their specific weights and the use of eddy-current-separations prior to float-sink-plants (Kletzmayr, 2022). However, cost-effectiveness is the major limiting factor. The share of copper in non-ICE vehicles is increasing dramatically, driven by changes in motorization. In fact, the copper content in EVs is estimated to be double the amount of copper in an ICE vehicle with 38.5kg, 60kg, and 83kg of copper in HEVs, PHEVs, and BEVs, respectively (International Copper Association, 2017). The Öko-Institut e.V. even assumes that BEVs contain about 121kg of copper compared to 19kg that are present in an ICE reference vehicle (Öko-Institut e.V., 2009a). The trend of using increasingly sophisticated alloys from ferrous material is increasing copper content, too (Nakamura, et al., 2012).

The expected increase for plastics material is even higher, with approximately double the amount in sold vehicles and an increase of the recycling rate from 2.6% to 50.4%. The underlying assumption is that the EU Plastics Strategy will continue to put pressure on ELV Directive legislators. In terms of weight, about 14.8% of the average European ELV today is mixed plastics - tires, wire sheathings, and battery casings excluded. This percentage is expected to reach up to 20% in new cars (100-200kg), though with different compositions than today, e.g., as housings for electronics. However, in 2019, about 40% of ELV plastics is disposed of. The trend to use new difficult-to-recycle plastics such as carbon fiber reinforced plastics further aggravates the situation (European Commission, 2021). A study by Emilsson et al. showed that acrylonitrile-butadiene-styrene (ABS) is relevant only for BEVs (Emilsson, Dahllöf, & Söderman, 2019). The coloring of ABS parts poses a serious problem to recyclers since near-infrared technology, which separates polystyrene (PS) very easily, for example, does not detect black color. And most ABS used in electronics is actually black. Even if electrostatic separation is used, which would be able to detect ABS in pre-concentrated scrap, the problems related to mixtures with different types of plastics and to contaminations with dust, glass, or metal residues remain (Sesotec, 2022).

3. Where are the main gaps between the current ELV recycling scheme and an ELV recycling scheme focused on EVs?

Although there are arguments for both a steel and an aluminum scrap surplus due to the introduction of EVs, the main gaps between the 2019 and the 2045-system refer to the increased share of copper, plastics, and rare earth metals in ELVs. For decades, recycling schemes in the EU have put emphasis on the recovery of ferrous metals and aluminum. The future recycling scheme needs to treat a larger variety of materials and find ways to recycle them separately and introduce them into new loops. It is expected that such a scheme will be even more open than the current one. Especially regarding EV batteries, new recycling facilities will need to be built. For the recycling industry, the dismantling of batteries (or, in case of FC, the dismantling of FC) containing cadmium (Cd), nickel (Ni), and others will be a new requirement (Janjić, Bukvić, & Stojanović, 2016).

Janjić et al. estimate that the recycling industry will have to adapt to hybrid vehicles by 2030, to electric vehicles by 2035, and to FC cars by 2050 (Janjić, Bukvić, & Stojanović, 2016). The European Commission assumes that ELV management will have to change considerably between 2030 and 2035, owing to the increasing share of BEVs in sold vehicles. The first effect will probably be higher ELV management costs (European Commission, 2021).

The MFAs showed that, overall, more material and more heterogenous material needs to be treated and recycled. More valuable as well as more difficult-to-recycle material will be used, which poses a huge challenge to ELV recycling.

4. Is the EU ELV recycling industry ready for the large-scale introduction of EVs?

From a legal point of view, the revision of the EU ELV Directive expected for 2022 has the potential to provide the industry with guidance related to ELVs of changing driving technologies. However, it is very unlikely that the updates will go beyond a reaction to the status quo. From a practical point of view, questions 1 to 3 have shown that the challenges are big. Expert inputs have shown that in Austria, dismantlers and shredders do not feel ready for a large-scale introduction of EVs. Recycling ELVs today deals with challenges from recycling ASR to recovering copper that will only intensify with changing driving technologies, from HEVs, to EVs, to FCEVs. Consequently, this question needs to be answered in the negative.

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Annex A: Interview with Ing. Walter Kletzmayr

Altfahrzeugrecycling in der EU

I: Die EU-Kommission hat im letzten Jahr eine Empfehlung verkündigt, die eine Null-Emissions-Strategie für den Transportsektor bis 2035 vorsieht, was bedeutet, dass dann keine Verbrennerautos mehr auf europäischen Straßen zu finden sein sollten. Für wie realistisch halten Sie solche Pläne?

WK: Sehr schwierig - die beste Prognose ist die, die man nicht abgibt. Aber nach meiner Einschätzung werden mittelfristig keine Hybrid-Fahrzeuge mehr sichtbar sein. Das ist eine Technologie, die mehr oder weniger als Trend zu bezeichnen wäre. Es war eine technologische Entwicklung, die hier und dort ihre Berechtigung hat, aber die Distanz, auf der elektrisch gefahren wird, ist eigentlich zu vernachlässigen. Auch in der Gesamtenergiebilanz ist sie einem echten Elektroantrieb total unterlegen. Man wird sich meiner Ansicht nach relativ rasch wieder von dieser Hybrid-Technologie verabschieden.

Ich war ursprünglich ein großer Kritiker der Elektromobilität, einerseits in Hinblick auf die Produktion des Stroms und andererseits in Hinblick auf die schwierige Verteilung über die Netze und die Belastung, die in manchen Netzbereichen entsteht, sowie auch die rasch umzusetzende Infrastruktur der Ladestationen - das habe ich alles immer sehr sehr kritisch gesehen. Allerdings habe ich mehr Probleme gesehen, als sich tatsächlich realisieren. Auf die Gesamtenergiebilanz bezogen, wenn man die Produktion und Verteilung von Benzin und Diesel unter die Lupe nimmt, wird man sehr schnell feststellen, dass auch das ohne elektrische Energie gar nicht funktioniert. Alleine für die Förderung und die Raffinerie von Rohöl zu Benzin braucht man für 5 bis 6l Sprit etwa 15 kWh Strom. Das entspricht aus heutiger Sicht in etwa der Fahrleistung eines Elektroautos für 100km.

Wenn wir alle Verbrenner wirklich ersetzen, wird uns sicher nicht der Strom ausgehen, und die Netze werden das aushalten - der Ausbau erfolgt außerdem relativ rasch. Ich sehe uns hier auf einem sehr, sehr guten Weg in Richtung Elektromobilität.

Was ich nicht einsehe und nicht verstehen kann, ist, dass man einzig und allein die Elektromobilität fördert. Es gibt viele andere Technologien, die noch untersucht werden und wo man aus heutiger Sicht die kühne Prognose stellen kann: Wir werden uns noch viele Jahre nicht von den Verbrennungsmotoren verabschieden, wir werden den Sprit wechseln.

I: Sie sprechen von E-fuels?

WK: Ja, Richtung synthetischer Treibstoffe, Richtung anderer Alternativen, die in ihrer Gesamt- CO_2-Bilanz in der Taxonomy-Betrachtung als "grün" gelistet sind. Wir haben in Europa hunderte Jahre gute Erfahrung mit der Herstellung von Automobilen und ich glaube, dass das Ende der Verbrennungsmotoren nicht gleichzeitig vonstatten gehen wird wie das Ziel mit der Gesamt-Nullbilanz. Es wird auch noch Wasserstoff-Antriebe und andere Alternativen geben, so wie die Nutzung von Photovoltaik zur Erzeugung von Druckluftmotoren, auch wenn das ein absoluter Exote ist und von der Effizienz nicht besonders toll. Aber es kommt immer auf die Rahmenbedingungen, auf das Einsatzgebiet, und auf die verfügbare Energie vor Ort an, welcher Antrieb letztendlich der Beste ist.

Aber ich denke in der Masse wird es die Elektromobilität sein - auch in Hinblick auf das Wachstum von Neuanmeldungen der Elektrofahrzeuge; von 2019 auf 2020 hatten wir ein Wachstum von 60%, von 2020 auf 2021 von etwa 75%. Es ist überraschend schnell gegangen, dass in Österreich von 5.1 Millionen Fahrzeugen bereits etwas über 2% im Bestand Elektrofahrzeuge sind.

Und um das Thema abzurunden: Die Attraktivität der Dieselfahrzeuge hat in den letzten Jahren nicht nur aufgrund des Dieselskandals abgenommen. Das übliche Bild in Österreich der Jahre zuvor, in denen bei den Neuanmeldungen wesentlich mehr Diesel- als Beninfahrzeuge waren, hat sich vollkommen gedreht. Bei Verbrennungsmotoren dominieren heute die Benziner.

I: Um den Bogen zu meiner Arbeit zu spannen, in der es ja eher um den letzten Schritt also um den ersten - die Neuanmeldungen - geht: Ist das Altfahrzeugrecycling in der EU, der auch in Österreich, derzeit Ihrer Einschätzung nach ein closed- oder open-loop System?

WK: Eigentlich ist es wirklich sehr offen. Fahrzeuge werden entlang der Wertschöpfungskette ganz klar anhand ihrer FIN, ihrer Fahrzeugidentifikationsnummer, identifiziert und diesbezüglich werden auch die Verwertungsquoten dokumentiert. Aber im Zuge der Behandlung verlieren die Altfahrzeuge ihre Namentlichkeit in dem Moment wo sie in den Schredderprozess eingebracht werden. Was dort hinten an zerkleinertem Material heraus gekommt, kann man nicht mehr einem bestimmten Fahrzeug zuordnen. Es werden auch verschiedene Materialien in den Schredder aufgegeben - verschiedene Bleche und anderer Sperrschrott. Grundsätzlich machen Altfahrzeuge etwa 10-15% des Inputs bei Schredderbetrieben aus. Die anderen 85-90% kommen aus ganz anderen Quellen, zum Beispiel vorbehandelte Elektroaltgeräte. Alle Materialien wurden zumindest gesichtet, in den meisten Fällen aber auch vorbehandelt. Das heißt man kann nicht einmal bei einem Schredderschrott, das ist der Output aus dem Shredder, dieser Schredderschrott hat in der EU-Schrottsortenliste die Bezeichnung E40, ist dort genau definiert, sagen, wie viel Prozent die Altfahrzeuge pro Charge ausmachen. Wir können es in der Masse prozentuell nachempfinden, aber keinesfalls zuordnen. Darum kann man hier auch nicht von einem geschlossenen Kreislauf sprechen - natürlich auch immer in Abhängigkeit, wie groß man den Kreis zieht. Ist sozusagen der Kreislauf geschlossen, wenn beim Stahlwerk das flüssige Roheisen hinten hinausrinnt? Nach meiner Ansicht, ja.

I: Passend dazu wäre meine nächste Frage zu den Recyclingraten und den Berechnungen dazu, bei denen es ja meines Wissens keine einheitliche Vorgangsweise gibt. Hier wäre ja wahrscheinlich ein EU-weites System sehr hilfreich, aber ist das überhaupt vorstellbar und realistisch? Und wenn Sie an einen Recycling-Prozentsatz denken, was verstehen Sie dann darunter?

WK: Eine einheitliche Methode zur Berechnung der Quoten wäre äußerst begrüßenswert, wir kämpfen seit 2004 darum. Wir waren in Österreich schon so gebrandmarkt von der Juristerei, dass wir uns das von der naturwissenschaftlichen Seite sehr genau angesehen haben und das Ministerium auf naturwissenschaftliche Fehler in der Gesetzgebung aufmerksam gemacht haben. Das war dann der Auslöser für die sogenannte Altauto-Studie 2004, die UVB beauftragte damals Dipl-Ing. Franz Neubacher. In der Studie wurden die Abweichungen formuliert und dann mit dem Ministerium ein Konsens geschaffen, wie wir damit umgehen. In der EU-Richtlinie steht zum Beispiel, dass die Verwertungsquote zu beziehen ist auf die im Kalenderjahr gesammelten Altfahrzeuge - Schwachsinn. Man kann eine Verwertungsquote nur auf die im Kalenderjahr verwerteten Fahrzeuge beziehen. Wir haben in Österreich diesen Konsens getroffen. In Deutschland hat man blind die EU-Richtlinie umgesetzt und wie dann zum Beispiel diese Verschrottungsprämie war, haben sich Lager aufgebaut, weil eine immense Anzahl an Altfahrzeugen zurückgekommen ist durch diese Verschrottungsprämie. Die hat man dann im Jahr darauf verwertet, diese Masse hat man umgelegt auf die im Kalenderjahr gesammelten und hat dann eine Verwertungsquote von 109% erreicht - und auch korrekt nach Brüssel gemeldet, juristisch ist das ja alles korrekt. Man darf den Deutschen da ja keinen Vorwurf machen, außer den, dass sie zu Beginn schon nicht mitgedacht haben. Wir waren hier in Österreich Vorreiter, und auch Rufer in der Wüste, weil es kein Problembewusstsein gegeben hat und das eigentlich allen egal war. Die Griechen hab beispielsweise jahrelang nichts gemeldet. In den Ländern wo wirklich exekutiert wird, und in Österreich wird besonders streng exekutiert, hat es da viele Probleme gegeben.

Jedenfalls war in Österreich diese Altauto-Studie 2004 der Ausgangspunkt, dass wir uns auf naturwissenschaftlicher Basis mit der Altfahrzeugverordnung auseinandersetzen und einerseits in Österreich die Verwertungsquote auf die im Kalenderjahr verwerteten Fahrzeuge beziehen und auch eine einheitliche Methode zur Berechnung der Verwertungsquote in Österreich entwickelt haben. Wir haben sechs Schredderbetriebe und es gibt viele unterschiedliche Ebenen, die man sich ansehen muss. Es gab eine wissenschaftliche Arbeit vom Herrn Prof. Felsenstein, der Mathematiker und ein Statistik-Genie ist und die statistischen Rahmenbedingungen der zu untersuchenden Altfahrzeuge für diese Bilanzierungen festgelegt hat. Es wird aufgrund der im Vorjahr von einem Schredderbetrieb übernommenen Fahrzeuge statistisch ermittelt, wie viele Stück von welcher Marke, Type, Modell, mit oder ohne Motor und und und gesammelt werden. Es entsteht ein Stichprobenplan, der dem Schredder vorgegeben wird. Dieser hat 6-8 Monate Zeit, diese Fahrzeuge zu sammeln und bereitzustellen. Dann erfolgt eine Bilanzierung des Schredderprozesses, nach genauen Vorgaben für alle 6 Schredder gleich. Die Restfraktionen, die beim Schredder als Output kommen und nicht direkt weiterverwertet werden können, gehen an die Post-Shredder-Technologien, wo weiter verkleinert, gesiebt, aufgetrennt und und und wird. Dort entstehen dann nochmals über 20 Fraktionen. Auch all diese Prozesse, die wir hier in Österreich bilanzieren, werden ebenfalls bilanziert. Und das alles schon seit dem Jahr 2006. Wir haben das in unzähligen Kanälen immer wieder beworben, zum Beispiel die von der EU beauftragte Ökopol. Aber bis heute gibt es keine einheitliche Vorgangsweise in Europa. Es gibt ein sehr gutes in Österreich, ein per Bescheid genehmigtes Berechnungsmodell der Verwertungsquote und es gibt unsere Altauto.at, eine gemeinsame Datenbank. Dort gibt die Rückgabestelle die Fahrzeugdaten ein. Die werden dann gegengecheckt - aber leider nicht lückenlos, weil es leider keine Verknüpfung gibt mit der zentralen Zulassungsstelle. In Wahrheit ist das ein bisschen pervers; wir sind verpflichtet FIN, Marke, Type, Zulassungsschein und Namen und Wohnort des Letztbesitzers zu erfassen. Das kommt in den Verwertungsnachweis, welcher 7 Jahre archiviert werden muss. Aber wir bekommen keinen Zugang zur Zulassungsdatenbank mit dem Hinweis auf Datenschutz. *(lacht.)*

In der Altauto.at sind aber all diese Daten drinnen, die Altauto.at generiert auch den Verwertungsnachweis. Diese Daten werden auch immer an den nächsten Betrieb weitergegeben - beispielsweise vom Fahrzeughändler zum Teileverwerter, der Demontagen tätigt und diese dokumentiert, das nennt sich dokumentierte Entnahmen. Dann geht das Fahrzeug zum Schredder, inklusive der Daten vom KFZ-Händler und vom Teileverwerter. So lasst sich dann am Ende auch eine Verwertungsquote berechnen. So lässt sich nicht nur ein Verwertungsnachweis generiert, sondern es werden auch fehlende Bauteile dokumentiert, wie ein fehlender Motor, der vom Letzthalter ausgebaut wurde. Der wird dann als fehlender Bauteil dokumentiert, aber der Verwertung zugerechnet - wenn das plausibel ist. Das ist aber nicht immer plausibel: Eine fehlende Seitenscheibe ist vermutlich kaputt und nicht irgendwo gebraucht. Oder wenn kein Öl mehr vorhanden ist, etc. Hier kommt es also zu einer Plausibilitätsbewertung.

Die dokumentierten Entnahmen werden auch nach ihren weiteren Behandlungswegen betrachtet. Zum Beispiel bei FCKW aus Klimaanlagen ist eine Verwertung verboten und muss beseitigt werden, das zählt dann zu Beseitigung. Andere Stoffe werden thermisch verwendet und der größte Teil der Entnahmen wird wiederverwertet oder am Second-Hand als Teile wieder in dem Umlauf gebracht.

I: Ist Österreich was die Datenbank betrifft ebenso ein Vorreiter? Gibt es ähnliche Systeme in anderen EU-Ländern oder ist das eher was Einmaliges?

WK: Eine Altauto.at in diesem Sinn ist eher einmalig. Es gibt natürlich verschiedene Lösungen, aber aufgrund der in Österreich wirklich komplexen Bürokratie sind das auch etwas andere EDV-Systeme, die viel mehr auf der Verwerter-Ebene ihre Daseinsberechtigung haben, eben um zum Beispiel den entsprechenden Markt zu bedienen für eine Lichtmaschine oder andere Ersatzteile. Die Altauto.at hat keine

Ersatzteil-Verwaltung. Da wird nur dokumentiert in Hinblick auf die Quote. In anderen Ländern ist alles was dort dokumentiert oder erfasst wird eigentlich aus wirtschaftlichen Gründen, aber nicht aus bürokratischen.

I: Wenn wir schon von Informationssystemen sprechen: Das IDIS wurde ja mit der EU-Richtlinie etabliert und wird jetzt mit der bevorstehenden Novelle wieder diskutiert. Hat dieses System in der EU ein Gewicht bzw. eine Rolle? Hat es etwas verändert oder gebracht?

WK: (seufzt.) Zwei Herzen schlagen in meiner Brust. Der Praktiker sagt sofort "Danke, nein". In der praktischen Anwendung ist es von Bedeutung wirklich nahezu null. Hier in Österreich haben wir sechs Schredderbetriebe: jeder weiß, was er jeden Tag tut. Und wenn sich der wo nicht auskennt, dann ist das sein Stolz, dass er da selbst draufkommt, auch wenn das eine Minute Arbeit in Anspruch nimmt, oder zwei. Der Computer wo der Marke, Type, Modell eingibt und irgendwelche Hinweise bekommt, die in der Praxis nicht wirklich weiterhelfen, wird von einem Praktiker nicht in Anspruch genommen.

Aber die Hersteller sind verpflichtet, Demontage-Informationen bereitzustellen. Und dass das über eine einheitliche Plattform stattfindet, ist wiederum sehr begrüßenswert.

Dass das in den vergangenen Jahren nur eine gewisse Feigenblattfunktion hatte, mag durchaus gewesen sein, aber das Bild hat sich etwas gewandelt, weil eben immer mehr Exoten den Weg in die Verwertung finden. Die Fragen kommen dann nicht wirklich vom Praktiker, also der, der das Öl ablasst etc., sondern die wenden sich an mich, weil die wissen, ich bin für alle 6 die Ansprechperson und kenne mich in IDIS gut aus und der einfachste Weg ist mich anzurufen "Du, wir haben da einen Exoten, was ist da alles drinnen, was ist da zu beachten". Insofern ist es hilfreich - manchmal.

Wie sich aber bei dem Tesla-Unfall im Oktober 2019 gezeigt hat, sind die Hinweise in IDIS nicht besonders hilfreich. Beispielhaft: Batterie: 550 kg, Angabe zur Lage: unten seitlich links. Es sind nicht alle Marken gleich fleißig in IDIS. Es gibt aber von den Herstellern bereitgestellt sehr detailreiche Demontage-Informationen, speziell für Elektro- und Hybridautos. Diesen Detailreichtum gibt es für die alten Verbrenner aber wirklich nur in Ausnahmen, und die Qualität der Hersteller ist sehr, sehr unterschiedlich.

Ich bin überzeugt, wenn man in Zukunft die Daten sinnvoll weiter einpflegt, wird das mehr und mehr belebt und hilfreich. Aber nicht so, dass der Mitarbeiter bei der Trockenlegung einen Touchscreen-Computer nutzt.

I: Der ELV-Richtlinie liegt ja auch das Prinzip Extended-Producer-Responsibility zugrunde. Der Produzent muss also für den Mehraufwand, der durch ordnungsgemäßes Recycling entsteht, geradestehen. Wie wird das genau in der Fahrzeugbranche sichergestellt? Eine Gebühr für die Entsorgung gibt es ja nicht, so wie mit anderen Produkten.

WK: In Europa ist das sehr, sehr unterschiedlich. Das geht von Pfandsystemen bis zu dem System zum Beispiel in Tschechien, wo für jedes Auto soundso viele Kronen abgeliefert werden müssen, bis hin zu einer vorgezogenen Gebühr in der Schweiz. In Österreich war das eigentlich unter dem Druck der Hersteller und aufgrund der historischen Entwicklung - wir waren ja schon in den 90er Jahren mit verschiedenen Herstellern/Importeuren mit der freiwilligen Vereinbarung 10 Jahre sehr gut in Kooperation, da hat sich auch ein gegenseitiges Verständnis gebildet. Und im Rahmen dieses gegenseitigen Verständnisses hat die Automobilindustrie sehr wohl gewusst, dass ihre Altfahrzeuge in jedem Fall noch etwas wert sind, auch wenn die Behandlungs- und Transportkosten immer teurer werden. So ist die Übereinkunft gekommen, dass in den Verträgen, die die Hersteller und Importeure mit den Schredderbetrieben haben, vereinbart ist, dass die KFZ-Händler die Altfahrzeuge als Rückgabestellen im Namen der jeweiligen Marke sammeln und die Schredderbetriebe holen diese dort ab, und die Abholung bei diesen Betrieben für die Hersteller/Importeure kostenlos erfolgt. Im Gegenzug gibt es einen Gefahren- und Eigentumsübergang an den Schredderbetrieb und damit stehen ihm alle Altstofferlöse aus dem Altfahrzeug zu.

In der Vergangenheit ist sich das immer ausgegangen. Je nach Schrottpreis bekommt dann nicht der Hersteller oder Importeur einen Erlös, sondern der KFZ-Händler, der das Altfahrzeug übernommen hat und dem Schredder gibt, weil der hat ja auch einen Aufwand. Wenn Schrott- und Metallpreise gut sind, gibt es für den KFZ-Betrieb einen geringfügigen Erlös, das wird nie dreistellig, oder nur in äußersten Ausnahmen. Für den Importeur ist das auf Null, auch wenn die Weitergabe von Erlösen möglich ist, kassiert die nicht der Importeur, sondern der KFZ-Händler. Andersherum würden die

Altstofferlöse nichts mehr wert sein, würden die Behandlungskosten die Erlöse übersteigen und dann würden wir aufzeigen und kassieren.

Das ist eine praktikable und gute Lösung, von der alle profitieren. Die Automobilbranche hat in der Vergangenheit wirklich Probleme gehabt. Zu einer Zeit, wo Opel noch General Motors geheißen hat und der Frank Stronach sich bemüht hat, als Magna General Motors zu übernehmen, hätte da ein Recyclingpfand in Österreich bestanden, hätte Stronach gar nicht mehr verhandeln müssen, denn die wären mausetot gewesen mit einer solchen Rückstellung. Heute sind die Verträge so gestaltet, dass das unbürokratisch passiert und es eine win-win-win Situation für Hersteller/Importeure, KFZ-Händler aber auch Teileverwerter und Schredderbetriebe einigermaßen profitieren. Im Gegenzug ist der Frust ist extrem, wir reden von etwa 25% der Fahrzeuge, die jährlich ausgeschieden werden, die verwertet werden. Der Rest verschwindet irgendwo hin ins Ausland, und dort gibt es keine Producer Responsibility, und schon gar keine Erweiterte.

I: Das heißt das passiert in Österreich alles auf bilateralen Verträgen?

WK: Ja genau. Diese Verträge, die Hersteller/Importeure bilateral mit den Verwertungsbetrieben haben werden als Eigenleistung in unser Altauto-System eingebracht wo dann für alle Teilnehmer kollektiv die Verwertungsquote berechnet wird.

I: *Und wenn Sie an einen Recycling-Prozentsatz denken, was verstehen Sie dann darunter? Das österreichische Beispiel scheint ja sehr gut zu funktionieren.*

WK: Ja, das funktioniert gut. Aber eben auf Basis der bestehenden Gesetzgebung. Und die bestehende Gesetzgebung verlangt eben eine gewichtsbezogene Verwertungsquote von 85% und eine Gesamtverwertungsquote von 95%, also man darf maximal 5% beseitigen. Mein Zugang ist hier, dass diese gewichtsbezogene Verwertungsquote ein Schwachsinn ist, da sie die Wirtschaft nur blockiert und nicht wirklich Entwicklungen vorantreibt und ökologisch vollkommen kontraproduktiv ist. Die Nachweise sind enorm und füllen mittlerweile Archive, das ist unaussprechlich. Da werden schon Gebäude erweitert, um die ganzen Dokumente aufheben zu können. Der Schredder in Laxenburg hat einen alten Postwagon aus dem Schrott sichergestellt und vor der Verschrottung gerettet, der dient jetzt als Archiv.

Aber das wirkliche Problem ist, dass diese Gewichtsprozente relativ rasch erreichbar ist. Aber damit ist nicht sichergestellt, dass auch kritische Rohstoffe zurückgewonnen werden. Wo bleiben die seltenen Erden, Neodym, und und und?

Beim Katalysator, da weiß man das ganz genau. Das weiß mittlerweile jeder Kriminelle. Es werden ja auch schon Katalysatoren von Fahrzeugen herausgezwickt und gestohlen, das hat jetzt nicht mit Altfahrzeugen zu tun. Das ist Diebstahl, weil die wissen, dass man mit einem Katalysator kann ich 50,70, mit einem großen vielleicht 100 oder mehr Euro einnehmen - auch auf dem Schwarzmarkt. Weil das Platin, Rhodium etc., diese Edelmetalle die da als Katalysatoren drinnen sind, sind sehr gut bewertet.

Aber das ist alles im Gramm-Bereich und würde für eine gewichtsbezogene Verwertungsquote nichts bringen.

I: Für die Quote nicht, aber es gibt doch einen wirtschaftlichen Anreiz.

WK: Ja, aber den Anreiz gibt es zum Beispiel für Tantal nicht. Tantal ist zum Beispiel in elektronischen Bauteilen, in Hochleistungskondensatoren. Neodym ist in geringen Mengen in den Magneten von Lichtmaschinen, Generatoren, etc. Also es gibt eine Vielzahl von wirklich wertvollen Metallen, die in Grammzahlen vorkommen und nicht gezielt erfasst werden, weil a) auch wenn all diese Metalle gut bewertet sind, aber die Arbeitszeit, die manuelle Tätigkeit, frisst den Erlös auf. Aber volkswirtschaftlich ist dann dieses Metall verloren und, Frau Gutschi, ich schwöre Ihnen, dass ist das, was uns volkswirtschaftlich am Allermeisten wehtut. Beim Eisenschrott haben wir in Europa zumindest in den letzten Jahren - vielleicht wandelt sich das auch wieder - einen Schrottüberschuss. Wir haben in Europa etwa 112% von dem, was die Stahlwerke nehmen können. Diesen Überhang exportieren wir dann die Türkei oder in andere Länder. Also mit Schrott, mit Stahl, gibt es kein Problem. Aber natürlich bei den Buntmetallen fangt es schon an, bei den Industriemetallen geht es weiter, und bei den seltenen Erden ist unterm Strich dann der größte volkswirtschaftliche Schaden, weil man da auch ganz genau weiß, dass China den Markt ja steuert nach politischem Gutdünken und nicht nach Angebot und Nachfrage.

I: Das ist ja auch ein Thema wen wir von den veränderten Antriebstechnologien und mehr Elektrofahrzeugen sprechen. Ich hatte zum Beispiel Kontakt mit einem

Autoverwertungsunternehmen, das eher pessimistisch eingestellt ist und mehr Probleme als Chancen sieht. Da war dann auch ein Thema, dass das Gewicht der Fahrzeuge durch die Verwendung anderer Materialien, die zurzeit kaum wiederverwertbar sind, versucht wird, zu reduzieren. Ich denke, dass sich da auch auf den Aufwand des Ausbaus bezogen wurde, weil sich der Anteil der seltenen Erden - aber auch von Kupfer - in Fahrzeugen erhöht. Wird sich das Altfahrzeugrecycling aufgrund dessen grundlegend verändern müssen, weil der Fokus auf andere Materialien switchen muss?

WK: Ich glaube, wenn man Verwertungsquoten sicherstellen will, wenn das der Wille der Gesellschaft ist und der Gesetzgeber meint, es muss nachgewiesen werden, ist die Lösung dieser Herausforderung die Vorgabe vom Gesetzgeber von sogenannte Behandlungsverfahren: Das und das ist zurückzugewinnen und diesem Verfahren zuzuführen. Nach diesem Zuführen braucht man dann eigentlich keine weiteren Nachweise mehr und hat damit sichergestellt, dass man alle Stoffströme, die für Wirtschaft und Gesellschaft interessant erscheinen, speziell wichtig sind hier die kritischen Rohstoffe, die die EU schon vor vielen Jahr geortet hat. Geht man weg von einer gewichtsbezogenen Verwertungsquote, wäre juristisch die Vorgabe von Behandlungswegen eine entsprechende Lösung dieses Problems und würde extrem viel Bürokratie abkürzen, aber auch die Sicherstellung von kritischen Rohstoffen gewährleisten.

I: Durch die bevorstehende Novelle der Richtlinie sind auch spezifische Quoten für gewisse Materialen im Gespräch; Aluminium, Kunststoff, und Glas werden hier konkret genannt. Wo sehen Sie einen Vorteil in solchen materialspezifischen Quoten?

WK: Ja, sehr wohl. Bei all dem, wo die haushaltsnahe Sammlung vorgehend steht. Glas, Altpapier, Metallverpackungen, Kunststoffverpackungen, PET-Flaschen, und und und. Hier sieht man eindeutig den Trend zu Pfandsystemen, das hat aber alles nichts mit Altfahrzeugen zu tun. Für diese kurzlebigen Produkte kann man ganz genau Auskunft geben, wie große der Marktinput ist, sprich welche Masse bringe ich in Umlauf, wie lange sind die im Umlauf, und wann ist der Zeitpunkt, wo sie wieder gesammelt werden können. Diese Zeitspanne ist äußerst kurz und es lässt sich auf die in Umlauf gebrachte Menge eine Sammelquote definieren. Und erst wenn es eine Sammelquote gibt, macht eine Verwertungsquote für die jeweilige Stoffgruppe Sinn. Es hätte ja keinen Sinn, zum Beispiel Altglas zu sammeln und das dann nicht entsprechend zu verwerten. Und dass man dann hier eine gewichtsbezogene Verwertungsquote haben will, ist verständlich - aber nur vor dem Hintergrund, dass es auch eine Sammelquote gibt, die sich auf den Marktinput bezieht.

So, was machen wir bei den Fahrzeugen? Bei den Fahrzeugen gibt es keine Sammelquote. Und es ist so komplex, dass Vorgaben für einzelne Stoffgruppen nur in Deutschland ein Notausgang war. In Deutschland wollte man diese extrem ausgeprägte Bürokratie wie in Österreich vermeiden, wo FIN-bezogen alles erfasst wird. In Deutschland hat man einen Konsens gefunden, dass man gesagt hat, wir haben 200 Fahrzeuge in diesem Betrieb und 150 Fahrzeuge in diesem Betrieb und 300 Fahrzeuge in diesem Betrieb und man hat dann, ich weiß es nicht mehr genau, ich glaube 1.500 Fahrzeuge in Summe bilanziert, in verschiedensten Demontagebetrieben und Schredderbetrieben. Und man hat festgestellt, der Metallgehalt ist in Summe betrachtet über alle Autos in jedem Fall, ich weiß es nicht mehr genau, 74 oder 75 oder 76%. Und damit man diese 76% nicht nachweisen muss, hat man sich auf diesen sogenannten fixed metal content geeinigt. Um diesen Gap von ca. 75% auf diese 80% in der ersten Phase und jetzt 85% stoffliche Quote muss man eben nur nachweisen, dass ich jetzt soundso viel Glas von den Scheiben und soundso viel Kilogramm Kunststoff verwertet habe. Und das über das Jahr betrachtet ist dann das Quotenergebnis in Deutschland. Darum ist das stoffgruppenbezogen, aber das ist keine Verwertungsvorgabe der EU-Richtlinie, sondern entstanden durch einen Konsens in Deutschland mit diesem fixed metal content.

I: Im EU Commission Staff Working Document zur Evaluierung der Richtlinie wurden, ich glaube, insgesamt über 40 Stakeholder befragt. Darin wurde kommuniziert, dass die Rückmeldung der Stakeholder großteils war, dass spezifische Quoten für Glas, Kunssttoff und Aluminium die Ziele der Richtlinie näherbringen. Natürlich haben das Stakeholder wie European Aluminium oder ACEA ganz anders gesehen in ihren Positionspapieren und Statements dazu. Welche Branchenvertreter sind das dann, die diese Quoten als positiv erachten?

WK: Der Hintergrund ist jetzt nicht direkt vergleichbar mit der derzeitigen Verwertungsquote. Soweit ich das kenne, geht es um Quoten zum Einsatz von Rezyklaten. Mit dem haben die Hersteller natürlich ein Problem. Dass hier eine Recyclingquote gewünscht wurde von den Verwertern geht in erster Linie zurück auf die Kunststoffverwerter, weil die Kunststoffgranulate, die die produzieren und die dann eigentlich ein Produkt sind, werden von der Fahrzeugindustrie nicht eingesetzt, weil es zu minder ist. Aber führende Marken wie BMW und Mercedes haben keine Scheu mehr, Rezyklate in ihren Produkten tatsächlich zu verwenden, wenn auch nur beigemengt. Das ist auch verbunden mit den Emotionen der Fahrzeugkäufer, die sagen "Ich kaufe mir jetzt um 150,000 Euro einen Mercedes und dann ist die Hutablage aus einem alten Filz, der nach Tabak stinkt, weil der Vorgänger geraucht hat". Das ist natürlich überspitzt formuliert, aber hier hat sich auch das Bewusstsein der Fahrzeuglenker gewandelt und es ist heute, glaube ich, für niemanden mehr ein Problem, wenn hier wirklich Rezyklate im Automobilbau eingesetzt werden. Der überwiegende Teil der Automobile wird aus Primärmaterialien produziert und darum hat auch die Recyclingbranche europaweit gefordert, es möge hier Quoten geben, wo die Hersteller gezwungen werden, Altglas von den Seitenscheiben, Front- und Heckscheiben, Altkunststoffe und und und wieder in Fahrzeugen einzusetzen. Um diese Quoten geht es, nicht um die Verwertungsquoten.

I: Soweit ich weiß, gab es hier zwei Themen; die von Ihnen genannten Quoten für Rezyklate in neuen Fahrzeugen und Vorgaben für deren Verwertung, welche ein besseres Ökodesign zur Folge hätten. Ich hätte aber noch eine Frage zur Rechtslage: Derzeit besteht ja die Problematik, dass viele Altfahrzeuge einerseits als Exporte aus der Definition "waste" rausfallen und andererseits eine große Anzahl auf unbekannte Weise "verschwinden". Man hat hier also eine Lücke in den Abmeldungssystem. Wo müsste man hier bei den Abmeldungen nachschärfen?

WK: Grundlegend ist Europa hier datentechnisch noch in der Steinzeit. Es sind viele Datenbanken in Europa noch nicht verknüpft, geschweige denn kompatibel. So ist es irrsinnig schwierig, Daten von einer Zulassungsstelle, von einer Nation, mit einer anderen Nation abzustimmen. Forderung Nummer Eins: Es gibt EDV-Projekte, die man global schaffen will; da gibt es dieses GAIA-Programm, Cartena-X ist sozusagen die Version davon für die Automobilbranche. Jetzt beginnt man sich insgesamt zusammen zu organisieren, dass es hier gemeinsame Schnittstellen gibt, gemeinsame Datenformate und und und. Das war in der Vergangenheit bisher auf europäischer Ebene alles nicht möglich. In Österreich hätten wir eigentlich eine ausreichende gesetzliche Regelung, wird aber traurigerweise nicht exekutiert. Das fängt bei den Zulassungsstellen an, weil die ja nicht vom Staat betrieben werden, sondern von Versicherungen im Auftrag des Staates. Aber auch KFZ-Händler wenn sie Versicherungen mit anbieten sind hier mit von der Partie.

Wenn jetzt ein Fahrzeughalter zu so einer Versicherungsstelle kommt und sagt, er will sein Fahrzeug abmelden, dann müsste die Versicherung eruieren, was mit dem Fahrzeug weiter geschieht. Wird es verkauft, müsste ein Kaufvertrag geprüft werden. Wird es endgültig stillgelegt, würde die Versicherung für die endgültige Abmeldung die Vorlage einer Verwertungsbestätigung brauchen. Das ist allerdings wieder kompliziert, möglicherweise 1 bis 2 bis 3 Tage Verzögerung entstehen dadurch - und man darf nie vergessen, der, der das will, ist Kunde der Versicherung. Und genau aus dem Grund wird die Person, wenn die den Hut aufhat "Zulassungsstelle" ganz sicher nicht um die Vorlage einer Verwertungsbestätigung fragen. Das ist eigentlich totes Recht. Nach unserer Beobachtung ist es in Österreich echt eine Seltenheit wenn eine Versicherung eine Verwertungsbestätigung verlangt. Das ist die Ausnahme und ganz sicher nicht die Regel.

So, das ist schon mal die erste Lücke. Die nächste Lücke ist leider die Unkenntnis des Abfallrechts vieler KFZ-Gutachter. Der KFZ-Gutachter, der dem Fahrzeugbesitzer mitteilen muss, dein Pickerl ist nicht mehr gültig, weil die Verkehrssicherheit mit diesem Fahrzeug nicht mehr gegeben ist. Dann hat der Fahrzeugbesitzer 3 Monate Zeit zur Nachbesserung und darf dann zur zweiten Prüfung antreten. Wenn er die auch nicht schafft, verliert er das Pickerl und damit auch die Straßenzulassungsberechtigung. Und damit ist das rein juristisch betrachtet ein latenter Abfall. Und latent deswegen, weil das österreichische Abfallwirtschaftsgesetz hier von einem subjektiven und einem objektiven Abfallbegriff ausgeht. Der subjektive Abfallbegriff ist geknüpft an die Entledigungsabsicht. Besteht keine Entledigungsabsicht, ist das Ding auch kein Abfall. Er könnte das Fahrzeug in seiner Garage, in seiner Werkstätte, sogar in seiner Gartenhütte verwahren - es ist kein Abfall. Würde er diesem Fahrzeug auf seinem eigenen Grundstück auf der Wiese das Öl ablassen, dann würde der objektive Abfallbegriff greifen, weil ja Grundwasser verseucht werden könnte und auch andere Rechtsmaterien wie zum Beispiel die kommunalen Vorgaben für die Ortsbildpflege beeinflusst werden könnten. Wenn also Gefahr in Verzug ist für das öffentliche Interesse, greift der objektive Abfallbegriff - oder im Falle eines Exports. Weil dann sprechen wir bereits von Abfallverbringung.

In Österreich gibt es die Möglichkeit, mittels einer sogenannten Reparaturfähigkeitsbescheinigung nachzuweisen, dass dieses Fahrzeug noch zu vernünftigen Kosten in Stand gesetzt werden kann. Dieses Dokument ist dann der Persilschein für den KFZ-Halter, dass er das Auto als Gebrauchtauto verkaufen kann. Hat er das nicht, ist das ein Umgehungsgeschäft und er hat sich eigentlich strafbar gemacht (in Österreich wird das bei Privatpersonen nicht exekutiert). Der Exporteur des Altfahrzeugs wird, falls er überhaupt erwischt und dingfest gemacht wird, wird zur Verantwortung gezogen, aber uns ist kein Fall bekannt, dass eine Privatperson hier jemals belangt worden wäre von der Behörde. Ausgestellt werden kann dieser Reparaturfähigkeitsnachweis von jedem Gutachter, der ein Pickerl machen darf. Und dann mit einer Gültigkeitsdauer von 1 Monat darf man das Auto als Gebrauchtwagen exportieren. Nur die Gutachter kümmern sich nur um 57a und Pickerl und wenn das abläuft, klären sie die Letztbesitzer leider nicht darüber auf, dass er einen Abfall hat, wenn er sich dessen entledigen will. Er könnte aber noch ein bisschen Taschengeld verdienen, wenn er eine Reparaturbescheinigung ausstellen würde. Lücken über Lücken über Lücken, an allen Ecken und Enden. Von Größenordnung 200.000 Fahrzeugen, die endgültig in Österreich ausgeschieden werden, kommen ca. 50.000 in die Verwertungsschieden und von 150.000 weiß es keiner. Ich geh davon aus, dass das ungefähr 100.000 echte Altfahrzeuge waren und 50.000 die man mit Fug und Recht noch als verkehrssicheres Gebrauchtauto bezeichnen kann. Also ein Drittel legal, zwei Drittel illegal, die man eigentlich hier in Österreich verwerten hätte können. Wir haben im letzten Jahr der freiwilligen Vereinbarung, im Jahr 2002, über 120.000 Fahrzeuge geschreddert in Österreich. Jetzt erreichen wir kaum 60.000. Also der Trend würde auch meine Annahme bestätigen, dass rund 150.000 als Altfahrzeug zu bezeichnen sind - als gefährlicher Abfall, den man behandeln, verwerten, und schreddern muss. Nur ein geschreddertes Altfahrzeug ist ein gutes Altfahrzeug.

I: Auf EU-Ebene sind es 35% der abgemeldeten Fahrzeuge, die "of unknown whereabouts sind".

WK: Ja, in Österreich ist das Verhältnis immer umgekehrt. Die EU ist im Verhältnis besser aufgestellt, bei uns ist der Schwund extrem groß, weil wir auch im Vergleich mit anderen EU-Nationen eine wesentlich höhere Bürokratie zu erfüllen haben und auch Bürokratie-Flucht eine Motivation ist.

I: In der Präsentation, die sie mir vorab geschickt haben, steht, dass es Anfang 2020 die Übereinkunft in Österreich gab, dass man Elektrofahrzeuge nur ohne Antriebstechnologie übernehmen darf. Sehen Sie da Veränderungsbedarf in Zukunft, wird es mit der EU-Batterie-Richtlinie zu neuen Vorgaben können? Oder wird das *weiterhin so bleiben, dass man Elektrofahrzeuge nur ohne Antriebstechnologie übernimmt?*

WK: Prognosen sind hier sehr schwer. Für die Marktbeurteilung insgesamt: Wenn ich einige Jahre zurückblicke, war es schon einmal nicht absehbar, dass aus General Motors wieder Opel, aus Fiat die FCA geworden ist etc. Heute gibt es die Stellantis Gruppe, die aus dieser PSA Gruppe hervorgegangen ist. Es hätte niemand vorhergesehen, dass Peugeot, Citroen, Fiat oder FCA mit all seinen Marken und Opel unter einer Führung stehen und somit das Händlernetz komplett neu aufstellen. Stellantis hat die Willensbekundigung geleistet, alle Fahrzeuge bei ihren KFZ-Händlern und Werkstätten zurückhaben zu wollen. Sie wollen die Verfügungsgewalt über die Batterie und das ist auch extremst sinnvoll. Rein aus dem Blickwinkel des Technikers: In verschiedenen Verfahren gibt es wirklich einen Knackpunkt, einen Break-Even-Point der kritischen Masse. Ich kann nicht eine Fabrik errichten für zwei Lithium-Batterien, das ist unmöglich. Eben um Gesamtkonzepte sinnvoll umzusetzen, bedarf es hier einer konzertierten und konzentrierten Sammlung. Nur dann können sinnvolle Projekte entstehen. Und die entstehen auch: im Süden von Graz gibt es eine Kooperation mit einigen Automobilherstellern gemeinsam mit AVL, die Messgeräte entwickelt haben für die komplette Batterie, bis hinunter auf die Modul- und Zellebene. Das sind intelligente Messgeräte, die dann, salopp gesagt, mit dem Anwender sprechen: ich hab noch soundso viele Ladezyklen, ich kann noch soundso lange leben, ich bin am Ende und muss in die stoffliche Verwertung, wie auch immer. Diese intelligent durchgetesteten Batterien können dann auch sinnvoll zugeordnet werden. Zum Beispiel dieser Energiepark, der für das gesamte Graz Energiekonzept in Zukunft wesentlich mehr Rolle spielen wird, ist quasi ein Containerpark, der befüllt wird mit alten Fahrzeug-Antriebsbatterien. Diese Container dienen als Zwischenspeicher wenn hier eine Spitzenlast produziert wird, wenn es viel Sonne gibt, wenn es viel Wind gibt, und und und. Dann wird das in diesen ehemaligen Antriebsbatterien gespeichert und bei einem Spitzenbedarf wieder abgerufen, und damit eine smarte Energiewirtschaft möglich. Wenn man hier weiterdenkt, ist das eine Möglichkeit, die einerseits im Kommunalbereich einen ganz wesentlichen Faktor in Zukunft ausmachen wird in der Energiewirtschaft, aber auch im Privatbereich. Zum Beispiel mit Photovoltaik: Viele Haushalte haben heute mittlerweile einen 10kW-Zwischenspeicher, das ist auch nichts anderes als ein Akku. Der ist wiederum kombinierbar mit einem 70kW-Speicher genannt Antriebsbatterie und jedenfalls über smarte Steuerung in der Lage, Spitzenlast und Spitzenbedarf auszugleichen. Von daher glaube ich ist grundsätzlich festzustellen, die Hersteller haben großes Interesse, die Batterien wieder in ihre Schiene zurückzubekommen. Es gibt unterschiedliche Zugang. Zum Beispiel in Kalsdorf bei Graz, wo dieser Containerpark entsteht. Andere Hersteller investieren gerade sehr viel in Forschung und Entwicklung, um Mikro-Reparaturen auf Zellebene durchzuführen, dass man das einzelne Element repariert um das Ganze wieder funktionsfähig zu machen. Dann gibt es wieder andere, die haben hier Allianzen gebildet mit Verwertern, zum Beispiel in Belgien, die sich um die stoffliche Verwertung dieser Lithium-Batterien und Metalle kümmern. Also es gibt mittlerweile sehr breit gestreut die verschiedensten Forschungssektoren. Die ergeben aber nur durchschlagend einen Sinn, wenn, so wie wir es in Österreich umgesetzt haben und es von beiden Seiten begrüßt wird: einerseits von den Herstellern, die die Importeure dirigieren und die Importeure verpflichten, die Altfahrzeuge zurückzunehmen - speziell die Elektroaltfahrzeuge in Zukunft. Und wir haben in den vergangenen Jahren auch darum gekämpft, dass KFZ-Händler und Kfz-Werkstätten, also die, die neue Fahrzeuge in Umlauf bringen, auch erlaubnisfrei Sammler für Altfahrzeuge sind und keine abfallrechtliche Genehmigung brauchen. Im Abfallwirtschaftsgesetz ist dann auch klargestellt, dass ein Ausbau von Batterien von KFZ-Händler und -Werkstätten auch erlaubt ist. Diese erlaubnisfreie Behandlung ist eine Riesenausnahme im Abfallwirtschaftsgesetz. Weitere Demontageschritte würden allerdings eine Behandlergenehmigung nach dem Abfallwirtschaftsgesetz benötigen. Zurzeit ist aber jedes einzelne Elektrofahrzeug noch ein Schulungsobjekt, jede Batterie eine Schulungsbatterie. Bei den Verwertern kommen natürlich auch Mengen an, aber die überwiegende Menge ist für Forschungs- und Schulungszwecke.

I: Die Batterie wird sicherlich eine andere Rolle einnehmen, wenn wir gesellschaftlich in ein anderes Energieversorgungssystem schreiten. Ich würde noch gerne auf die Materialgruppen, die ich in meiner Arbeit untersucht habe, zu sprechen kommen. Was den Stahl betrifft, ist vermutlich nicht allzu viel Veränderung zu erwarten, oder?

WK: Nein, in Wahrheit erleben wir einen Riesenumbruch in der Stahlindustrie. Wir merken eindeutig, dass sich die Konzerne neu orientieren. Die sogenannte Wasserstoffreduktion, um CO_2 einzusparen, ist in aller Munde. Das bedeutet eine riesige verfahrenstechnische Umstellung. Die Reduktion mit Wasserstoff funktioniert zwar sehr gut, aber mir hat bis jetzt noch niemand erklären können, woher die Energie kommen soll, um den Prozess flüssig zu erhalten, weil es muss ja dann der Rohstahl auch irgendwo herausrinnen. Das ist der große Unterschied zwischen endotherm und exotherm: Ich muss bei der Wasserstoffreduktion Energie zuführen, um es flüssig zu erhalten. Im Hochofen läuft das von selbst. Vielleicht ist auch deswegen der Atomstrom grün gelistet, damit in Zukunft die Wasserstoffreduktion in Europa mit Energie versorgt werden kann. Das wiederum bedeutet enorme Investitionen in Europa, die nach meiner Beobachtung sehr großzügig getätigt. Meine Prognose ist, dass man hier einerseits aus preispolitischen Gründen seitens der Stahlindustrie Exporte erschweren will, aber auch schon um genug Material zu haben für die kommenden Jahre und Jahrzehnte weil es wird der Schrotteinsatz mit Sicherheit erhöht werden in Europa. Dann haben wir nicht 112 oder 115% Deckung, sondern auf einmal nur mehr 90%. Das heißt auch beim Stahlschrott sehe durch diese Investitionen in neue Technologien, die auch wieder einen Massen-Break-Even haben, mehr Schrotteinsatz, weil es für den Schrotteinsatz auch CO_2-Boni gibt, und und und. Die Schrottnachfrage wird in Europa in den nächsten Jahren steigen. Auch bei anderen Metallen, das trau ich mich sagen. Vorausgesetzt natürlich es gibt eine vergleichbare Wirtschaftsentwicklung wie vor dem Ukraine-Krieg, das muss man jetzt ausklammern, weil ob die Welt morgen noch so ausschaut wie heute ist seit Februar 2022 zweifelhaft.

I: Sehr interessant. Aber die Bedeutung des Stahls für Elektroautos ist ja auch noch nicht klar, speziell das Aluminium-Stahl Verhältnis. Wenn wir bei den Metallen bleiben, was gibt es für Möglichkeiten heutzutage bzw. in Zukunft das wertvolle Kupfer vom Metallschrott zu extrahieren?

WK: Wenn in der Zerkleinerung in der Schreddermühle das Material so zerkleinert wird, dass das Kupfer in blanker Form vorliegt, dann wird das auch in stückiger Form als Rotmetallfraktion zurückgewonnen. Rotmetallfraktion deswegen, weil da nicht nur reines Kupfer drinnen ist, sondern mehrere Kupferlegierungen wie Messing, Rotguss, und Ähnliche. Es ist relativ einfach, Rotmetall und diese Graumetalle zu trennen, das geht über das spezifische Gewicht - Aluminium oder Messing ist zum Beispiel viel leichter als Kupfer und wird in einer Schwimm-Sink-Anlage getrennt. Aber in diese Schwimm-Sink-Anlage kommt nicht die ganze Restfraktion, sondern das ist davor schon über einen Wirbelstromscheider getrennt worden. Es gibt auch Sortiertechniken mittels Sensoren, die haben sich in Quantensprüngen weiterentwickelt. Speziell für die Problematik Kupfer in Stahlschrott, das ist eine bekannte Problematik und beim Schredder insofern ein Problem, weil moderne Autos mit bis zu 70 Elektromotoren ausgestattet sind: Fensterheber links, Fensterheber rechts, vorne, hinten, Schiebedach, Servolenkung, Kofferraum, und und und. Diese Rotoren, die einen Eisenkern und Kupferlegierungen haben, sind so klein, dass sie beim Schredder durch die Rostöffnungen durchgehen, ohne dass sie zur Gänze aufgesplittet werden. Das ist dann ein Eisen-Kupfer-Verbundstoff. Hier gibt es zwar die technische Möglichkeit mittels Röntgenstrahlsortierung, das Kupfer zu detektieren und lückenlos auszuschleusen, das ist aber eine extrem teure Anlage und lohnt sich bei wirklichen Großanalgen mit mehr als 150 Tonnen Output pro Stunde. Das hat in Österreich niemand. Die 6 Schredder in Österreich sind relativ klein und man hat hier sehr gute Erfahrungen mit der Handsortierung. Am Förderband lauft das Material vorbei und die Sortierer spüren bevor sie sehen, dass da ein Teil mit Kupfer vorbeikommt, und ist in seiner Arbeit auch sehr motiviert, weil es Prämien pro Kilogramm gibt, im Rahmen einer Gewinnbeteiligung. Diese Teile werden nicht weiter zerkleinert, weil eine Zerkleinerung sehr viele dieser Materialien aus denen die Wellen beschaffen sind - das sind oft Edelstähle - extrem verschleißintensiv wäre. Daher wird dieses Material in dieser Form auch gehandelt, nennt sich Verhüttungsmaterial, geht an die Kupferhütte und wird beim Schwarzkupfer eingeschmolzen. Weil die brauchen diesen Eisenanteil, das ist verfahrenstechnisch für die Kupferhütte total in Ordnung. Das wird dort in dieser Gesamtheit Schwarzkupfer eingeschmolzen. Kupfer und Eisen differenzieren im spezifischen Gewicht, das wird abgegossen, und dann hat man annähernd zwei reine Fraktionen. Das Kupfer wird dann noch weiterverarbeitet bis hin zur Elektrolyse und ist dann annähernd 100% rein. Und so wird jetzt einerseits blankes Kupfer erfasst, andererseits dieses Verhüttungsmaterial - das ist eben Stahl und Eisen mit bis zu 20,25% Kupferanteil für das Schwarzkupfer in der Kupferhütte. Und dann gibt es auch noch jede Menge Kabel, Kabelreste, mit und ohne Isolierung. Das befindet sich meist in der Schredderleichtfraktion, geht dann zur Post-Schredder-Technologie, wird dort aufwendig nachaufbereitet, so dass wirklich jede einzelne Kupferlitze freigelegt wird von der Isolierung und auch wirklich nahezu restlos alle Metalle zurückgewonnen werden. Die Kunststofffraktion geht dann in Österreich zu einem hohen Ausmaß in den Hochofen in Linz als Reduktionsmittel.

I: Es wird ja auch die Ausnahme von Kupfer bezüglich dem maximal erlaubten Bleianteil, die in Annex II festgehalten ist, diskutiert.

WK: Der Annex II bezieht sich ja auch auf diese HB-Kriterien, diese Kandidaten-Liste mit gefährlichen oder unerwünschten Stoffen, wie eben zum Beispiel Flammschutzhemmer, Weichmacher, aber natürlich auch Blei. Da gibt es aktuell das Problem, dass es einerseits die ECHA gibt, die europäische Chemikalienagentur mit Sitz in Helsinki, die REACH verwaltet, die Registration, Evaluation, Authorisation and Restriction of Chemicals-Verordnung, und wenn man ein Produkt auf den Markt bringen will, muss das grundsätzlich einmal die Anforderungen von REACH erfüllen. Und in den letzten Jahren hat man dieses Chemikalien-Recht in seiner Gesamtheit in ganz Europa über das Abfallrecht drüber gestellt. Das führt dann leider in vielen Punkten zu Verwerfungen, weil das Chemikalienrecht von einer risikobasierten Betrachtung ausgeht, das Abfallrecht aber von einer Betrachtung der Gefahren. Und Gefahr kommt von Fürchten, und in Österreich fürchtet man sich vor allem. Aber zu Tode gefürchtet ist auch gestorben.

So, jetzt gibt es diese HB-Kriterien, die führen aber dazu, dass zum Beispiel Altkabel in Österreich zum gefährlichen Abfall erklärt wurden, weil eben Blei und andere Substanzen drinnen sind. Ja, die sind drinnen. Aber in einer risikobasierten Betrachtung nach Chemikalienrecht muss man sagen, das Risiko, dass man ein Kabel isst oder einatmet, ist äußerst gering. Vielleicht ein Mader oder eine Ratte im Kabelkanal, aber die sterben weder am Weichmacher noch am Blei, sondern am Elektroschock. Also das Risiko ist annähernd null, weil die Weichmacher und auch das Blei, welches als Stabilisator in diesen Kabeln drinnen ist, extra hineinlegiert wurden, damit dieses Kabel 150 Jahre alt wird und sich nicht verabschiedet, wenn es irgendwo eingegraben ist, oder im Verputz verlegt im Haus, und und und. Aber durch die gefahrenbasierte Betrachtung und die mögliche Überschreitung von Grenzwerten, denkt man, das ist giftig. Und das ist ein ganz gravierendes Problem, weil wir ja nachweislich orten können, dass diese Stoffe, die da drinnen sind, zu keinem Zeitpunkt bioverfügbar sind und nichts und niemanden schädigen können. Ähnlich wie eine Hochofenschlake, da sind die Giftstoffe im Gestein der Schlake gebunden und kommt da nie mehr raus. Beispiel: Ein Kristallglas aus dem wir trinken, hat über 30% Blei. Das Abfallrecht fürchtet sich davor, das Chemikalienrecht kennt dazu nicht einmal ein Sicherheitsdatenblatt, weil es nicht bioverfügbar ist. Aus dieser Divergenz hat die Chemie mit Recht erkannt, diese Stoffe sind unerwünscht. Niemand will Bisphenol-A, Bisphenol-B, etc. und das soll auch ausgeschleust werden. Aber den Bogen zu überspannen und Dinge zu verbieten nur weil es gerade modern ist, ist auch nicht die Lösung. Wenn man die Produktion der gesamten Automobilindustrie hernimmt und berechnet, wie groß die Gesamtmasse an Blei ist, die nach Annex II überhaupt noch erlaubt ist, ist das nur ein Bruchteil dessen was als Munition allen im Burgenland an Bleischrott auf Wasservögel gejagt wird. Der Bleischrott gelangt dann in den nassen Grund und Boden, oxidiert dort und dann aber schon bioverfügbar ist - und das ist immer noch erlaubt. Mein Zugang ist immer: Für die Umwelt in erster Linie, und gegen die Bürokratie. Und der nächste Punkt ist die Verhältnismäßigkeit. In der Praxis wird niemand etwas erfüllen, das nicht nachvollziehbar ist.

Die Hersteller haben mit diesem Annex II genug Probleme, weil diese zwei Zugänge noch nicht zusammengeführt sind.

I: Zum Abschluss möchte ich noch auf Kunststoffe zu sprechen kommen. In Fahrzeugen wird ja das meiste nicht wiederverwendet. Glauben Sie, dass sich daran etwas ändern wird?

WK: Kunststoff ist ganz eine eigene Problematik, wenn man den Blick in die Zukunft richtet. Es stellt sich wieder die Frage, ob nicht Verwertungs- sondern Einsatzquoten tatsächlich der richtige Weg sind. Wir wissen mittlerweile, dass sich Kunststoff aus vielen Rohstoffmaterialien herstellen lässt; Cellulose, Holz, in den 20er Jahren hat Ford schon Karosserien mit Kunststoff aus Hanf hergestellt, die haben wunderbar funktioniert. Ich denke, dass hier mehr und mehr ein Trend verfolgt werden wird von der Automobilindustrie, naturgewonnene, nachwachsende Materialien, aber auch Öko-Kunststoffe, die nicht aus Erdöl produziert werden, zu verwenden. Angenommen es würde sich tatsächlich eine Karosserie aus einem Hanfkunststoff durchsetzen, wie soll man dem zum Beispiel Polyethylen-Granulate beimengen... Das heißt, ich sehe das übliche Bild in der Gesetzgebung: Man ist zwar auf den Augenblick fixiert, aber schon wieder Jahre hinten nach, weil der Prozess zu lange dauert. Bis das Gesetz in Kraft tritt, ist es eigentlich schon wieder überholt, und die Anwender stolpern in die Schlinge, die dieses Gesetz legt. Und das sehe ich auch mit der neuen ELV-Richtlinie wieder so kommen - das als relativ gesicherte Prognose *(lacht.)* Ich glaube, dass noch viele Erfahrungen gewonnen werden müssen mit der kommenden Batterie-Verordnung. Dann wird man erst wirklich sehen, wohin der Zug rollt, wohin geht das Gefällte. Wie unser österreichischer Philosoph Herr Liessmann sagt: Das Gefälle geht immer in Richtung des Geldes und man kann mit dem Geld alles steuern.

Da komme ich zurück auf eine Frage, die Sie zuvor gestellt haben: Was wäre sozusagen die Lösung, um durch Abmeldungen ein gesichertes Einbringen in die Verwertungsschiene zu sichern? Vor zwanzig Jahren habe ich mit dem leider verstorbenen Peter Jung, der der Gründer der Altauto.at war, ein Modell entwickelt, das nennt sich Kautionsmodell. Und eine Kaution ist juristisch ganz genau definiert und etwas anderes als ein Pfand. Bei einer Wohnungsvermietung dient sie dazu, dass sichergestellt ist, dass Schäden am Mietobjekt am Ende durch die Kaution gedeckt werden können. Und ein solches Modell hätten wir für die Altfahrzeuge entwickelt, und haben uns auch preislich an diesem Schwarz- und Graumarkt orientiert und gesagt, würde diese Kaution 500 Euro ausmachen - und bei einem Fahrzeugpreis von 20.000 Euro, was ist dann 500 Euro Kaution, die man am Ende wieder zurückbekommt? Wir haben das finanztechnisch sehr gut überlegt, haben dieses Modell für ganz Europa entwickelt, mit dem Hintergedanken, dass die eingenommene Kaution in die Aktien der Automobilindustrie investiert wird logischerweise. Dadurch erleben diese logischerweise auch eine Verzinsung und nach 15 Jahren Lebensdauer sind aus diesen 500 Euro, keine Ahnung, 750 geworden. Würde der Letzthalter bei seiner Abmeldung diese 750 Euro ausbezahlt bekommen, hätte er auch einen Anreiz, sein Auto in die Verwertungskette einzubringen. Würde der Afrikaner mehr bezahlen als 750 Euro, dann ist es mit Fug und Recht ein Gebrauchtfahrzeug. Weil die werden gehandelt um in etwa 200 Euro. Dieses Kautionsmodell ist extrem gut angekommen - aber leider nicht bei allen Herstellern, und so hat es in Europa keine Einigung gegeben und dieses Modell hat sich nie umgesetzt. Aber es ging eben um diesen finanziellen Anreiz, den in Wahrheit die Fahrzeugkäufer selbst bezahlen. Diese Kaution ist auch begründet durch das Gesetz selbst, denn die Verantwortung liegt beim Hersteller. Und wie bitte kann der Hersteller die Verantwortung tragen, wenn der Letztbesitzer aber entscheidet, was mit dem Auto passiert.

I: Korrekt. Das ist wirklich ein interessantes Modell - da bin ich sehr froh, dass wir darauf noch zu sprechen gekommen sind. Ich danke Ihnen allgemein für Ihr Antworten und dieses interessante Gespräch!

Ing. Water Kletzmayr is CEO of the Austrian ARGE-Schredder GmbH, a consortium of six Austrian shredder companies. The interview was held on May 4th, 2022, via Zoom.

Annex B: Data and Calculations

B.1 Figure 16: New car registrations by fuel type in the EU

Period	Diesel	Petrol	BEV	PHEV	HEV
2017	6,617,051	7,563,739	97,920	120,416	426,769
2018	5,402,079	8,521,418	147,694	152,844	598,462
2019	4,650,558	8,964,034	285,347	174,103	896,785
2020	2,776,665	4,724,417	538,734	507,917	1,184,526
2021	1,901,191	3,885,432	878,432	867,092	1,901,239

Figures for 2017 and 2018 are taken from (ACEA, 2019).
Figures for 2019 are taken from (ACEA, 2020b).
Figures for 2020 and 2021 are taken from (ACEA, 2022b).

B.2 Calculation of the MFA of ELVs in 2019 (Figure 5)

Item	Calculation	Description
Sold cars	13,006,331	New car registrations in 2019 (ACEA, 2022d)
	*(6,889,000:6,057,000)	Total vehicle weight of ELVs 2019:Number of ELVs in 2019 (Eurostat, 2022)
	= 14,792,903	New car registrations in 2019 in tons
Cars in use	243,491,725	Passenger cars in use in 2019 (ACEA, 2022a)
	*(6,889,000:6,057,000)	Total vehicle weight of ELVs in 2019 in tons:Number of ELVs in 2019 (Eurostat, 2022)
	= 276,938,170	Cars in use in tons
Deregistered cars	4,000,000	Vehicles of unknown whereabouts in 2019 (European Commission, 2021)
	: 0.35	Percentage of total deregistered cars that are

		vehicles of unknown whereabouts (European Commission, 2021)
	*(6,889,000:6,057,000)	Total vehicle weight of ELVs in 2019 in tons:Number of ELVs in 2019 (Eurostat, 2022)
	= 12,998,420	Deregistered cars in 2019 in tons
Unknown whereabouts	4,000,000	Cars of unknown whereabouts (European Commission, 2021)
	*(6,889,000:6,057,000)	Total vehicle weight of ELVs in 2019 in tons:Number of ELVs in 2019 (Eurostat, 2022)
	= 4,549,447	Deregistered cars of unknown whereabouts in 2019 in tons
Reported ELVs	6,057,000	Number of ELVs in 2019
	*(6,889,000:6,057,000)	Total vehicle weight of ELVs in 2019 in tons:Number of ELVs in 2019 (Eurostat, 2022)
	= 6,889,000	Reported ELVs in 2019 in tons
Export	12,998,420	Deregistered cars in 2019 in tons
	- 4,549,447	Deregistered cars of known whereabouts in 2019 in tons
	- 6,889,000	Reported ELVs in 2019 in tons
	= 1,559,973	Exported ELVs in 2019 in tons
Recycled	6,889,000	Reported ELVs in 2019 in tons
	*0.896	Reuse and recycling rate of ELVs in 2019 (Eurostat, 2022)
	= 6,172,544	Recycled ELV material in 2019 in tons
Recovered	6,889,000	Reported ELVs in 2019 in tons

	*0.055	Reuse and recovery rate minus recycling rate in 2019 (Eurostat, 2022)
	= 378,895	Recovered ELV material in 2019 in tons
Non-reusable material	6,889,000	Reported ELVs in 2019 in tons
	- 6,172,544	Recycled ELV material in 2019 in tons
	- 378,895	Recovered ELV material in 2019 tons
	= 337,561	Non-reusable material in 2019 in tons

All figures refer to the EU.

B.3 Calculation of the MFA of ELVs in 2045 (Figure 7)

Item	**Calculation**	**Description**
Cars in use	525,000,000	Population in 2045 (Eurostat, 2019)
	*0.51	Estimated motorization rate in 2045 based on (Shell Deutschland, 2014)
	267,750,000	Cars in use in 2045
	*[(0.86*1.14)	Estimated vehicle curb weight in 2045 in tons based on (Bailo, et al., 2020)
	+0.500]	Estimated battery-pack weight in 2045 in tons based on (Enrg.io, 2020)
	= 395,769,599	Cars in use in 2045 in tons
Sold cars	395,769,599	Cars in use in 2045 in tons
	: 15	Average lifetime of a car based on (European Commission, 2021)
	= 26,384,640	New car registrations in 2045 in tons
Deregistered cars	395,769,599	Cars in use in 2045 in tons
	: 15	Average lifetime of a car based on (European Commission, 2021)

	= 26,384,640	Deregistered cars in 2045 in tons
Unknown whereabouts	26,384,640	Deregistered cars in 2045 in tons
	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts based on (European Commission, 2021)
	= 9,234,624	Deregistered cars of unknown whereabouts in 2045 in tons
Export	26,384,640	Deregistered cars in 2045 in tons
	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 3,166,487	Exported ELVs in 2045 in tons
Reported ELVs	26,384,640	Deregistered cars in 2045 in tons
	- 9,234,624	Deregistered cars of known whereabouts in 2045 in tons
	- 3,166,487	Exported ELVs in 2045 in tons
	= 13,983,529	Reported ELVs in 2045 in tons
Recycled	13,983,529	Reported ELVs in 2045 in tons
	*0.85	Estimated reuse and recycling rate of ELVs in 2045 based on (Eurostat, 2022)
	= 11,886,000	Recycled ELV material in 2045 in tons
Recovered	13,983,529	Reported ELVs in 2045 in tons
	*0.1	Estimated reuse and recovery rate minus recycling rate in 2045 based on (Eurostat, 2022)
	= 1,398,353	Recovered ELV material in 2045 in tons
Non-reusable material	13,983,529	Reported ELVs in 2045 in tons
	- 11,886,000	Recycled ELV material in 2045 in tons

	- 1,398,353	Recovered ELV material in 2045 in tons
	= 699,176	Non-reusable material in 2045 in tons

All figures refer to the EU.

B.4 Calculation of the MFA of steel in 2019 (Figure 8)

Item	**Calculation**	**Description**
Sold cars	13,006,331	New car registrations in 2019 (ACEA, 2022d)
	*0.9	Average weight of steel per car in 2019 in tons (World Steel Association, n.d.)
	= 11,705,698	Amount of steel in sold cars in 2019 in tons
Cars in use	243,491,725	Passenger cars in use in 2019 (ACEA, 2022a)
	*0.9	Average weight of steel per car in 2019 in tons (World Steel Association, n.d.)
	= 219,142,553	Steel in cars in use in 2019 in tons
Deregistered cars	11,428,571	Deregistered cars in 2019 based on B.2
	*0.9	Average weight of steel per car in 2019 in tons (World Steel Association, n.d.)
	= 10,285,714	Steel in deregistered cars in 2019 in tons
Unknown whereabouts	10,285,714	Steel in deregistered cars in 2019 in tons
	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts based on (European Commission, 2021)
	= 3,600,000	Steel in deregistered cars of unknown whereabouts in 2019 in tons
Export	10,285,714	Steel in deregistered cars in 2019 in tons

	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 1,234,414	Exported ELV steel in 2019 in tons
Reported ELVs	10,285,714	Steel in deregistered cars in 2019 in tons
	- 3,600,000	Steel in deregistered cars of unknown whereabouts in 2019 in tons
	- 1,234,414	Exported ELVs in 2019 in tons
	= 5,451,300	Reported ELV steel in 2019 in tons
Recycled	5,451,300	Reported ELV steel in 2019 in tons
	*0.94	Reuse and recycling rate of ELV steel in 2019 based on (Merkisz-Guranowska, 2018)
	= 5,124,222	Recycled ELV steel in 2019 in tons
Recovered	5,451,300	Reported ELV steel in 2019 in tons
	*0.0	Estimated reuse and recovery rate minus recycling rate in 2019
	= 0	Recovered ELV material in 2019 in tons
Non-reusable material	5,451,300	Reported ELV steel in 2019 in tons
	*0.06	Estimated rate of non-recycled material based on (Merkisz-Guranowska, 2018)
	= 327,078	Non-reusable ELV steel in 2019 in tons

All figures refer to the EU.

B.5 Calculation of the MFA of steel in 2045 (Figure 9)

Item	**Calculation**	**Description**
Sold cars	17,850,000	New car registrations in 2045 based on B.3

	*0.489	Estimation of the average weight of steel per car in 2045 in tons
	= 8,728,650	Steel in sold cars in 2045
Cars in use	267,750,000	Cars in use in 2045 based on B.3
	*0.489	Estimation of the average weight of steel per car in 2045 in tons
	= 130,929,750	Steel in cars in use in 2045 in tons
Deregistered cars	17,850,000	Deregistered cars in 2045 based on B.3
	*0.489	Estimation of the average weight of steel per car in 2045 in tons
	= 8,728,650	Steel in deregistered cars in 2045 in tons
Unknown whereabouts	8,728,650	Steel in deregistered cars in 2045 in tons
	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts (European Commission, 2021)
	= 3,055,028	Steel in deregistered cars of known whereabouts in 2045 in tons
Export	8,728,650	Steel in deregistered cars in 2045 in tons
	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 1,047,547	Exported ELV steel in 2045 in tons
Reported ELVs	8,728,650	Steel in deregistered cars in 2045 in tons
	- 3,055,028	Steel in deregistered cars of unknown whereabouts in 2045 in tons
	- 1,047,547	Exported ELV steel in 2045 in tons
	= 4,626,075	Reported ELV steel in 2045 in tons
Recycled	4,626,075	Reported ELV steel in 2045 in tons

	*1	Assumed reuse and recycling rate of ELV steel in 2045
	= 4,626,075	Recycled ELV steel in 2045 in tons

All figures refer to the EU.

B.6 Calculation of the MFA of aluminum in 2019 (Figure 10)

Item	**Calculation**	**Description**
Sold cars	13,006,331	New car registrations in 2019 (ACEA, 2022d)
	*0.180	Average weight of aluminum per car in 2019 in tons (Drucker Frontier, 2019)
	= 2,341,140	Aluminum in sold cars in 2019 in tons
Cars in use	243,491,725	Passenger cars in use in 2019 (ACEA, 2022a)
	*0.180	Average weight of aluminum per car in 2019 in tons (Drucker Frontier, 2019)
	= 43,828,511	Aluminum in cars in use in 2019 in tons
Deregistered cars	11,428,571	Deregistered cars in 2019 based on B.3
	*0.180	Average weight of aluminum per car in 2019 in tons (Drucker Frontier, 2019)
	= 2,057,143	Aluminum in deregistered cars in 2019 in tons
Unknown whereabouts	2,057,143	Aluminum in deregistered cars in 2019 in tons
	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts (European Commission, 2021)

	= 720,000	Aluminum in deregistered cars of unknown whereabouts in 2019 in tons
Export	2,057,143	Aluminum in deregistered cars in 2019 in tons
	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 246,883	Exported ELV aluminum in 2019 in tons
Reported ELVs	2,057,143	Aluminum in deregistered cars in 2019 in tons
	- 720,000	Aluminum in deregistered cars of unknown whereabouts in 2019 in tons
	- 246,883	Exported ELV aluminum in 2019 in tons
	= 1,090,260	Reported ELV aluminum in 2019 in tons
Recycled	1,090,260	Reported ELV aluminum in 2019 in tons
	*0.95	Reuse and recycling rate of ELV aluminum in 2019 based on (European Aluminum, 2020)
	= 1,035,747	Recycled ELV steel in 2019 in tons
Recovered	1,090,260	Reported ELV aluminum in 2019 in tons
	*0.0	Estimated reuse and recovery rate minus recycling rate in 2019 (Eurostat, 2022)
	= 0	Recovered ELV material in 2019 in tons
Non-reusable material	1,090,260	Reported ELV aluminum in 2019 in tons
	*0.05	Estimated rate of non-recycled aluminum

		based on (European Aluminum, 2020)
	= 54,513	Non-reusable ELV steel in 2019 in tons

All figures refer to the EU.

B.7 Calculation of the MFA of aluminum in 2045 (Figure 11)

Item	**Calculation**	**Description**
Sold cars	17,850,000	New car registrations in 2045 based on B.3
	*0.225	Estimation of the average weight of aluminum per car in 2045 in tons based on (Djukanovic, 2018)
	= 4,016,250	Aluminum in sold cars in 2045 in tons
Cars in use	267,750,000	Cars in use in 2045 based on B.4
	*0.225	Estimation of the average weight of aluminum per car in 2045 in tons based on (Djukanovic, 2018)
	= 60,243,750	Aluminum in cars in use in 2045 in tons
Deregistered cars	17,850,000	Deregistered cars in 2045 based on B.4
	*0.225	Estimation of the average weight of aluminum per car in 2045 in tons based on (Djukanovic, 2018)
	= 4,016,250	Aluminum in deregistered cars in 2045 in tons
Unknown whereabouts	4,016,250	Aluminum in deregistered cars in 2045 in tons
	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts (European Commission, 2021)
	= 1,405,688	Aluminum in deregistered cars of

		unknown whereabouts in 2045 in tons
Export	4,016,250	Aluminum in deregistered cars in 2045 in tons
	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 482,000	Exported ELV aluminum in 2045 in tons
Reported ELVs	4,016,250	Aluminum in deregistered cars in 2045 in tons
	- 1,405,688	Aluminum in deregistered cars of unknown whereabouts in 2045 in tons
	- 482,000	Exported ELV aluminum in 2045 in tons
	= 2,128,562	Reported ELV aluminum in 2045 in tons
Recycled	2,128,562	Reported ELV aluminum in 2045 in tons
	*1	Assumed reuse and recycling rate of ELV aluminum in 2045
	= 2,128,562	Recycled ELV aluminum in 2045 in tons

All figures refer to the EU.

B.8 Calculation of the MFA of copper in 2019 (Figure 12)

Item	**Calculation**	**Description**
Sold cars	13,006,331	New car registrations in 2019 (ACEA, 2022d)
	*0.019	Average weight of copper per car in 2019 in tons (Öko-Institut e.V., 2009a)
	= 247,120	Copper in sold cars in 2019 in tons
Cars in use	243,491,725	Passenger cars in use in 2019 (ACEA, 2022a)

	*0.019	Average weight of copper per car in 2019 in tons (Öko-Institut e.V., 2009a)
	= 4,626,343	Copper in cars in use in 2019 in tons
Deregistered cars	11,428,571	Deregistered cars in 2019 based on B.3
	*0.019	Average weight of copper per car in 2019 in tons (Öko-Institut e.V., 2009a)
	= 217,143	Copper in deregistered cars in 2019 in tons
Unknown whereabouts	217,143	Copper in deregistered cars in 2019 in tons
	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts (European Commission, 2021)
	= 76,000	Copper in deregistered cars of known whereabouts in 2019 in tons
Export	217,143	Copper in deregistered cars in 2019 in tons
	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 26,060	Exported ELV copper in 2019 in tons
Reported ELVs	217,143	Copper in deregistered cars in 2019 in tons
	- 76,000	Copper in deregistered cars of unknown whereabouts in 2019 in tons
	- 26,060	Exported ELV copper in 2019 in tons
	= 115,083	Reported ELV copper in 2019 in tons
Recycled	115,083	Reported ELV copper in 2019 in tons
	*0.6	Reuse and recycling rate of ELV copper in 2019 based on (Merkisz-Guranowska, 2018)

	= 69,050	Recycled ELV copper in 2019 in tons
Non-reusable material	115,083	Reported ELV copper in 2019 in tons
	*0.4	Estimated rate of non-recycled copper based on (Merkisz-Guranowska, 2018)
	= 46,033	Non-reusable ELV copper in 2019 in tons

All figures refer to the EU.

B.10 Calculation of the MFA of copper in 2045 (Figure 13)

Item	**Calculation**	**Description**
Sold cars	17,850,000	New car registrations in 2045 based on B.3
	*0.083	Estimation of the average weight of copper per car in 2045 in tons based on (Copper Development Association Inc., 2022)
	= 1,481,550	Copper in sold cars in 2045 in tons
Cars in use	267,750,000	Cars in use in 2045 based on B.4
	*0.083	Estimation of the average weight of copper per car in 2045 in tons based on (Copper Development Association Inc., 2022)
	= 22,223,250	Copper in cars in use in 2045 in tons
Deregistered cars	17,850,000	Deregistered cars in 2045 based on B.3
	*0.083	Estimation of the average weight of copper per car in 2045 in tons based on (Copper Development Association Inc., 2022)
	= 1,481,550	Copper in deregistered cars in 2045 in tons
Unknown whereabouts	1,481,550	Copper in deregistered cars in 2045 in tons

	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts (European Commission, 2021)
	= 518,543	Copper in deregistered cars of unknown whereabouts in 2045 in tons
Export	1,481,550	Copper in deregistered cars in 2045 in tons
	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 177,805	Exported ELV copper in 2045 in tons
Reported ELVs	1,481,550	Copper in deregistered cars in 2045 in tons
	- 518,543	Copper in deregistered cars of unknown whereabouts in 2045 in tons
	- 177,805	Exported ELV copper in 2045 in tons
	= 785,202	Reported ELV copper in 2045 in tons
Recycled	= 785,202	Reported ELV copper in 2045 in tons
	*0.85	Assumed reuse and recycling rate of ELV copper in 2045
	= 667,422	Recycled ELV copper in 2045 in tons
Non-reusable material	785,202	Reported ELV copper in 2045 in tons
	*0.15	Estimated rate of non-recycled copper in 2045 based on (Merkisz-Guranowska, 2018)
	= 117,780	Non-reusable ELV copper in 2045 in tons

All figures refer to the EU.

B.11 Calculation of the MFA of plastics in 2019 (Figure 14)

Item	**Calculation**	**Description**

Sold cars	13,006,331	New car registrations in 2019 (ACEA, 2022d)
	*0.170	Average weight of plastics per car in 2019 in tons based on (European Commission, 2021)
	= 2,211,076	Plastics in sold cars in 2019 in tons
Cars in use	243,491,725	Passenger cars in use in 2019 (ACEA, 2022a)
	*0.170	Average weight of plastics per car in 2019 in tons based on (European Commission, 2021)
	= 41,393,593	Plastics in cars in use in 2019 in tons
Deregistered cars	11,428,571	Deregistered cars in 2019 based on B.3
	*0.170	Average weight of plastics per car in 2019 in tons based on (European Commission, 2021)
	= 1,942,857	Plastics in deregistered cars in 2019 in tons
Unknown whereabouts	1,942,857	Plastics in deregistered cars in 2019 in tons
	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts (European Commission, 2021)
	= 680,000	Plastics in deregistered cars of unknown whereabouts in 2019 in tons
Export	1,942,857	Plastics in deregistered cars in 2019 in tons
	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 233,167	Exported ELV copper in 2019 in tons
Reported ELVs	1,942,857	Plastics in deregistered cars in 2019 in tons
	- 680,000	Plastics in deregistered cars of unknown

		whereabouts in 2019 in tons
	- 233,167	Exported ELV copper in 2019 in tons
	= 1,029,690	Reported ELV plastics in 2019 in tons
Recycled	1,029,690	Reported ELV plastics in 2019 in tons
	*0.026	Reuse and recycling rate of ELV plastics in 2019 based on (Cardamone, Ardolino, & Arena, 2022)
	= 26,772	Recycled ELV plastics in 2019 in tons
Recovered	1,029,690	Reported ELV plastics in 2019 in tons
	*0.55	Thermal recovery rate of ELV plastics based on (Cardamone, Ardolino, & Arena, 2022)
	= 566,330	Recovered ELV plastics in 2019 in tons
Non-reusable material	1,029,690	Reported ELV plastics in 2019 in tons
	- 26,772	Recycled ELV plastics in 2019 in tons
	- 566,330	Recovered ELV plastics in 2019 in tons
	= 436,588	Non-reusable ELV plastics in 2019 in tons

All figures refer to the EU.

B.12 Calculation of the MFA of plastics in 2045 (Figure 15)

Item	**Calculation**	**Description**
Sold cars	17,850,000	New car registrations in 2045 based on B.3
	*0.296	Estimation of the average weight of plastics per car in 2045 in tons based on (European Commission, 2021)
	= 5,283,600	Plastics in sold cars in 2045 in tons

Cars in use	267,750,000	Cars in use in 2045 based on B.3
	*0.296	Estimation of the average weight of plastics per car in 2045 in tons based on (European Commission, 2021)
	= 79,254,000	Plastics in cars in use in 2019 in tons
Deregistered cars	17,850,000	Deregistered cars in 2045 based on B.3
	*0.296	Estimation of the average weight of plastics per car in 2045 in tons based on European Commission 2021
	= 5,283,600	Plastics in deregistered cars in 2045 in tons
Unknown whereabouts	5,283,600	Plastics in deregistered cars in 2045 in tons
	*0.35	Percentage of total deregistered cars that are vehicles of unknown whereabouts (European Commission, 2021)
	= 1,849,260	Plastics in deregistered cars of known whereabouts in 2045 in tons
Export	5,283,600	Plastics in deregistered cars in 2045 in tons
	*(1,559,973:12,998,420)	Share of official export based on B.2 and (Eurostat, 2022)
	= 634,098	Exported ELV plastics in 2045 in tons
Reported ELVs	5,283,600	Plastics in deregistered cars in 2045 in tons
	- 1,849,260	Plastics in deregistered cars of unknown whereabouts in 2045 in tons
	- 634,098	Exported ELV plastics in 2045 in tons
	= 2,800,242	Reported ELV plastics in 2045 in tons

Recycled	2,800,242	Reported ELV plastics in 2045 in tons
	*0.504	Estimated reuse and recycling rate of ELV plastics in 2045 based on (Cardamone, Ardolino, & Arena, 2022)
	= 1,411,322	Recycled ELV plastics in 2045 in tons
Recovered	2,800,242	Reported ELV plastics in 2045 in tons
	*(1-0.504)	Estimated thermal recovery rate of ELV plastics based on (Cardamone, Ardolino, & Arena, 2022)
	= 1,388,920	Recovered ELV plastics in 2045 in tons
Non-reusable material	2,800,242	Reported ELV plastics in 2045 in tons
	- 1,411,322	Recycled ELV plastics in 2045 in tons
	- 1,388,920	Recovered ELV plastics in 2045 in tons
	= 0	Non-reusable ELV plastics in 2045 in tons

All figures refer to the EU.